Policy Incentives to Prevent Introduction of Non-Indigenous Species Via Shipping

Hyma Gollamudi, 1995
The Ohio State University

Thesis and Dissertation Series
OHSU-TD-063

The Ohio State University
Ohio Sea Grant College Program
1995

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Funding Support

This publication (OHSU-TD-063) is a result of work from Ohio Sea Grant's research project *A Policy Framework for Nonindigenous Species in the Great Lakes* by Alan Randall at The Ohio State University, as project R/ZM-14, grant NA26RG0445 from the National Sea Grant College Program of the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. Support is also provided by the Ohio Board of Regents, The Ohio State University, Ohio State University Extension, and participating universities. The Ohio Sea Grant College Program is administered by The Ohio State University.

POLICY INCENTIVES TO PREVENT THE INTRODUCTION OF NON INDIGENOUS SPECIES VIA SHIPPING

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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* * * * *

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1995

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ACKNOWLEDGMENTS

My sincere thanks to Prof. Alan Randall for his excellent guidance throughout the research. His capacity to understand any given problem, and foresee its depth and breath will never cease to amaze me. Although it is a joyous occasion for me to be graduating, there is a certain amount of regret in losing his association. I also thank Dr. Schnitkey for his valuable guidance especially in the final stages of my research. Sincere thanks to Dr. Sheldon for his timely suggestions and comments.

Special thanks to Prof. Carlton of Williams College, Mystic, Connecticut, who widened my knowledge base tremendously. His sincere concern and continuous support is much appreciated; his friendship is much valued.

My heartfelt thanks to my parents who taught me the importance of being a good person; and to my father-in-law, Dr. G.S. Rao, for his continuous encouragement. Special thanks to my good friends, Shubhra and Damitha, who always believed in me.

My admiration and gratitude to our six-month old daughter, Shreya, who adjusted to my crazy schedule without any complaint; and to my husband, Chandra, who has been a pillar of support throughout this research. Since words cannot express what he means to me, I dedicate this thesis to him, as a small token of my appreciation.

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POLICY INCENTIVES TO PREVENT INTRODUCTION OF NON-INDIGENOUS SPECIES VIA SHIPPING

By

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Invasion of non-indigenous species poses an ecological threat to local environments and also has a major economic impact on local communities. Ballast water carried by ships is one of the ways through which these exotic species get transported to alien ecosystems. Mid-Ocean Exchange (MOE) of ballast water can control these introductions to some extent, but is recommended as transitory option only, because of some inherent problems with it. A list of permanent technology options are currently under consideration by the scientific community. This study provides (i) a monitoring mechanism to ensure that ships follow MOE in the short run; and (ii) incentives, using asset replacement principles, for adopting permanent technology in long-run.

A state-dependent monitoring scheme, which allows for dynamic transition among states is chosen. Using a game-theoretic format, all ships are divided into three groups depending on their past compliance history. Probabilities of monitoring and other penalties for violation (of MOE) differ according to group. This scheme is both cost effective (to the monitoring agency due to low probabilities of monitoring) and politically feasible (due to low fines and penalties).

Ships comply with MOE when (i) monitoring cost transferred to ships in compliance is less than those in non-compliance; and (ii) cost of compliance is less than cost of non-compliance. Analysis shows that over 96% of ships comply with MOE under this scheme. We also obtain the minimum monitoring pressure needed to ensure compliance and calculate budgetary needs.

The scheme is formulated so that the stream of costs associated with MOE increase with number of trips to port. This aspect, along with decreased annualized cost of permanent technology becomes a strong incentive for ships to adopt permanent technology in the long run.

The proposed scheme is tested with two case studies. The savings to the monitoring agency by adopting this scheme is shown to be anywhere from 25% to 93%. This is one of the few studies that combines monitoring mechanism with asset replacement principles to not only ensure compliance with low costs, but also provide incentives for adoption of preferred technology.

CHAPTER I

INTRODUCTION

There is an increasing awareness regarding water pollution in recent literature. Most studies discuss how agricultural run-off, toxic dumps, sedimentation etc., affect water quality. There is yet another kind of problem with water systems that is beginning to get the attention of the professional community. It is the invasion of non-indigenous aquatic organisms into local bodies of water. Exotic organisms enter native water systems frequently via various routes. Sometimes these organisms not only survive the alien environment but establish themselves successfully and, if not checked in time, become a nuisance species. They may be introduced purposefully or they may enter accidentally through international shipping. Accidental introductions are more problematic since the nature of the species that enters the ecosystem is unknown.

Introduction through international shipping occurs mainly in and around ports where ships dock in order to load/unload their cargo. Ships take sea water into their ballast tanks either at the beginning of the voyage, and/or during voyage, and retain it till their destination. These waters help in stabilizing and trimming the ship. Normally, ships pump-out (deballast) water at the time of fueling or while loading cargo and pump-in (ballast) water at the time of unloading. The extent of these ballast operations is determined by the cargo, weather, wind pattern etc. It is estimated that in 1991 alone over 19,686,000,000 gallons (57,000,000 metric tons) of ballast water was released in U.S. ports (NABISS, 1995). When water is ballasted-in at the departing port, marine organisms are also pumped in. These organisms sometimes survive the long voyages and enter the new waters where they are released along with the ballast water. Some do not survive in the new environment, some survive but remain benign, while a few others not only survive but also become aggressive in the new environment. They interfere with the food chain and, if no predator exists, may bring about an ecological imbalance. The Zebra mussel in the Great Lakes is a case in point. More than 95% of all vessels sampled in U.S., Canadian, and Australian studies have been found to contain living organisms in their ballast water and sediments(NABISS,1995; Costlow et al,1984; Carlton, 1987,1989; Allen, 1952). Hence, ballast water is a likely mode of transportation for a wide variety of marine organisms.

1.1 The Problem

Most aquatic ecosystems are vulnerable to invasion by non-indigenous species (NIS). The problem is extremely severe in the case of fresh water systems like the Great Lakes. Although there are both benefits and costs to such invasions, it is often the detrimental introductions that motivate a concern about policy. An invasion by nuisance species can cause both ecological and economic damage--it can cause a reduction in the biodiversity of the ecosystem and also affect the services provided by the ecosystem to the local communities. For instance, the Zebra mussel in the Great Lakes has not only negatively affected the biodiversity of the Lakes, but has also been causing numerous problems for utility companies which use raw water, by clogging their water intake pipes. It is estimated that the economic impact on the communities affected by its introduction into the Great Lakes may reach five billion dollars by the year 2000 (Federal Register, 1993).

Hundreds of such exotic species have already been accidentally released in the U.S. waters and will continue to be released in the future. One can easily visualize the potential damage from harmful introductions in future. In order to control such costs a coherent policy is needed regarding the introduction of non-indigenous species via shipping.

1.2 The Policy

Policy responses have to be different depending upon the type of introduction. In the case of purposeful introductions, policies can be framed to control them and discourage escapement. Policy responses are generally more difficult to frame in case of inadvertent introductions. Here the focus is on minimizing the probability of such introductions. Inspection, quarantine, eradication of biota before release etc., can be used as instruments in controlling such releases. A good policy should outline procedures to be followed by concerned parties to mitigate the possibility of such introductions.

This study will focus on inadvertent introductions via shipping. The two main parties to this policy are the shipping industry and the (government) agencies concerned with the issue of non-indigenous species introduction. A "good" policy is one which considers the constraints and limitations under which each party operates and offers only those solutions which are feasible and which can be implemented by both parties. As regards the shipping industry this means a minimal disruption in their economic operations. As for the authorities, administrative/political feasibility, trade and social welfare aspects are important. Furthermore, the options/alternatives suggested by the policy should be cost effective and within the budget constraints of both parties. This study will provide a coherent package of incentives that will encourage ships to follow/adopt certain regulations that will achieve some of the above objectives. These regulations will be framed in the most cost effective manner.

1.3 Objectives of study

The main objectives of this research can be summarized as follows:

I. To develop policies that will minimize losses (loss due to entry of NIS and regulation implementation costs) in the context of NIS introductions due to trans-oceanic shipping. To achieve this, we develop a policy framework to prevent inadvertent introduction of non-indigenous marine species via shipping.

1. Identify a set of control options for cleaning ballast water.
2. Identify optimal asset replacement rules and develop their implications for installation of permanent control technology on ships.
3. Develop a mechanism to monitor the activities of ships regarding their ballast clean-up operations.
4. Develop a penalty scheme (i) to enforce compliance with the monitoring mechanism and, (ii) to quicken the adoption of relevant technology by ships.

II. To conduct two case studies, to examine the empirical implications of implementing the policy developed to meet Objective I. The first case study relates to the Great Lakes. The second case study is undertaken for the Chesapeake Bay.

1.4 Terminology and Approach

This section introduces the terminology used and the approach to this study. The technology followed (temporary and permanent) by ships to clean their ballast water will be denoted by set Y. Currently ships do not follow any specific mechanism to clean their ballast water. This situation will be termed as "following technology y_1". This study proposes a regulation that will make it mandatory for all ships entering U.S. coasts to perform Mid Ocean Exchange (MOE). This will be a transitory solution and will be called y_2. All ships may have to adopt some kind of permanent technology on board the ship in the long run. Such a technology will be denoted by y_3, which may contain an array of permanent options. Experimental studies are already being conducted in this regard at various research institutions, such as BHP Research, Newcastle, Australia (Rigby, 1993); Mystic port, U.S.A.(NABISS,1995). Ships found with y_1 may be ordered by the authorities to perform some alternate mechanism to clean their ballast water. This will be denoted by y_4. Clearly y_1, y_2, y_3, y_4 belong to set Y.

MOE is complete deballasting of water followed by reballasting. It does not require any special equipment or specialized labor training. However, it incurs fuel and labor costs; and may cause time delays because ships have to generally slow down during ballast operations.

Most of the permanent technologies involve investment decisions. Hence a ship must identify the least costly of the permanent options, and adopt it only if it is less costly than a lengthy stream of MOE operations. Asset replacement/investment principles help us in understanding the intricacies of such decisions. A general asset replacement criteria will be discussed in Chapter II. Sometimes a ship may find it optimal to adopt a new technology after several time periods. But the policy maker may want to induce an early adoption and provide incentives for ships to adopt these options. This issue will also be briefly discussed in chapter II.

It is costly for ships to follow the regulations, but the potential cost to the environment is very high if they do not comply. The authorities must monitor ships to ensure compliance, but the agency budgets for monitoring are limited. It is a standard result of simple theoretical models that compliance can be induced at least cost by allowing the probability of monitoring to approach zero as the penalty approaches infinity. However, this strategy is considered unpracticable because there is a implicit limit on the magnitude of penalties for non-compliance.

A coherent monitoring mechanism is needed to assist the authorities in monitoring MOE operations. A game-theoretic approach is used to construct the monitoring mechanism which divides all ships into different categories. The probability of monitoring differs according to the category. The penalty scheme is so devised that the optimal strategy for the ships will be to follow MOE right away and move to a permanent mechanism as quickly as possible. We discuss the economic rationale for the proposed game-theoretic approach in Chapter II.

The technology y_2, MOE, involves only variable costs (no capital costs) whereas y_3 may involve both capital and variable costs. It is difficult for the regulator to differentiate between y_1 and y_2. The monitoring mechanism presented in the following chapters is developed to overcome this difficulty. This scheme simultaneously encourages adoption of permanent technology also. We assume that monitoring permanent technology is relatively simple and is therefore not discussed in this study.

1.5 Case studies

The conceptual model developed for preventing the introduction of non-indigenous species via shipping, without substantial disruption to transoceanic trade, will be applied to two empirical applications. One case study addresses the Great Lakes shipping. Accidental introductions of at least three exotic European freshwater organisms in the Great Lakes in the 1980s are believed to have been mediated by unintentional inter continental transfer in the ballast water of ocean-going vessels (Canadian Technical Report, 1991). As of May 1993, Mid-Ocean Exchange is required by regulation for all ships entering the Great Lakes after trans-oceanic voyages (Federal Register, 1993). The cost of monitoring ships under the proposed scheme are calculated and compared with costs that are currently incurred by the monitoring agency (U.S. Coast Guard). The proposed scheme will be shown to be cost-effective.

A second case study is conduced for the Chesapeake Bay, which includes the shipping traffic of Norfolk and Baltimore. Unlike the Great Lakes, no ships are currently monitored here. This case study assumes that MOE is made mandatory in the Chesapeake Bay, and calculates the cost of monitoring ships entering the Bay.

1.6 Organization of the study

This study is organized into seven chapters. Chapter I introduced the problem and defined the objectives. Chapter II provides the conceptual framework. This will include a discussion on asset replacement principles, monitoring theory, and other relevant concepts. Chapter III gives a profile of the shipping industry and discusses various control options. Chapter IV develops the model for preventing the introduction of NIS. Chapter V analyzes the model and presents the results. Chapter VI has a discussion of the Case studies. Chapter VII summarizes the study and provides directions for future work.

CHAPTER II

CONCEPTUAL FRAMEWORK

In this chapter, we discuss the conceptual framework of the study. The chapter begins with a discussion of our main objective. While establishing a method of achieving our objective, current literature is also surveyed. Theoretical foundations for some relevant concepts are also examined.

Invasion of marine non-indigenous species into domestic water systems has become a major threat to the sensitive ecosystems. The social costs to the society due to the introduction of NIS are generally very high. As society becomes aware of these problems, the pressure to regulate the affecting parties increases. The affecting party, in this case, happens to be the shipping industry. On the other hand, excessive regulation can adversely affect the shipping industry. Increased regulation could mean increased costs to the industry resulting in trade losses.

One of the important tasks of this study will be to provide cost effective mechanisms so that net welfare losses are at a minimum. The social welfare maximizer has a function that has three arguments: loss due to entry of NIS, costs of monitoring and loss in trade due to regulation. This study deals predominately with the cost of monitoring, as data requirements preclude empirical estimation of all three components.

Although not explicitly stated at every juncture, social cost minimization will be the ultimate goal of the policy maker. This goal may be partially achieved by devising a scheme that will encourage ships to prevent NIS introductions via ballast water. This is achieved by regulating the industry and ensuring that the regulation is followed.

In this study, we propose a regulation scheme in which it will be mandatory for all ships to follow at least MOE, (y_2). Incentive schemes will be developed to enable movement from MOE (y_2) to permanent technology (y_3).

Replacement of one technology by another is a complex issue. The ship owner weighs the returns from the new technology against the costs (both monetary and opportunity cost) of installing such technology. New technology is adopted only if and when it is profitable to do so. As this study proposes to devise an incentive scheme to encourage ships to invest in the preferred technology, one has to understand the principles behind such replacements properly. Section 2.1 of this chapter discusses some of the fundamental concepts needed to understand the dynamics of asset replacement.

As mentioned in the introduction, monitoring mechanism will differ according to the technology followed. Since there appears to be a problem in observing and differentiating between y_1 and y_2, a rigorous monitoring scheme is developed for MOE. Monitoring y_3 is beyond the scope of this study. A potential violator compares returns to compliance with the highest return available from non-compliance while deciding to comply or not (Jones, 1989). If this monitoring (game) is to be played repeatedly, then the enforcement authority can base the expected penalty and inspection frequency on a firm's past performance. Landsberger and Meilijson (1982) show that such a method is more cost-effective than a system in which the inspection frequency is random and independent of past outcomes. More about such schemes is discussed in section 2.2. The conceptual basis for a multi-group dynamic game-theoretic approach in case of y_2 technology is also discussed in section 2.2. To be credible, the monitoring mechanism should be accompanied by a penalty system. Section 2.3 discusses the fine function and how the monitoring mechanism is designed to also serve as an incentive for movement to permanent technology, y_3.

To summarize, this chapter develops conceptual foundations for three aspects: (1) asset replacement principles for a movement from y_2 to y_3; (2) a rigorous monitoring scheme to ensure y_2, and not y_1, is followed, and (3) a punishment scheme for enforcing compliance that combines asset replacement principles with monitoring mechanism.

2.1 Asset Replacement Principles

In this section we discuss the principles behind asset replacement and the underlying marginal relationships for smooth replacement. Our goal is to test if this can be applied to adoption of y_3 technology. In choosing an asset, the motivation of the asset manager is to maximize the present value of entire future stream of residual earnings from the productive process associated with the asset. The policy maker wants to guide the asset manager to the "right" set of assets and also provide incentives for an early adoption. To do so, the policy maker must have a clear understanding of optimal replacement principles.

Asset replacement principles for technologically improved assets differ from those for self replacement (assets that are identical). We are interested in technologically improved asset replacements i.e. the current asset is replaced by a superior technology asset. Once replaced, we have an infinite series of identical replacements. What we seek to optimize here is the replacement age of the current asset.

A survey of asset replacement literature shows that the optimal replacement age of the current asset is at that point where the discounted revenue from retaining the asset is equal to the discounted revenue obtained by replacing the asset by an improved technology asset.

As a practical matter, a decision maker might compute C, the present value of the stream of residual earnings from the improved technology asset each year, and compare $\{\rho(M(c) + C\}$ with the returns from the old asset. ρ is the rate of interest and M(c) is the market value of the asset at age c. If net returns from old asset are greater, it is retained for another year at which time an updated comparison is made, and so on (Perrin, 1972).

In this study, the asset manager has to make two decisions regarding asset replacement. One, *when* to replace MOE by permanent technology?; and two, *which* one of the new technologies must be adopted? The policy maker is interested in the first and would like to devise incentive schemes to hasten such a replacement. If the performance characteristics differ across these new technology options, then the policy maker may have an interest in technology choice also.

It is sometimes difficult to attribute returns to the use of a particular asset. This problem can be overcome by reformulating the profit maximization problem as one of cost minimization (Chisholm,1974). The model is changed to reflect costs, and it minimizes the present value (PV) of a constant flow of machine services over an infinite planning horizon.

Minimizing the PV of the stream of costs for a perpetual chain of machines, the optimal condition is defined as (Chisholm,1974):

$$V_n = Q_n / (1-(1+r)^{-n}) \qquad (1)$$

where V_n = after tax PV stream of costs for an infinite chain of identical machines, Q_n = after tax PV stream of costs of a single machine, r = firm's discount rate, and n= replacement age. To help one analyze the effects of any changes in the variables on optimal replacement, a complete replacement criterion which incorporates marginal conditions is derived as:

Marginal cost of holding machine for a further year ≥ amortized cost of a new machine ≥ marginal cost during preceding year. i.e.

$$MC_{t+1} \geq {''AC''} \geq MC_t \qquad (2)$$

At this point in time, MC with respect to time most closely approximates amortized cost (Average cost per unit of time) or "AC"(Chisholm, 1974). In empirical applications, the best method to determine optimal replacement age is to evaluate the middle expression of equation (2) for each year, n = 1,2, 3, ... and select that integer value of n for which "AC" is minimum. Notice that equation (2) assumes an increasing MC function. If this equation is to be used in our analysis, this aspect will be of importance.

2.2 Monitoring Mechanism

We begin this section by a survey of monitoring mechanism literature. We discuss the advantages of multi-state schemes over simple, static schemes. Greenberg (1984)'s monitoring model is analyzed in detail. Our proposed model is then introduced, compared and contrasted with the Greenberg model.

Accidental releases of NIS, while inherently random processes, are influenced by preventive actions taken by ship-captains. Certain actions taken by the ships can decrease the probability of such releases. The objective of the monitoring authority is to design policies for controlling both deliberate and accidental spills.

If monitoring is costly, then social cost is minimized when the probability of monitoring approaches zero and fines approach infinity. But social convention limits extent of fines that can be imposed. Under such circumstances, simple monitoring schemes have been shown to be less cost-effective than state-dependent monitoring schemes (Landsberger et al, 1982). In case of a simple monitoring scheme, a penalty is levied whenever a ship is found in non-compliance. This static system has a constant probability of detection which is independent of past outcomes. This can be modelled as a simple two-person game where the agency announces beforehand the probability of inspection. The firm then calculates the probability of detection (p), penalty function if caught in non-compliance (f), and the cost of compliance (c). If $pf > c$ the firm complies with probability one, otherwise it violates. If such a penalty is based on any measure of potential economic damage, then the probability of detection should also be included in the penalty function. This results in very high penalties. Levying and collecting penalties can itself become a costly activity in such circumstances. Comparing a 'state-dependent' scheme with a simple stratified monitoring scheme, it can be shown that with mere stratification, agents follow the myopic rule of reporting truthfully only if $c < \rho f$ which results in less frequent reporting of truth.

Under 'state-dependent' systems, states are associated with the classification of individuals in terms of their recent record in imposing undesirable externalities. Harrington (1988) shows that a state-dependent model is more cost effective than a state-independent model when $c > f$. In a state-dependent dynamic model, compliance can be achieved even though the expected penalty is not large enough to ensure compliance in a static model. For instance, consider a dynamic scheme consisting of two groups: G_1 and G_2. Let G_1 represent the "good" ships category and G_2 represent the "bad" ships category. Let the cost of being in G_2 be higher than G_1. If a ship is found in violation in G_1 it is moved to G_2. Then, a potential violator in G_1 not only considers the one-shot penalty if detected (static case) but also the entire stream of future costs associated with G_2.

Harrington (1988) also discusses the advantages of a three-group model. The reduction in the minimum resources needed to achieve a given level of compliance with the addition of third group is illustrated with the help of two numerical examples. The "adaptive" three-stage model is shown to be more cost-effective than the non-adaptive or state-independent models. The thrust here is to design an optimal penalty function that takes into account ship-captain's reactions, their willingness to evade compliance and face the risk of punishment. Dynamic games allow for such interactions.

Game theory has been applied to monitoring mechanisms in various ways. Greenberg (1984) uses a repeated game-theoretic approach to design an optimal auditing scheme in order to monitor tax-avoidance. Under Greenberg strategy, all individuals are classified into one of three groups - G_1, G_2, and G_3. Each group is characterized by two parameters: (i) probability of being audited in that group, (ii) into which group will an individual move if (a) he reported truthfully, or (b) he cheated. All individuals start in G_1. G_3 is the "absorbing state" i.e. once in G_3 an individual remains in that group forever. The penalty scheme is severe in G_3. Greenberg shows that the optimal strategy in this game is to cheat in G_1, move to G_2 but report truthfully in G_2. In equilibrium, G_3 is a null set. No more than α percent of the individuals will cheat, where $\alpha < \varepsilon$ = the "allowable" percentage of tax evaders.

Romstad et al.,(1993) adapt Greenberg's approach to an environmental problem. They develop a single period compliance-inducement model and then extend it to multi periods. One important difference between the single period and multi period analysis is that in multi period analysis the firms need to incorporate the probabilities of moving from one group to another also, as expected profits differ across groups.

In this study, our purpose would be to ensure compliance from ships. The most effective way appears to be one with dynamic transition among states especially in case of following y_2 (MOE) technology. Since actions taken by ships for cleaning their ballast water are unobservable, we need to look for second-best solutions. Monitoring improves the nature of such solutions.

A game-theoretic approach is followed in this study. Although dynamic programming may be a suitable candidate, it is believed that a game theoretic approach captures the behavioral aspects of ships better. The objective is to use tools such as penalties and replacement of technology, to ensure that all ships follow y_2 in the short-run and adopt y_3 in the long-run. The strategy is partially based on Greenberg's model discussed above. The strategy is as follows: Let there be three groups: G_1, G_2, and G_3. All ships start in G_1. G_2 will consist of ships with "bad" reputation. G_3 will consist of ships with permanent technology. Unlike most other studies, transition among these groups is based not only on compliance record but also on the technology followed.

Ships in G_1 are presumed to be following y_2 technology. If found to be in non-compliance (i.e. if found to be following y_1), they are moved to G_2. Anytime a ship adopts y_3(either in G_1 or G_2), it is moved to G_3. G_3 is an absorbing state. A ship in G_2 must build its reputation as a 'good' ship by being in compliance for k consecutive inspections before it is moved back to G_1. The probability of detection and payment schemes differ across the groups. Each group is characterized by two parameters (i) the probability of being monitored in that group, and (ii) the transition function giving the new group for the ship if it (a) cheated, (b) followed procedure truthfully, (c) installed permanent technology on board. Given this choice of parameters, it is shown that in equilibrium, the proportion of ships that comply approaches one.

At the conceptual level, this model differs from Greenberg's model in five important aspects:

(i) an effective fine function not only provides an incentive for compliance but is also a disincentive for maintaining MOE. Hence, this function has a role of bringing together asset replacement and monitoring mechanism. No principal-agent environmental enforcement model has ever attempted this before;

(ii) three options are available to the agents in this model. The Greenberg model has two options (cheat/be truthful), and so does Romstad et al model (pass/fail). In our study, an agent can (a) report truthfully, or (b) report falsely, or (c) install permanent technology;

(iii) transition among groups depends not only on compliance but also on the type of technology followed;

(iv) the objective of the policy maker is to see that all ships are in G_3; and

(v) in equilibrium there is almost a zero level of allowed offenders. Over time, G_1 and G_2 will be null sets.

At the operational level, the threat of transferring the cost of monitoring to ships in non compliance acts as a sufficient incentive for compliance in G_1. This aspect is also fairly unique to our model.

2.3 Fines and Incentives for early replacement

As discussed in the introduction, early replacement of an asset can be encouraged by anything that reduces the cost of the new asset or increases the cost of holding on to the old one. Although subsidies are one way of achieving early adoption of y_3, they are dismissed as not being viable options because of various reasons -- they are not cost effective tools, they may change the cost patterns in the industry thereby having a major effect on international trade. Certain logistical problems, such as who provides subsidies, and to whom, also exist.

The objective of the policy maker is to ensure that all ships eventually follow y_3 technology. The monitoring scheme, along with its peculiarities, will ensure that all ships follow y_2 and not y_1. Further, this scheme is designed so that it provides an incentive for movement from y_2 to y_3 technology. In the long run, every time a ship comes into a particular port, the real cost of operating y_2 increases. The stream of costs, which are in effect fines, associated with G_1 and G_2 increase. (i.e. in equation (2), MC_{t+1} is higher than MC_t). As the frequency of visits increase, so do these costs. A ship owner may then find it optimal to adopt y_3 and move to G_3 as quickly as possible. These details are discussed further in the following chapters.

2.4 Punishment function

A survey of the penalty function literature shows that the effectiveness of any penalty system depends on two elements - the penalty function and the probability of detection. Earlier we discussed the superiority of a penalty system that is state dependent. However, most studies in the monitoring mechanism literature take fines as exogenously given (Groves et al., 1992). Others suggest "massacre" contracts (all agents but one are punished when output is low) or "scapegoat" contracts (one agent is chosen at random to be the 'scapegoat' and all others benefit at his expense). Rasmusen (1987) shows that massacre is a better contract than scapegoat in the sense that it is feasible for a strictly larger set of liability bounds and risk-aversion parameters. These kinds of penalty systems, although effective, may never be applied due to political infeasibility. Sometimes accidents occur even when all the precautions are taken. Under such circumstances there are limits to punitive penalties that can be levied. Another major disadvantage of the above mentioned penalty schemes is that they are all ex-post analysis i.e. output-dependent. In our study, such output-dependent penalties do not have much role to play. Output, in our context would be the introduction of non-indigenous species.

In our study, a shipping firm that does not have y_3 technology faces two decisions beyond that of its output: 1. to conduct MOE or not, 2. if and when to adopt permanent technology. Any ship in G_1 that is not inspected is presumed to be in compliance. If inspected and found in non-compliance, it is fined and moved to G_2 where it faces a series of costs which act as penalties themselves.

An interesting situation would be when a ship does not comply but voluntarily reports non-compliance. This study leaves the burden of such a situation to the agency -- the agency may assess the authenticity of the case and use its judgement in categorizing ship to a particular group.

For a model of a profit maximizing firm which emits pollution, Harford (1987) supports a non-linear penalty function and shows that there is a trade-off between encouraging the firm to reduce pollution and encouraging it to report honestly. Jones (1988) argues that to deter large violation, a fine function must be increasing at an increasing rate in the severity of violation.

Certain peculiarities of the shipping industry must be considered before deciding on a penalty scheme. This industry has a wide variety of ships operating at different levels of market imperfection. A hastily designed penalty system can, therefore, have severe trade repercussions. One has to devise a penalty scheme that is high enough to enforce compliance but low enough to keep the disturbances in the industry within acceptable limits of the industry equilibrium. Since a firm compares returns from compliance with that of non-compliance in its decision to comply or not, the policy maker must also know about the cost of compliance. Hence, an estimate of the cost of MOE and operating cost of y_3 are crucial in framing a penalty system. This study designs a penalty scheme that incorporates compliance costs and other costs (such as time delays).

Another objective here is to achieve political feasibility. This study strives to keep penalties as low as possible. Since compliance involves certain costs to the industry, one can devise a scheme where the real cost of being in a "bad" group is so high that it is economical to comply. Thus the cumulative cost of being in the "bad" group acts as a very strong penalty for non-compliance. The ingenuity of this study is showing that compliance from ships can be achieved by keeping "fine" very low. Other variables such as 'cost of monitoring' transferred to ships in G_2 act as fines in making the cost of being in G_1 cheaper than cost of being in G_2.

The longer a ship remains in the "bad" group, the higher its cumulative costs. The cost of non-compliance becomes greater than cost of compliance. Notice how this relationship is used to encourage the adoption of permanent technology, y_3. Permanent technology involves higher (and lumpy) investment cost. On the other hand, MOE starts with low operating costs but as one adds the time delay costs associated with each visit, the real cost of complying and operating y_2 technology increases over time. At some point it becomes uneconomical for ships to remain with MOE. A ship considers the cumulative cost of operating MOE and switches to y_3 when these costs equal or become higher than the one time lumpy investment of y_3. Thus the cost of operating the old technology becomes the MC of following that technology. This attains increasing MC function which is needed for asset replacement (equation (2)). Thus this relationship establishes a link between asset replacement and monitoring mechanism.

The objective behind any penalty scheme is to change the relative cost of non compliance more than the cost of compliance. In this study the penalty scheme achieves this objective by making the cost of not following any technology higher than cost of MOE; the cost of adopting permanent technology cheaper than the cost of MOE. Thus, for this scheme to succeed the total cost of following y_1 must be greater than that of y_2, which itself should be higher than that of y_3. i.e.

$$Cost(y_1) > Cost(y_2) > Cost(y_3) \tag{3}$$

To conclude, we use the categorizing of ships into groups in our monitoring mechanism model to differentiate costs between G_1, G_2 and G_3. The dynamic aspect of the game implies that the future stream of costs associated with (i) G_1 increase with number of visits to port; and (ii) G_2 increase over time. This information plays a pivotal role in achieving the relationship in equation (3), thus encouraging movement from y_1 to y_2 in the short run, and y_2 to y_3 in the long run. Movement from y_1 to y_3 may also occur. Further, this provides excellent connection between monitoring mechanism and asset replacement. We begin Chapter III by discussing costs of the industry and various control options. Chapter IV uses information in Chapter II and III, and constructs a model that is solved in Chapter V.

CHAPTER III

SHIPPING INDUSTRY AND CONTROL OPTIONS

In order to prevent introduction of NIS via shipping, all ships must conduct some (ballast water) clean up operations. This implies an additional economic burden on ships. To avoid costs and time delays associated with MOE, a ship may decide to adopt permanent technology. All these are fundamentally financial decisions. In this chapter we discuss the economic aspects of the industry so that one can understand better how the proposed regulation affects the industry.

One has to understand the cost and profit structure of this industry and its role and place in global transportation to frame a feasible policy. Although this study focuses on bulk carriers in the range of 25,000 to 75,000 DWT, a comprehensive profile of the industry is needed to understand the dynamics involved. This chapter is divided into two sections. Section 3.1 discusses the basic economic structure of the industry. An important question that a shipping firm must resolve is how long must MOE be followed and when must the firm adopt y_3? The answer depends on the cost structure of the firm, the cost of operating MOE and the cost of operating y_3. Section 3.2 gives a brief introduction to various control options including MOE.

3.1 The shipping industry

The shipping industry appears to be a volatile industry and one has to understand the composition and peculiarities of this industry to comprehend its dynamics. The industry has been facing a depression since 1974 with some improvement since 1985. In general, the industry seems to be moving towards higher value-added goods. Presently there is a large surplus of ships resulting in "breakup yards". Surplus tonnage as a percentage of the active world merchant fleet was 36.1% of ships in 1982 and it decreased to 10.4% by 1991. The average age of a ship is 14 years (UNCTAD,1991).

Ships can be classified according to their commercial operations and the cargo they carry. Based on their commercial operations, ships can either be liner or tramp ships. Liner ships are public, and are required by law to accept any cargo. These ships are highly organized and conduct regular, repeat operations. Goods are procured through the traffic department, and have a uniform Bill of Lading for all customers. Tramp ships on the other hand, are private, and do not follow regularly scheduled routes. Typically, they carry greater volume commodities and the cargo is generally arranged through a broker. In neither of these are passengers allowed. Tramp ships are popular because of their demand sensitivity, intimate knowledge of the market, and low cost of operation. Industrial carriers or special carriers do not fall under either of these categories. Ships can also be divided according to the cargo they carry. They can be bulk carriers, tankers, and container ships.

An interesting feature of the maritime industry is the concept of Flag of Convenience. When a ship owner of one country registers a ship in a different country in order to take advantage of the less stringent working conditions and other benefits thereof, that ship is said to be operating under a flag of convenience (FOC). FOC ships are generally found to be substandard and working/safety conditions of the seamen inferior (Toh et al, 1993; Branch (1992); Stopford (1988)). As of 1991, 48.2% of total world tonnage was registered under this category. Liberia with 39% and Panama with 30% of the total open registry fleet are two prominent countries in this aspect (UNCTAD,1991).

3.1.1 Shipping Costs

There are three kinds of capacities in the shipping industry -- 1. Holding capacity, 2. Hauling capacity, and 3. Handling capacity. Holding capacity is the maximum amount of cargo that the ship can hold; the ship size is defined as the holding capacity of the ship. The handling capacity is the amount of cargo that can be loaded and unloaded to/from the ship per unit of time. The hauling capacity is the number of ton-miles hauled per unit of time. Economies of scale exist in (mobile) hauling operations but diseconomies of scale exist in (fixed) handling operations. The optimal size of the ship is obtained at the intersection of these two opposing relationships. The salient feature of this optimization problem is a trade-off of handling costs against hauling costs. This character of the problem boils down to an inherent technological conflict of design. Thus, ship design and shipping costs are closely connected. Since ships are generally designed according to the cargo they carry and the route they operate, a single cost structure may not capture all the elements of the industry.

1. Capital costs: The most well-known principle with a bearing to shipbuilding cost is the 'two-thirds power rule'. This rule-of-thumb says that a ship's capital cost is proportional to two-thirds power of the ship size. The main items of capital cost are hull and propulsion machinery.

2. Operating costs: The single most important source of size economies are crew wages. This is counter balanced by maintenance and repair costs and insurance. For smaller ships, crew cost is normally the larger item, but it is the smaller item for bigger ships.

3. Fuel Costs: Fuel costs are also related to the size of the ship. Fuel consumption and installed horsepower are assumed to be proportional. Economies of ship size in fuel consumption are expected to be enjoyed because of the fact that the horsepower requirement is somewhat less than proportional to ship size. Regressing fuel cost on ship size, Jansson et al., (1987) obtain elasticity of 0.72 .

$$\log(\mathit{fuel\ cost}) = \log 6.25 + 0.72 \log S \qquad \textbf{(4)}$$

Ships generally lose speed while conducting MOE. MOE increases fuel costs in two ways - (i) ships lose speed, take a longer time to reach destination and, therefore, use more fuel; and (ii) operating ballast pumps requires fuel. Further use of ballast pumps may need additional fuel. These aspects can result in higher fuel usage.

In addition to the above costs, all ships entering a port have to pay port charges. These charges are levied by the port authorities to recoup part of the costs of berthing facilities, cranes etc. These costs are levied partly on the loaded/unloaded cargo, and partly on the ships themselves in one way or the other. Hence, it is not unusual to transfer some of the costs incurred by port authorities to ships. This is the justification for transferring part or full costs of monitoring to ships in certain categories.

The information provided above gives a rough estimate of the cost structure in shipping industry. The following table gives ship size elasticities of capital cost, operating cost, and fuel cost from different studies.

Table 1 Ship size elasticities of capital, operating and fuel cost

SHIP TYPE	CAPITAL COST	OPERATING COST	FUEL COST
Tramps (Thornburn)	0.67	0.4	1.00
Liner (Getz et al.)	0.6	0.6	
Dry bulk carrier (Goss and Jones)	0.7	0.4	0.8
Tanker (Heaver)	0.6	0.3	0.6
Jansson et al. study (regression results)	0 6	0.4	0.72

This table can be used to assess the variations in costs between a bulk carrier and other types of ships. Notice that capital costs are at a maximum in the case of bulk carriers (0.7 of ship size) whereas it is only 0.4 of ship size for operational costs. MOE falls under operational costs whereas installation of permanent technology may fall under the capital cost category.

3.1.2 Profit function

Profits in the shipping industry are affected by freight rates and its fluctuations. Freight rates depend on the type of cargo and the trade route, in addition to other market forces. In 1991 the freight rate for ore trade ranged from $6.50 per ton to $13.70 per ton. In the case of fertilizer trade, it was between $18.50 per ton and $48.50 per ton (UNCTAD,1991). This section predominantly talks about the Liner industry profits for which most data is available.

The liner shipping industry is dominated by the price-cartel organizations, called the Conference system. These liner conferences fix the freight rates and also look after market division and supply regulations. Freight rates for some popular trade routes are sometimes kept "open" by the conference to tackle competition from tramps, air cargo. Cheating by individual liners (reducing freight rates below published rates) may be punished by "policing bodies". Generally, the competition within each conference is fierce and the competitive edge is attained by providing better "quality" or services. Because of fierce competition, ships may accept large volumes of cargo below their marginal cost structure. Jansson et al argue that the conferences are out of line with marginal cost structure, and, therefore, many low-rated commodities are being shipped at freight rates below their marginal rates. Conferences may be setting freight prices that are the same as direct handling costs. To that is added a margin, based on the principle of "charging what the traffic can bear". This results in an absence of super normal profits in a thoroughly cartelized liner-shipping industry. Potential monopoly profits are turned into costs - costs of inputs into the fight for expected awards. The result is rigged freight rates and too high quality of service. Given these conditions, it appears that any recommendation that involves high monetary penalties or imposition of high costs will be infeasible in this industry.

3.2 Control options

In this section we consider alternatives for controlling the introduction of NIS via shipping (especially through ballast water). The philosophy here is same as the basic philosophy of quarantine science in general : ballast management should seek to prevent the introduction of all organisms, ranging from bacteria and viruses to algae, higher plants, invertebrates, fish and all other life (NABISS,1995). It should be noted that no one option is likely to satisfy this objective. A vector of control options to be implemented simultaneously may achieve the results.

3.2.1 Control Options

Conceptual approaches to ballast management fall under four broad categories. 1.Voyage approach, 2.Vessel approach, 3.Industry approach, and 4.the Treatment approach.

The Voyage approach is a primary method that categorizes the entire spectrum of control options. This means that control options under this approach can be applied either on departure, enroute or on arrival of ships in ports. The Vessel approach offers solutions according to the size of vessels (small and large), and also for vessels that need retrofitting and those that need new design. The Industry approach examines the options available assuming (i) no change in standard procedures, (ii) moderate changes and (iii) extensive changes. The Treatment approach discusses various biocidal, mechanical and preventative options available.

NABISS (1995) identifies thirty-two potential control options. Each one of the thirty-two options fall under one of the four approaches mentioned above. They all concern the shipping industry, but each approach affects different aspect of shipping operations. Once a control option is chosen, the approach under which it falls tells us how this option is going to affect shipping operations. Thus, these approaches connect the options to the shipping industry. Some of the options which seem promising are listed below. This list is by no means exhaustive.

1. Chemical biocides
2. Elevated temperatures.
3. Install thermal / ultra sound equipment
4. Mid ocean exchange
5. Discharge ballast water to a lighter

Of these, option#4, Mid Ocean Exchange (MOE) is most popular. Because of the disadvantages (discussed below), this option is offered as only a transitory mechanism by this study.

Although the range of options under consideration is extensive, a permanent option selected should satisfy several criteria such as: environmental and technical safety; cost-effectiveness; and practicality. Rigby et al (1991) experiment with sodium hypochlorite and show that it is an effective biocidal treatment. At a level of 20 ppm, it costs around 48 (Australian) cents per liter of ballast water. However, the environmental aspect of discharging free chlorine makes this option unattractive. Hydrogen peroxide is another biocidal option which does not have environmental problems, but costs around $10,000 for 50,000 tons of ballast water. Further, there are storage and handling problems which may make it impractical. Options such as ultraviolet radiation and ozonization are dismissed as impractical since they are costly and ineffective against certain types of cysts (Rigby et al.,1995). A popular option with the scientific community seems to be Elevated temperatures. Waste heat from the main engine of ships can be transferred to the ballast tanks to heat the ballast water. This would need flushing the hot water from the engine to ballast tanks in sequence. However, the effectiveness depends on ocean temperatures -- the colder the ocean water, the less effective is the mechanism because of insufficient heat. Another problem is that the heating must take place during the voyage, as ship's engines are generally not in operation during ballast exchange. Results from experiments have shown that with 33° C for two hours, or 36°C for several minutes, most of the dinoflagellates die in the ballast water. However, it is not clear whether this option will be equally effective for other aquatic organisms. Although there are several options under consideration, the scientific community is yet to decide on any particular option. Because of the diversity in the structure and size of ships, more than one option may be recommended. Once a option (or an array of options) is decided upon, specific schemes for encouraging that option can be devised.

3.2.2 Mid Ocean Exchange

MOE is also known as open ocean, deep water, or high seas exchange. Under current Canadian, U.S. and IMO guidelines, exchange is advised in waters with depths greater than 2000 meters (NABISS, 1995).

Two major biological and ecological principles that provide the scientific foundation for exchange are:

1. If exchange occurs far enough from the continental margin, probabilities of reciprocal introductions are virtually non-existent. The oligotrophic (low food) conditions, higher ultraviolet radiation levels, high salinities, predators, and other conditions of the oceanic environment create inhospitable conditions for freshwater, estuarine, or most inshore coastal organisms discharged into this environment. Conversely, oceanic organisms ballasted up in their place, and later discharged into freshwater, estuarine, or inshore coastal waters will encounter similar hostile conditions.

2. a. Ocean currents would take too long to transport the released organisms back to original waters ("too long" defined as beyond the life of the organisms).
   b. Ocean gyre would prevent the released organisms from leaving the release site before they died.

It should be noted here that neither the diversity nor the abundance of organisms in the "mid ocean" is part of the scientific foundation of exchange.

Some benefits of MOE are:

1. high probable efficacy of this method in killing/removing freshwater organisms
2. high probable efficacy in reducing the numbers and diversity of these organisms
3. present ability of most vessels to undertake some measure of exchange without retrofitting costs.

Some of the concerns with this mechanism are:

1. Compromise to the integrity of vessel. "Mid-ocean" exchange also potentially places a vessel at sites where exchange, because of sea conditions, may often be the most difficult.
2. increased operating / fuel costs
3. high probability of residual organisms remaining when original water is brackish or salty
4. low probability of washing out large sedimentation (and organisms therein) by the exchange process.

It is important to note that there is no minimum amount of original water which, when mixed with exchange site water, "guarantees" the absence of organisms from the original ballasting site. For vessels completing partial exchange, organisms can still occur in exchanged water. Post-exchange salinity expectations under complete exchange conditions are relative to where exchange took place. Lastly, the strict application of depth alone as a focal point for exchange sites may be limited by the potential proximity of such depths to some continental margins.

The procedure for calculating the cost of Mid-Ocean Exchange is elaborated on in Chapter V.

Summary

Since shipping is the targeted industry of our regulation, an understanding of the industry is essential for our analysis. In this chapter some basic cost and profit relationships of this industry were discussed. Some peculiarities of this industry such as flag of convenience ships and conferences were also discussed. The purpose of this chapter is to understand the extent of costs/fines that these shipping firms can absorb without substantial disruption to the equilibrium of the industry.

We now move to chapter IV where the basic model of our study is presented.

CHAPTER IV

THE MODEL

The objective of this research is to frame policy incentives to prevent introduction of NIS via shipping. In this chapter a monitoring system / asset replacement model is developed that forces ships to clean their water (and thereby reduce problems of introduction of NIS and associated loses to society) and allows the agency to monitor ships in a cost effective manner. In Chapter II, certain general principles/conditions that are applicable to the problem were identified. One condition is given by the asset replacement literature-(equation (2)). A second condition is given by monitoring mechanism theory-a monitoring system that has at least two states and has a state-dependent transition is more efficient and cost-effective than a simple,stratified scheme. A third condition is obtained from the penalty function literature (equation 3).

In this chapter, the above conditions are applied to this study. In section 4.1, the relevance of the first condition and its equivalent for this study is discussed. Section 4.2 examines the monitoring mechanism. In this section, a multi-state monitoring scheme in a game theoretic format is derived. In section 4.3, we examine these conditions and simultaneously formulate an incentive scheme. The goal is to devise an incentive scheme which, when incorporated into the maximization function of the shipping firms, results in (i) following the procedures laid down by the authorities in the short run, and (ii) adopting permanent technology in the long run, as optimal decisions.

4.1 Asset Replacement

Equation (2) of Chapter II tells us that an asset manager will replace his asset when the marginal cost of holding the asset for one more period is greater than the amortized cost of the new asset. The equation is reproduced here:

$$MC_{t+1} \geq "AC" \geq MC_t \tag{2}$$

Interpreting this condition in the context of this study, a shipping firm will replace y_2 technology with y_3 only when the amortized cost of operating y_3 equals the marginal cost of y_2. The optimal period for a ship to adopt y_3 is when $MC_{y2t+1} > AC_{y3} > MC_{y2t}$ (or approximately $MC_{y2} = AC_{y3}$). If $MC_{y2} > AC_{y3}$, then y_3 is adopted instantaneously. On the other hand, if $MC_{y2} < AC_{y3}$, a scheme must be developed that will attain the condition $MC_{y2} = AC_{y3}$ i.e. either increase MC_{y2} or, decrease "AC" of y_3. An increasing MC_{y2} can be achieved by making cost of MOE strictly increasing either in time or in number of visits to port. It can also be increased by shifting partial/complete costs of monitoring to ships.

This study will use number of visits and cost of monitoring transferred to ships as arguments for increasing marginal cost of MOE. Cost reducing innovations may bring down the cost of y_3 also. The net effect that the policy maker is interested in is:

$$\underset{\uparrow}{MC_{t+1}} > \underset{\downarrow}{AC} > \underset{\uparrow}{MC_t} \tag{5}$$

such that at some(time/visit) period t*,

$$MC_{y2} = AC_{y3} \tag{6}$$

and replacement takes place. The assumption here is that a ship visits a port only once in each time period.

4.2 Monitoring Mechanism

This section begins by identifying some important variables and setting the stage for a monitoring mechanism. The structure of the game follows.

The purpose of devising the monitoring mechanism is to ensure that all ships follow at least y_2 technology. Shipping firms hire ship-captains to run the ships. A ship captain is generally responsible for all the activities aboard the ship. In our analysis, a ship's captain will be synonymous with the shipping firm. i.e. the actions of the ship captain will be treated as the actions of the shipping firm. Further, the actions taken by the ship captain or any other responsible crew member will be considered as action taken by the "ship" itself.

For economic reasons, ships (agents) may not want to follow any mechanism to clean their ballast tanks. The U.S. Coast Guard, USCG (principal), would want ships to follow y_2 as a transitory mechanism and to install y_3 in the long run. This gives rise to a moral hazard problem.

Traditionally, moral hazard issues have been discussed by setting up a maximization problem and solving it with a participation constraint. But, in our case, monitoring stretches over various time periods and involves sequential actions. Hence a dynamic game is formulated to capture certain behavioral aspects of this problem. The usefulness of dynamic state-dependent games was discussed in Chapter II. A game-theoretic approach will be followed in this study. The task of USCG is to design a policy in such a manner that the ships, when minimizing their own cost function under the modified payoffs, achieve the agency's objective function also.

Model

Let Y denote the set of clean-up mechanisms available to the ships. As described earlier, y_1, y_2, y_3, $y_4 \in$ Y. There are no qualitative, tangible differences in the capital requirements for y_1 and y_2. MOE, y_2, should be performed in mid-ocean only. On the other hand, y_3 can be performed either in port or in transit. We also allow for y_4=y_2. The USCG strictly prefers y_3 to y_2 and y_2 to y_1 ($y_3 \succ y_2 \succ y_1$). A complete list of variables used in this study is given at the beginning.

Each ship is assumed to go into port for T time periods. At each period t, a ship has to decide which procedure (or technology) it should follow. Each ship has a cost function that it tries to minimize. Its decision to follow a procedure is influenced by three factors: (i) cost of following procedure, (ii) probability of being caught in non-compliance; (iii) the punishment if found in non-compliance.

The dynamics of the proposed game is given by the following flow-chart.

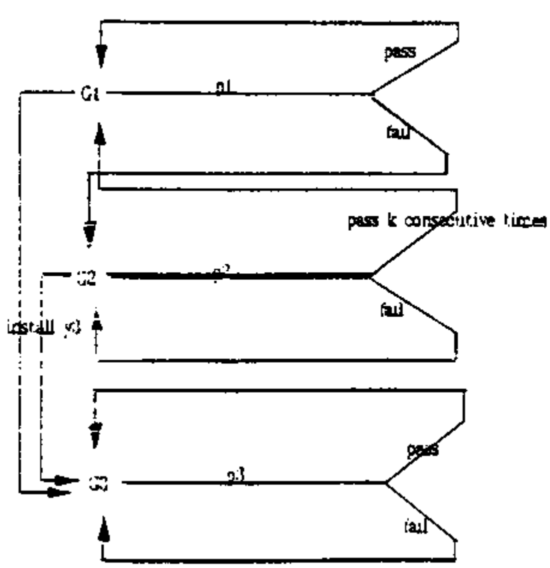

Figure 1 The dynamics of the proposed model

All ships belong in G_1 initially. Every ship in G_1 must follow y_2, (MOE). If monitored and found to be cheating, it is moved to G_2. If not monitored, it does not pay any costs. It is presumed to have followed y_2 and incurred R_1, cost of MOE. G_2 is the "bad" category. Here, the probability of being monitored is higher than in G_1. A ship in G_2 can return to G_1 only after passing the compliance test for 'k' consecutive inspections. Therefore, the minimum time a ship must spend in G_2 is k periods, so long as it does not adopt y_3 technology. At any time in the game, a ship can move to G_3 by adopting the permanent technology, y_3. Once in G_3, a ship will always remain in G_3. The game ends when all ships move to G_3. G_3 has its own monitoring/penalty scheme which is not elaborated here. The proportion of ships in G_1,G_2, and G_3 is (1, 0, 0) respectively at t=0; and will approach (0,0, 1) as t=T.

Consider a ship in G_3. Regardless of whether it cheats or not it will stay in G_3 forever. The probability of being monitored in $G_3(p_3)$ is independent of the probability of being monitored in G_1 (p_1) and in G_2 (p_2). Further, at t=0, there will be 0 ships in G_3 and as the game proceeds, the number of ships in G_3 increase. Therefore, it is plausible that $p_3 \approx 1$ at the beginning of the game, and falls as $t \rightarrow T$. A high p_3 and/or a (arbitrary) high penalty function will ensure compliance with the use of permanent technology in G_3. Alternatively, the pay off function could be framed in such a way that investment in y_3 is a credible pre-commitment to not cheat, and hence not be inspected. Therefore, it appears that one can devise a simple penalty scheme where the optimal response for the ships in G_3 is to be truthful. Monitoring under G_3 is not discussed here.

Consider G_2. A high probability of monitoring, p_2, and some "effective fines" such as 'cost of monitoring' transferred to ships will ensure that the ships in G_2 will follow the mechanism as an optimal response.

Now consider G_1. Notice that in this game the Coast Guard cannot obtain information regarding the ship's past behavior unless it was inspected in the past. A ship in G_1 can follow one of the following strategies. (Here 'i' is the decision variable).

Strategy 1: Be truthful in G_1 until it reaches G_3. i.e. i = 1

Strategy 2: Cheat in G_1. i.e. i=0; if monitored and found in noncompliance, move to G_2.

Anytime a ship adopts permanent technology, it is moved to G_3. Let such decision be denoted by i=3.

The decision to follow a particular strategy depends on

1. The punishment scheme / pay-offs.
2. Length of time (or, approximate number of visits to the port) before it adopts permanent technology.

Pay-offs:

Consider Strategy 1 i.e. i=1 (truthful in G_1 until move to G_3). A ship with i=1 decision faces the following costs: costs of MOE (R_1), time delay costs associated with MOE (d_1). It may also face cost of monitoring (c_1). Let $Costs_{i=1}$ = total discounted costs in G_1 with compliance.

Consider strategy 2: (Cheat in G_1, go to G_2 if detected, pass inspection test k consecutive times in G_2, move back to G_1 and so on till the ship goes to G_3). A ship with i=0 decision faces the following costs: As long as the ship is not monitored, its costs are zero. Once monitored in G_1 and found in non compliance, its immediate costs include: cost of alternate mechanism (R_2), fine for violation (f_1), cost of monitoring transferred to the ship (C_1), and time delays associated with alternate mechanism (D_1) to be performed when found in non compliance with MOE. It will continue to face costs of monitoring (c_2), cost of compliance of MOE (R_1) and time delays associated with it (d_2) as long as it complies and stays in G_2. Since costs of monitoring transferred to ships is similar to levying of fines, the condition should hold so that $p_1c_1 < p_2c_2$ i.e. expected (monitoring) costs in G_1 < expected (monitoring) costs in G_2.

Further, the frequency with which it incurs these costs increases as the probability of monitoring increases. Let $Costs_{i=0}$ denote total discounted costs associated with i=0 decision. The above analysis implies that so long as equation (7) holds, a cost minimizing shipping firm would prefer strategy i=1 to i=0.

$$Costs_{i=1} < Costs_{i=0} \tag{7}$$

This relationship is very important in formulating and solving the game. Notice that in a static framework the difference between $Costs_{i=1}$ and $Costs_{i=0}$ must be wider to ensure compliance but in a dynamic framework the stream of costs associated with $Costs_{i=0}$ make it significant.

4.3 The Penalty Scheme

In chapter II, we discussed the importance of having a penalty system that ensures $costs(y_1) > costs(y_2) > costs(y_3)$. From the previous section we know that the policy maker is interested in ensuring that strategy i=1 is followed. The task in this section is to connect these two conditions. Here a preliminary examination of costs of following y_1, y_2 and y_3 is conducted. These costs are then put together and tested to determine if the above mentioned condition holds true and when incorporated into the objective function of the shipping firm, if it gives following i=1 strategy as the optimal solution.

Consider the potential costs under y_1. This situation occurs when a ship in G_1 violates and is therefore moved to G_2. In such a situation, a ship must pay (i) a fine for violation, f_1; (ii) cost of monitoring, C_1 and (iii) incur the cost of an alternate mechanism, R_2. Thus a ship with y_1, if detected, must pay

$$Cost(y_1) = R_2 + f_1 + C_1 + D_1 \tag{8}$$

It is then moved to G_2. As long as it is in G_2 and complying, it incurs monitoring costs (c_2), cost of MOE (R_1), and time delay costs (d_2). i.e. $R_1 + c_2 + d_2$.

Consider costs under y_2. This is a ship in G_1, in compliance. A ship arriving in port with y_2 incurs cost of MOE (R_1) and time delay costs (d_1) and may incur cost of monitoring(c_1).

$$Cost(y_2) = R_1 + c_1 + d_1 \tag{9}$$

Consider costs under y_3. This would be for a ship in G_3. A ship that adopts permanent technology incurs R_3 in our model. R_3 is the annualized cost of installing and operating y_3. The costs incurred by a ship with y_3 will be:

$$Cost(y_3) = R_3 \tag{10}$$

As mentioned earlier, these relevant penalties and costs may be treated as MC_{y1} and MC_{y2}. Re-examining the optimality condition (equation 3) from Chapter II. i.e.

$$Cost(y_1) > Cost(y_2) > Cost(y_3) \tag{3}$$

and substituting the arguments for each of the items in the above equation we get:

$$R_2 + f_1 + C_1 + D_1 \geq R_1 + c_1 + d_1 \geq R_3 \tag{11}$$

i.e.

$$Cost_{i=0} \geq Cost_{i=1} \geq Cost_{i=3} \tag{12}$$

Equation (11) refers to a specific point in time, t=0. However, in the case of dynamic analysis, a discounted stream of these values must be considered.

Summary

Strategy i=1 is preferred to i=0 by the policy maker and i=3 is preferred to i=1. The policy maker may, therefore, provide incentives for asset replacement and frame a monitoring mechanism in such a manner that it is optimal for ships to follow the i=1 decision in the short run, and move to i=3 in the long run. To achieve this goal, the agency can make use of certain tools such as controlling the probability of monitoring in each group. The primary objective of the agency is to minimize NIS introduction, which can be achieved through high compliance from ships. The agency is, therefore, interested in a set of (p_1,p_2) values that optimize compliance. This study will also calculate a rate of compliance under each decision for the entire time horizon under consideration and adjust monitoring pressure to achieve maximum compliance. Since the agency is also interested in minimizing costs, that combination of (p_1,p_2) which minimizes the budget will be recommended.

CHAPTER V

ANALYSIS

In chapter IV we discussed monitoring mechanism and asset replacement principles in detail. In this chapter we use dynamic programming methods to solve the game and analyze the results. Section 5.1 begins by identifying some of the parameters used and the procedure for calculating the cost numbers. Section 5.2 shows how the conceptual model is reduced to a k=3 case (k is the number of times a ship must pass the compliance test in G_2 before it is moved back to G_1). Bellman equations are formulated here. Section 5.3 gives the solution methodology. Here we break down the programming process to provide information on all aspects of the problem and how it is displayed in the output. Section 5.4 analyzes these results. Section 5.5 shows the relationship between the rate of compliance and monitoring probabilities. We also obtain the locus of minimum combinations of (p_1,p_2) that will result in compliance from ships. Section 5.6 discusses the budgetary needs and develops a relationship between the monitoring budget, compliance and probability of monitoring.

Two questions are raised and answered in this chapter: 1. Can the agency get compliance in G_1 with low (p_1,f_1)?; 2. When will ships adopt permanent technology? There are two conditions under which compliance can be obtained with low (p_1,f_1): (i) when cost of monitoring transferred to ships in compliance in G_1 is less than cost of monitoring transferred to ships in compliance in $(G_2,*)$ i.e. $c_1<c_2$; (ii) cost of compliance is less than cost of non-compliance. The second condition is efficiently achieved with $R_2 > R_1$. Ships adopt permanent technology when (i) annualized cost of permanent technology, R_3, is less than \$50,000 and (ii) as number of trips to port increase.

5.1 Calculation of some relevant parameters

1. Size of ships: The shipping industry consists of various types and sizes of ships. The cost of operation depends on the size/type of ships. All ships are divided according to their size into four categories: <25,000 Dead Weight Tonnage(DWT), 25,000 to 75,000 DWT, 75,000 to 125,000 DWT and >125,000 DWT. The entire analysis focuses on bulk carriers only, in the range of 25,000-75,000 DWT. A survey of literature shows that it is reasonable to assume 60% of the DWT as ballast water. i.e. around 30,000 tons of ballast water for the bulk carrier in our study.

2. Cost of Mid-Ocean Exchange (R_1):An approximate cost of conducting Mid Ocean Exchange is essential for the analysis. A BCA study by the US Coast Guard (CGD 91-066) shows that a ship in the size range of 7,000-10,000 tons of ballast water incurs a cost of $1,147 for each MOE operation. This is approximated to $1,200 for every 10,000 tons of ballast water, giving $3,600 as the cost of MOE.

3. Time delay costs (D): All ships lose speed while conducting MOE.This in turn reduces the number of trips that a ship can make per year. Since this has direct economic impact on the costs, this loss (in dollars) due to time delays is also accounted for. This cost is calculated by combining results from two different studies. A study conducted by Rigby (1991) estimates 12 hours as the approximate number of hours it takes for a ship size of over 140,000 DWT to deballast, assuming that the MOE is done continuously. Using this data we calculate the number of hours it takes for a ship with 30,000 tons of ballast water to conduct MOE (deballast and reballast) as 8 hours. The implicit assumption here is that the time taken to exchange ballast water is strictly linear in tons of ballast water. Branch (1992) estimates the voyage costs of a bulk carrier (26,500 DWT) on a popular U.S.-Europe route and reports the net profit of that ship as $4,092 per day. The ship generally makes 11 trips a year. Assuming that MOE is needed only on one leg of its round trip, we calculate the loss in revenue due to time delay associated with MOE as

approximately $1,700. This cost does not take into consideration the time delays that the ship may encounter at the port due to monitoring delays.

4. Cost of monitoring(C): The US Coast Guard (USCG) incurs a cost of $750,000 per annum to maintain a monitoring unit at Mesenna, New York.[1] Although 455 ships entered the Great Lakes in the 1990 shipping season, only 198 were subject to regulation (CGD 91-066). Thus the cost of monitoring a ship is around $3,750. It is assumed that monitoring costs are the same for all ports in the U.S.A.

5. Cost of installing permanent technology(R_3): Some of the options under consideration were discussed in Chapter III. The scientific community has not yet recommended any particular permanent technology option. NABISS (1995) gives approximate cost numbers for some of these options. This cost is very sensitive to the size and type of the ship. A wide range of costs were tested with respect to the ship size of our model. The results showed that this model responds to a cost of around $50,000. The analysis is first conducted for R_3=$100,000 and then reduced to less than $50,000. R_3 represents the annualized cost of installing and operating permanent technology.

5.2 Equation Formulation and some working details

Assume that the agency announces the rules of the proposed game and the probabilities of monitoring under each group. All ships start in group G_1 which has a monitoring probability of p_1. Ships found in violation are moved to G_2 which has a probability of monitoring, p_2. Ships that pass k consecutive inspections in G_2 are moved back to G_1. Any time a ship adopts permanent technology to clean its ballast water it moves to G_3. Figure 1 of Chapter IV captures the key components of the game.

[1]USCG presentation at the Chesapeake Bay Commission meetings, Oct 24, 1994, Washington, D.C.

At any given time, a ship is in one of (k+2) states: G_1, $(G_2,0)(G_2,1)...(G_2,k-1)$, G_3. A state (G_2,a), indicates that a ship which is in group G_2 was found in compliance 'a' consecutive inspections. Henceforth, the G_2 group will be addressed along with its subgroups, represented by '*'. In this analysis, we use k=3 i.e. a ship in G_2 must pass the compliance test 'k' consecutive times before it is moved away from G_2. The three states in G_2 are $(G_2,0)$, $(G_2,1)$ and $(G_2,2)$. The following figure explains the dynamics of the game for k=3.

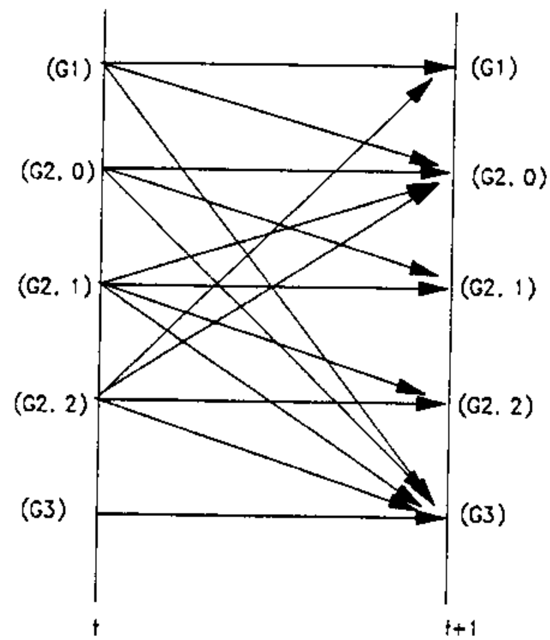

Figure 2 :Flow chart of the game for k=3 case

If a ship has not yet adopted permanent technology, it must decide whether or not to conduct MOE at each time-period, t. This decision is dependent on the expected stream of costs associated with each group. If it conducts MOE, it incurs the cost of MOE, and will face time-delays associated with MOE. On the other hand, if it does not follow MOE and is found in non-compliance, it is penalized and moved to (G_2,*) which has a higher stream of costs than G_1.

The most efficient way to analyze this problem is by formulating Bellman equations. The four equations given below are the Bellman's equations for ships in each of the states. The decision of ships in group G_3 is not discussed here.

$$G1 \qquad \underset{i}{Min} \begin{cases} i=1 & R_1+\beta V_{t+1}(G_1)+c_1+d_1 \\ i=0 & p_1[R_2+f_1+C_1+D_1+\beta V_{t+1}(G_2,0)]+(1-p_1)[\beta V_{t+1}(G_1)] \\ i=3 & R_3+\beta V_{t+1}(G_3) \end{cases} \tag{13}$$

$$(G_2,0) \qquad \underset{i}{Min} \begin{cases} i=1 & p_2[R_1+c_2+d_2+\beta V_{t+1}(G_2,1)]+(1-p_2)[R_1+d_1+\beta V_{t+1}(G_2,0)] \\ i=0 & p_2[R_2+f_2+C_2+D_2+\beta V_{t+1}(G_2,0)]+(1-p_2)[\beta V_{t+1}(G_2,0)] \\ i=3 & R_3+\beta V_{t+1}(G_3) \end{cases} \tag{14}$$

$$(G_2,1) \qquad \underset{i}{Min} \begin{cases} i=1 & p_2[R_1+c_2+d_2+\beta V_{t+1}(G_2,2)]+(1-p_2)[R_1+d_1+\beta V_{t+1}(G_2,1)] \\ i=0 & p_2[R_2+f_2+C_2+D_2+\beta V_{t+1}(G_2,0)]+(1-p_2)[\beta V_{t+1}(G_2,1)] \\ i=3 & R_3+\beta V_{t+1}(G_3) \end{cases} \tag{15}$$

$$(G_2,2) \qquad \underset{i}{Min} \begin{cases} i=1 & p_2[R_1+c_2+d_2+\beta V_{t+1}(G_1)]+(1-p_2)[R_1+d_1+\beta V_{t+1}(G_2,2)] \\ i=0 & p_2[R_2+f_2+C_2+D_2+\beta V_{t+1}(G_2,0)]+(1-p_2)[\beta V_{t+1}(G_2,2)] \\ i=3 & R_3+\beta V_{t+1}(G_3) \end{cases} \tag{16}$$

R [R_1, R_2, $R_3 \in R$] represents costs of cleaning ballast water, C [$C_1,C_2,c_1,c_2 \in C$] represents costs of monitoring transferred to ships, D [$D_1,D_2,d_1,d_2 \in D$] represents time delay costs and f [$f_1,f_2 \in f$] represents fines in case of non-compliance. A complete list of symbols used is provided under 'List of Variables' at the beginning. The discrete control variable 'i' represents the decision variable: i=1:follow MOE; i=0: not follow MOE; and i=3: install permanent technology,y_3. The state variable is the group into which a ship belongs at each stage. There are (k+2) state variables G_1,(G_2,0),(G_2,1),(G_2,2) and G_3. Decisions under G_3 are not provided here. The goal of the policy maker is to formulate the game in such a way that all ships have an incentive to stay away from (G_2,*) by either complying in G_1 or moving to G_3. This is achieved by making the present value of costs for staying in (G_2,*) higher than that for complying in G_1 or moving to G_3.

The numeric parameters given to the ship owner are cost of MOE (R_1), cost of alternate mechanism suggested by the agency if the ship is found in non-compliance (R_2), cost of adopting and operating permanent technology (R_3); costs of monitoring transferred to ships under various groups (C_1, C_2, c_1, and c_2); costs due to time delays (D_1, D_2, d_1 and d_2); and fines and probabilities of monitoring (f_1, f_2, p_1,, and p_2).

5.3 Solution Methodology

5.3.1 Value Functions

The above four equations are solved using Bellman's backward recursive procedure. At each stage t, value functions in each of the five states are calculated. The decision 'i' in each state is determined by evaluating the value functions and choosing that decision which has minimum value function. This procedure is repeated for each of the t stages.

We solve the dynamic formulation using a computer program (written in 'C' language). The analysis is conducted for a bulk carrier with approximately 30,000 tons of ballast water. Output from one of the cases (case 22 in table 6 of Appendix B) is used as an example for this discussion. See Appendix A for the output of the program. In the output for case 22, the input parameter values are summarized in the first 7 lines. Value functions for most cases converge around T=30. Under 'DECISIONS', decisions and the corresponding value functions in the 5 states are shown for each of the 30 stages.

5.3.2 Rate of compliance and rate of installation of y_3

In addition to knowing the decision of a ship in each period, we are also interested in knowing (1) the compliance rate of each ship over the entire time period and (2) the rate of installation of permanent technology. These rates are used in subsequent sections to simulate the future composition of bulk carriers.

The rate of compliance for MOE is represented by ρ, the rate of installation of y_3 is represented by γ. These rates are calculated under each group. Thus ρ_1, ρ_2 represent rates of compliance in G_1 and $(G_2,*)$ respectively; γ_1, γ_2 represent rates of installation of y_3 by ships in G_1 and $(G_2,*)$ respectively.

The procedure for calculating these rates is as follows: the decision of each ship under each group is given to us in the output ("0', "1" and "4" represent "do not follow MOE","follow MOE", and "adopt and use permanent technology"). By adding all "1"s, and dividing by T under each group, we get rate of compliance of MOE (ρ_1 and ρ_2). Adding all "4"s and dividing by T, we get the rate of installation of y_3 (γ_1 and γ_2). Table 2 shows these calculations for our example.

Table 2 : Calculation of ρ_1, ρ_2, γ_1 and γ_2

GROUP	TIME						ρ	γ
	1	**2**	**3**	**4**	**..**	**30**		
G_1	0	0	0	0	..	1	ρ_1=12/30 = 0.4	γ_1=0/30 = 0
$(G_2,0)$	1	1	1	1	..	1		
$(G_2,1)$	1	1	1	1	..	1	ρ_2=90/90 = 1.0	γ_2=0/90 = 0
$(G_2,2)$	1	1	1	1	..	1		
G_3	4	4	4	4	..	4		

We obtain one such table for each case we run. These rates, obtained by simple average, are then used along with probabilities of monitoring (p) to obtain a transition matrix.

5.3.3 Transition matrix (P):

A transition matrix tells us the probabilities of a ship moving from a particular group in this period to another in the next period. Rows represent the group the ship is currently in and columns represent the group the ship will be in the next period. The value in the cells is the probability of a ship moving from a given state (row) to a new state (column).

Table 3: Transition Matrix for the game with k=3

	G_1	$(G_2,0)$	$(G_2,1)$	$(G_2,2)$	G_3
G_1	$(1-\gamma_1)[1-(1-\rho_1)p_{1,}]$	$(1-\gamma_1)(1-\rho_1)p_1$	0	0	γ_1
$(G_2,0)$	0	$(1-\gamma_2)[1-\rho_2 p_2]$	$(1-\gamma_2)\rho_2 p_2$	0	γ_2
$(G_2,1)$	0	$(1-\gamma_2)(1-\rho_2)p_2$	$(1-\gamma_2)(1-p_2)$	$(1-\gamma_2)\rho_2 p_2$	γ_2
$(G_2,2)$	$(1-\gamma_2)\rho_2 p_2$	$(1-\gamma_2)(1-\rho_2)p_2$	0	$(1-\gamma_2)(1-p_2)$	γ_2
G_3	0	0	0	0	1

Ten of the elements in the above matrix have zeros. The game does not allow a ship to move from $(G_1,*)$ to either $(G_2,1)$ or $(G_2,2)$ directly. The element (5,5) is "1" since once a ship enters G_3 it is in the 'absorbing state' and, therefore, will remain in G_3 forever.

Consider element (3,2) in the above matrix. It tells us that the probability of a ship moving from $(G_2,1)$ group to $(G_2,0)$ is $(1-\gamma_2)(1-\rho_2)p_2$. $(1-\gamma_2)$ is the probability of the ship not installing y_3. (1-ρ2) is the probability of the ship not following MOE and p_2 is the probability of the ship being monitored. Since a ship is moved from (G_2,1) to (G_2,0) only if (1) it does not follow MOE, (2) does not install y_3, and (3) it is monitored and found in noncompliance --[$(1-\gamma_2)(1-\rho_2)p_2$] captures the probability of all three events occurring simultaneously. Similar explanation holds for each of the elements in the above table. Although this table is unique for the model, the mathematical values differ for each case we run. The transition matrix for the example is given under table 4. The same values can be seen in the output (Appendix A) under "TRANSITION MATRIX".

Table 4: Transition Matrix for the example

	G_1	(G_2,0)	(G_2,1)	(G_2,2)	G_3
G_1	0.88	.12	0	0	0
(G_2,0)	0	.2	.8	0	0
(G_2,1)	0	0	.2	.8	0
(G_2,2)	.8	0	0	.2	0
G_3	0	0	0	0	1

This transition matrix gives the probability of a ship moving to each one of the five states for the next period only. As we are interested in the composition of bulk carriers 20 time periods from now, additional calculations must be conducted. Section 5.3.4 discusses these calculations.

5.3.4 Composition of Bulk Carriers

To obtain the probability of a ship being in one of the five states after 20 time periods, the state occupancy probability vector at a given period must be post multiplied by the transition matrix, **P** for each of the 20 periods. Let $\pi i(t)$ be defined as the probability that the game will occupy state i in stage t. Then $\pi(t)$ is defined as the row vector of the state occupancy probabilities $\pi i(t)$. The components of this vector give the probability of a ship being in the corresponding state at stage t. In our analysis this vector has five components. By post-multiplying the state occupancy probability vector at time t with the transition matrix, P, we obtain the probability of the ship being in one of the five states at time t as $\pi(t) = \pi(t-1)P$[2]. In our example:

$\pi(0) = [1, 0, 0, 0, 0]$: ship is in $(G_1,*)$ at the beginning

Transition equation: $\pi(t) = \pi(t-1) . P$

i.e. $\pi(1) = \pi(0) . P = [.88, .12, 0, 0, 0]$ ... end of time period 1

$\pi(2) = \pi(1) . P = [.77, .23, 0, 0, 0]$ .....end of time period 2

....

$\pi(20) = \pi(19) . P = [0.71, 0.10, 0.10, 0.10, 0]$ .. end of time period 20

To obtain future composition of the cohort of bulk carriers in the 25,000-75,000 DWT range, these probabilities must be multiplied with the number of ships. In the output of our example, under "AGING" the probability of a ship being in each of these five states for each of the 20 time periods is shown. Notice that in the example considered, after 20 time periods, around 70% of ships are under G_1 and the rest under $(G_2,*)$. [All sub groups of G_2 are grouped under $(G_2,*)$].

One of the shortcomings of this analysis, as already mentioned, is that it deals with one given cohort of ships only. A second shortcoming is that it deals with retrofitting of ships currently in operation and does not incorporate replacement of old ships by new ships. But the proposed incentive mechanism will influence technology on the new ships- ships that are built to replace old ones may be equipped with (ballast water)

[2] For more details of this method, refer to "Application of stochastic processes to summarize dynamic programming solutions", Technical Report #91-1, Texas A&M University, 1991.

cleaning technology, thereby further accelerating the rate of installation of permanent technology (and movement of ships to G_3 group).

5.4 Results

The analysis was conducted using the solution methodology specified in Section 5.3. The nineteen variables are p_1,, p_2, f_1, f_2, T, k, β, R_1, R_2, R_3, C_1, D_1, C_2, D_2, c_1, d_1, c_2,d_2 and A. Variables k, β, R_1, and A were not varied; C_1, C_2, D_2 were varied but with no consequential changes. Initial values of some variables are: p_1,=0.2, p_2=0.8, f_1=\$5000, f_2=\$10000, T=30, k=3, β=0.9, R_1=\$3600, R_3=\$100000, C_1=C_2=c_1=c_2=\$3750, D_1=D_2=d_1=d_2=\$1700 and A=20. We test for $R_1 > R_2$ and $R_1 < R_2$.

In this section we seek answers to the following two questions:(1) Can the agency get compliance in (G_1,*) with low p_1, and f_1?, (2) When will ships adopt y_3?

5.4.1 How can the agency get compliance in G_1 with low p_1 and f_1?

The objective of the agency is to minimize introduction of NIS via ballast water. In order to achieve this goal, the agency is interested in ensuring that all ships comply with MOE in G_1. Since the agency would like to achieve this goal with minimal costs, (low p_1,f_1) we seek to answer the above question.

For this analysis, the set of variables is divided into four categories and variables under each category are varied systematically. Step I discusses the analysis of these four categories. The results from each category are reported in Appendix B. In the tables, Row 'COMPLIANC' gives the compliance rates. For instance "0,1,1,1,4" implies that a ship in G_1 will not follow MOE, will follow in (G_2,0),(G_2,1), (G_2,2) and adopt and use y_3 in G_3. Row "SIMULATION" shows the probability of a ship being in a particular group 20 periods later (A=20). Conversely it can be said that these are the simulated values of the future composition of the bulk carrier fleet. For instance ".87,.12,0" implies that 20 periods later 87% of ships will be in G_1, 12% in (G_2,*) and none in G_3. Composition of the fleet in each of the sub-groups in (G_2,*) are also obtained but not reported here. Important results from each category are then combined in Step II. Table 5 reports these results. The results show that it is indeed possible to achieve compliance in G_1 with low (p_1,f_1) under certain conditions.

Step I:

Four categories are analyzed in this step. In category 1, relative cost between R_1, the cost of MOE, and R_2, the cost of the alternate mechanism, is examined. The results show that if $R_2<R_1$,then (i) $c_1=0$ and (ii) $D_1 \geq$ \$10,200 must hold for compliance; if $R_2>R_1$, then (i) $c_1=0$ and (ii) $R_2 \geq$ \$8,255 must hold. Hence, from Category 1, it appears that $c_1=0$ is essential for compliance. In category 2, we try to achieve compliance with low f_1. The results show that one can get compliance with low f_1 so long as c_2 is high. Under category 3, compliance is checked with low p_1 and f_1. Results show that this is possible so long as c_2 is kept high. Under category 4, results from category 2 and category 3 are incorporated and tested for $R_2<R_1$. The following discussion gives further details of this analysis.

Category 1: The first issue examined is the importance of relative cost between R_1, the cost of MOE, and R_2, the cost of an alternate mechanism that must be performed in case a ship is found in non-compliance. Given that R_1= \$3,600, only values of R_2 are varied.

For $R_2<R_1$, in general there is compliance only when (i) D_1 > \$10,200 and (ii) $c_1=c_2=0$. D_1 is the time delay cost associated with the alternate mechanism, c_1 and c_2 refer to costs of monitoring levied on ships that are in compliance in G_1 and (G_2,*) respectively. Since $R_2<R_1$, it may be economical for ships to not comply with MOE but follow an alternate mechanism. In such a case, having a high time delay cost associated with the alternate mechanism may be the only incentive for making ships comply with MOE. Table 16 of Appendix B shows the same results.

Next, the model is examined for $R_2 > R_1$. The initial R_2 value is set at \$3,600 and gradually increased. At R_2= \$7,550, compliance in G_1 is noticed so long as $c_1 = 0$. To get compliance with $c_1>0$, R_2 must be at least \$16,050. Further analysis strengthened the inference that R_2 and c_1 have a direct relationship. Additional simulations show that 95% of ships are in compliance so long as c_1=0 and $R_2 \geq$\$8,255. Tables 17 and 18 (of Appendix B) give more information on this result. Based on this study, it is recommended that c_1 be 0 and $R_2 \geq$\$8255 for compliance in G_1.

Category 2: In the next step, the significance of fines (f_1 and f_2) is studied. Table 19 of Appendix B has data on these results. Fines in (G_2,*), f_2, do not appear to be important for compliance in G_1. An interesting result is that f_1 and c_2,cost of monitoring transferred to ships in compliance in (G_2,*), have a strong inverse relationship. For instance, if f_1=0, then c_2 must be $\geq$ \$3,750 for compliance in G_1; for c_2=0, $f_1 \geq$ \$12,795. This implies that f_1 can be low (even zero) as long as c_2 is positive and at least \$3,750. This is an important result as one of the objectives of this study is to keep f_1 low and still attain compliance in G_1.

Category 3: (Table 20 of Appendix B) Probabilities of monitoring, (p_1 and p_2) are varied along with fines, f_1 and f_2. It is observed that the variable p_2 has minimal impact on compliance in G_1. As expected p_1 and f_1 have an inverse relationship. It is found that for p_1 =.2, we need $f_1 \geq$ \$5000; for p_1 =.1, $f_1 \geq$ \$23,943 for compliance in G_1.

Category 2 tells us that f_1 and c_2 have an inverse relationship. Category 3 shows an inverse relationship between p_1 and f_1. Since the objective here is to see if there is compliance in G_1 with low p_1 and f_1, it is interesting to check if this can be accomplished by having high c_2. i.e. achieve compliance in G_1 with low probability of monitoring and low fine , so long as the cost of monitoring ships that are in compliance in (G_2,*) is high. The assumption here is that monitoring costs are transferred to ships in (G_2,*). This hypothesis is examined under Step II.

Category 4: To complete the analysis under Step I, the result from Category 1 is tested once again with the additional information received, for the $R_2<R_1$ case. Table 21 of Appendix B has more information on this analysis. This shows that so long as $R_2<R_1$ and with $c_1=0$, it is *not* possible to achieve compliance in G_1 with low p_1 and f_1.

Step II

From Step I, it appears that compliance in G_1 can be obtained so long as (i) $R_2>R_1$, (ii) $c_1=0$; (iii) inverse relation between f_1, and c_2 is maintained; and (iv) inverse relation between p_1 and f_1 is maintained. Under step II, all these results are tested together with (a) $R_2>R_1$,(b) $c_1=0$, (c) low $f_1(f_1=0)$, (d) high c_2 and (e) low p_1 $(p_1=0.2)$. Table 5 gives a synopsis of these results.

Table 5 Results from Step II

	a	b	c	d	e
p_1	.2	.2	.2	.2	.2
p_2	.8	.8	.8	.8	.8
f_1	0	0	0	0	0
f_2	10K	20K	10K	10K	10K
T	150	150	150	150	150
k	3	3	3	3	3
β	.9	.9	9	.9	.9
R_1	3600	3600	3600	3600	3600
R_2	8255	8255	16050	16050	16050
R_3	100K	100K	100K	100K	100K
C_1	3750	3750	3750	3750	3750
D_1	1700	1700	1700	1700	1700
C_2	3750	3750	3750	3750	3750
D_2	1700	1700	1700	1700	1700
c_1	0	0	0	3750	6000
d_1	1700	1700	1700	1700	1700
c_2	3750	3750	3750	3750	3750
d_2	1700	1700	1700	1700	1700
A	20	20	20	20	20
COMPLIANC	1,1,1,1,4	1,1,1,1,4	1,1,1,1,4	1,1,1,1,4	0,1,1,1,4
P_1,P_2,C_1,C_1	.96,1,0,0	96,1,0,0	99,1,0,0	97,1,0,0	0,1,0,0
SIMULATION	87,.12,0	97,.12,0	99,.01,0	98,.02,0	57,.42,0

Case 'a' in Table 5 is the baseline case. Case 'b' represents variations in f_2. Case 'b' was conducted to see if f_2 gained any importance when results from Step I were combined. The analysis showed that f_2 remains unimportant. Cases 'c' and 'd' show the relationship between c_1 and R_2. One can achieve compliance with c_1=0 so long as $R_2 \leq$ \$16050; if $0 \leq c_1 \leq \$3750$ then $R_2 \geq \$16050$. For $c_1 > \$3750$, R_2 must be strictly greater than \$16050 for compliance. Case 'e' shows this result. The results show that with a high c_2 (c_2=\$3750) one can achieve compliance with low p_1 and f_1.

This analysis was conducted for T=150 since the value function did not converge until T=140 in a few cases. Notice that $\rho 1 \geq 96\%$ in most cases. Any ship with $\rho_1 \geq 96\%$ is taken to be in compliance. So far in the analysis there has been no movement to G_3 i.e. no installation of permanent technology, y_3. We now continue with the analysis to check for the movement of ships to G_3.

5.4.2 When will ships adopt y_3?

Step III

Section 5.4.1 showed that although several variables were varied, none of them had an effect on adoption of permanent technology. Two variables play an important role in adoption of permanent technology. R_3, the cost of installing permanent technology and T, the number of visits to port. Analysis shows that as R_3 decreases or as T increases, ships adopt permanent technology.

This analysis gave identical results for $R_2 > R_1$ and $R_2 < R_1$ cases. Table 6 below brings out these observations clearly. Each Column represents decision vector [G_1, (G_2,0), (G_2,1), (G_2,2)]. For instance, (0,3,1,1) implies that ships in (G_1 will not follow any technology; ships in (G_2,0) will adopt y_3; and ships in (G_2,1) and (G_2,2) will follow MOE.

Table 6 Relation between R_3, T and adoption of y_3

	1,1,1,1	0,3,1,1	0,3,3,1	0,3,3,3	3,3,3,3
R_3@T=10	>32,500	32,500	32,000	29,000	27,500
R_3@T=20	>43,500	43,500	43,000	39,000	36,000
R_3@T=30	>47,000	47,000	46,000	41,000	36,000
R_3@T=40	>48,000	48,000	46,000	41,000	37,000
R_3@T=50	>49,000	49,000	46,000	41,000	37,000
R_3@T=150	>49,000	49,000	46,000	41,000	37,000

We begin the analysis with R_3=\$100,000 and then reduce it at a \$1,000 interval to check for movement to G_3. This process is repeated for various T values.

We begin by examining rows of table 6. Notice that for a given T, there is a cut-off R_3 level beyond which ships do not adopt y_3. As cost of installation, R_3, is decreased, ships in (G_2,0) adopt first, followed by ships in (G_2,1), (G_2,2). Last come ships in the G_1 group. Ships in (G_2,0) have the highest cost under the proposed monitoring system, followed by ships in (G_2,1), (G_2,2) and G_1. Hence, it can be concluded that ships adopt y_3 in that order.

The columns of Table 6 bring out the importance of T, the number of visits to port. As T increases, adoption of y_3 takes place at higher R_3 values -- consistent with the intuition that ships that frequent a port most (T higher) would rather adopt y_3 technology and move to G_3 than face the monitoring / penalty system and the stream of costs associated with it. Ships that plan to visit the port only few times (say T=10) will not adopt permanent technology if the cost of adoption is higher than \$32,500. If that ship is in (G_2,0), it will adopt y_3 at \$32,500. A ship in G_1 will adopt at \$27,500. A ship that plans to visit a port several times (T=50), will adopt y_3 at \$49,000 if it is in (G_2,0); and will adopt at $37,000 if it is in G_1. Thus not only R_3 value, but the frequency of its visit to port also determines the decision to adopt y_3. The following figure brings out these features clearly.

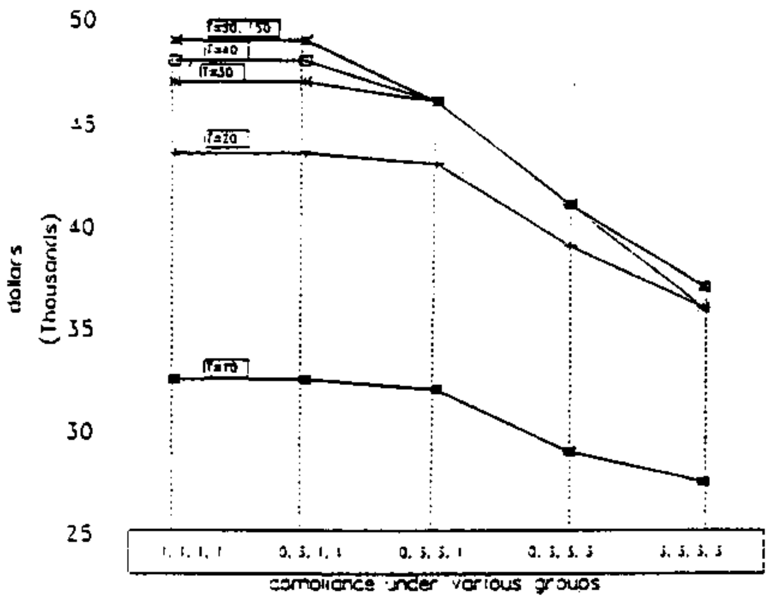

Figure 3: Relationship between R_3,T and y_3

These results are for a bulk carrier with 30,000 tons of ballast water. Preliminary results showed that ships that are larger will adopt y_3 at higher R_3 and lower T values.

5.5 Relation between rates of compliance of MOE (ρ) and probabilities of monitoring (p_1,p_2)

Having determined what fetches compliance from ships, we now move to optimal combinations of probabilities (p_1,and p_2) to enable the agency to monitor ships with lowest cost. Since the agency would like to see as many ships in G_3, G_1 and (G_2,*) as possible, in that order, we seek to develop a relationship between rate of compliance of MOE (ρ_1) and probabilities of monitoring (p_1,and p_2) in this section.

The program is re-run for all combinations of (p_1, p_2) in $0 \le p_1,p_2 \le 1$, with increments of 0.1. Rates of compliance for each (p_1,p_2) combination is tabulated and summarized in Table 7.

Table 7 Compliance of MOE(ρ_1) in Group G_1
(rows - p_2, columns - p_1,)

	0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
0	0	0	0	0	.01	.01	.01	.01	.01	.01	.01
0.1	0	0	0	0	.01	.01	.01	.02	.02	.03	.03
0.2	0	0	0	0	.01	.07	.22	1	1	1	1
0.3	0	0	0	.97	1	1	1	1	1	1	1
0.4	0	0	0	.98	1	1	1	1	1	1	1
0.5	0	0	0	.99	1	1	1	1	1	1	1
0.6	0	0	0	.99	1	1	1	1	1	1	1
0.7	0	0	0	.99	1	1	1	1	1	1	1
0.8	0	0	.96	.99	1	1	1	1	1	1	1
0.9	0	0	.97	.99	1	1	1	1	1	1	1
1.0	0	0	.97	.99	1	1	1	1	1	1	1

Columns represent p_1 values, rows represent p_2 values. The value in the cells is the compliance rate. One can clearly see the area of compliance and the non-compliance, and the locus of (p_1,p_2) combinations which separate the two in the following graph. It is a two dimensional map of compliance space, with p_1, and p_2 on X- and Y-axes respectively.

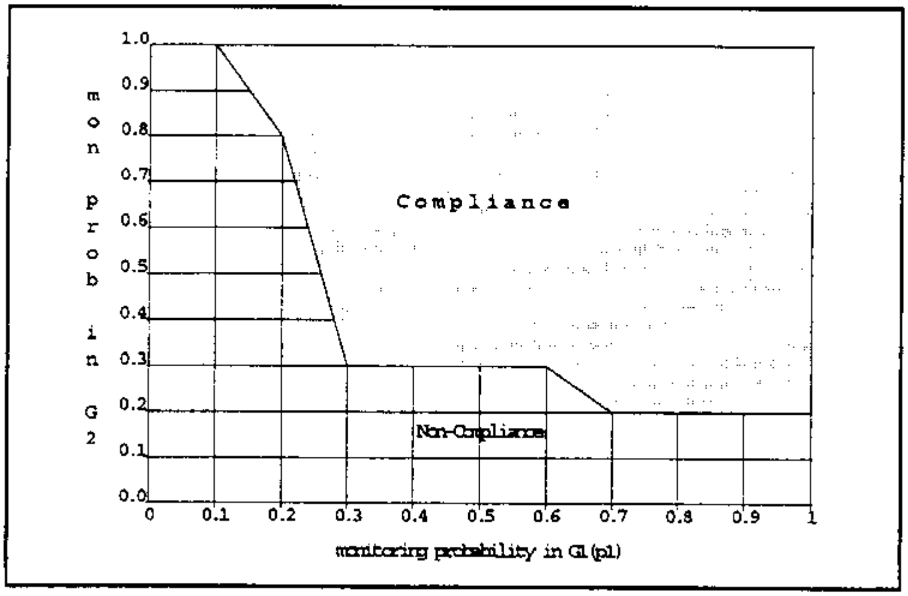

Figure 4: MOE Compliance Space

The line gives the locus of (p_1,p_2) combination that will achieve compliance with minimal monitoring. Any point to the right of the line fetches total compliance from ships but is not cost-minimizing, as monitoring pressure is more than what is necessary to achieve compliance. Combinations (.2,.8), (.3,.3), (.4,.3) are some of (p_1,p_2) combinations that achieve over 96% compliance from ships. Although this result is independent of the size /type of ship, the variables used may themselves rely on the size/type of ship.

5.6 Relationship between monitoring budget, probabilities and compliance

One of the main goals of this study is to achieve compliance in a cost effective manner. In order to decide an optimal combination of (p_1, p_2), it is important for the agency to assess the budget needed for carrying out these monitoring operations. In this section we calculate such budgetary needs.

Calculation of monitoring budget

Assume that the number of ships that visit the port per period (N) is 1,000. $n_1(t)$ represents ships in G_1 at stage t, and $n_2(t)$ represents total ships in (G_2,*) at stage t; (n_1+n_2 = N). Further, assume that the average cost of monitoring a ship per visit (M) is $1,000.

Let B(t) = monitoring budget for stage t. At t = 0, all ships are in G_1.

At t=0, B(0) = $N.p_1.M$.

At t, B(t) = ($n_1(t).p_1$,.M) + ($n_2(t).p_2$.M).

Total monitoring budget for T stages is then given by:

$$B=\sum_{t=0}^{t=T} B(t) \tag{17}$$

The following table gives budgets needed for different combinations of (p_1,p_2).

Table 8 Monitoring Budget for (p_1,p_2) combinations

	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	890580	990776	999441	1006687	1006710	1013513	1013513	1013513	1013513	1013513
0.1	2100000	2595388	2766294	2855015	2910810	2944594	2974636	2992857	3013242	3024637
0.2	3309418	4200000	4533147	4703344	4841856	5054699	14700001	16800002	18900002	21000002
0.3	3867861	5451812	6300000	8400000	10500000	12600000	14700001	16800002	18900002	21000002
0.4	4432724	5479814	6369826	8400000	10500000	12600000	14700001	16800002	18900002	21000002
0.5	4874956	7338926	6380126	8400000	10500000	12500000	14700001	16800002	18900002	21000002
0.6	5229634	8066643	6404305	8400000	10500000	12600000	14700001	16800002	18900002	21000002
0.7	5519999	8691134	6422635	8400000	10500000	12600000	14700001	16800002	18900002	21000002
0.8	5761983	4524573	6436971	8400000	10500000	12600000	14700001	16800002	18900002	21000002
0.9	5966665	4430071	5374673	8400000	10500000	12600000	14700001	16800002	18900002	21000002
1	6142010	4439767	6379375	8400000	10500000	12600000	14700001	16800002	18900002	21000002

Notice that in general, as probabilities of monitoring increase, the monitoring budget B increases. Budget needs increase when there are more number of ships in $(G_2,*)$ This observation can be made by examining Table 7 along with Table 8. For those combinations of (p_1,p_2) where the compliance switches from 0 to ≥ 96% (figure 4), it can be seen that the corresponding budget drops or stabilizes without much further increase. The budget relationship to (p_1,p_2) correlates well with the compliance relationship to (p_1,p_2). Figure 5 shows the relation between budget and probabilities of monitoring.

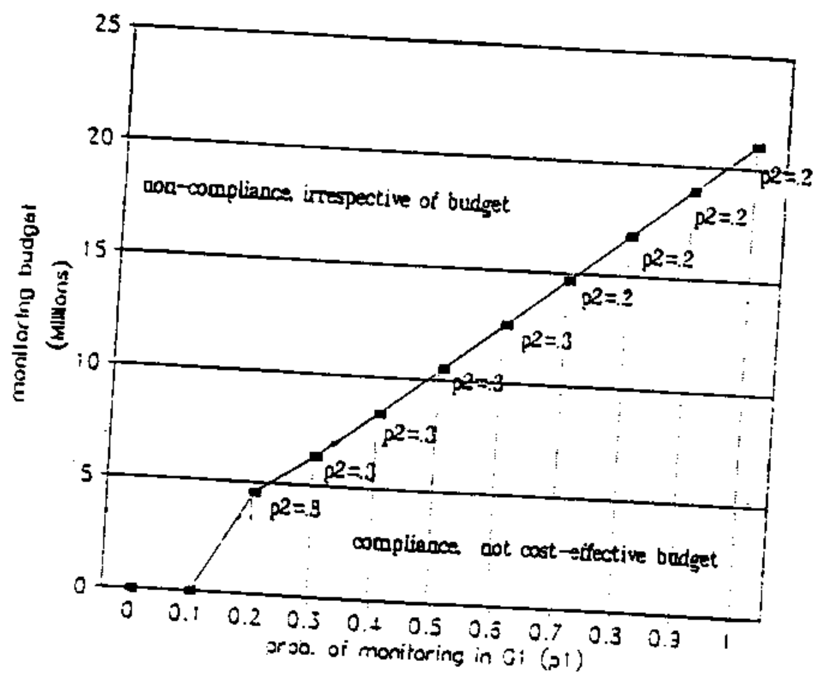

Figure 5 Relation between monitoring budget, probabilities and compliance

The line in the graph gives the budget requirements for those combinations of (p_1,p_2) which achieve compliance from ships. This indeed is the minimum budget required to get compliance from ships. Points to the right of the line show budget numbers that will fetch compliance but are not cost-efficient. Special note must be made of the points to the left of the line. These points represent budget numbers that will not fetch compliance from ships. This clearly shows that right combinations of (p_1,p_2) are more important than sheer extent of budget. This study provides some such combinations.

Summary

This chapter discussed the analysis conducted. Answers to two fundamental questions were found -- compliance can be achieved with low p_1,and f_1 in G_1; and ships adopt y_3 when R_3 decreases or as T increases. Appropriate monitoring pressures that satisfy our scheme were discussed. As pointed out in Chapter II, the scheme was so formulated that the stream of costs of being in each group acts as a strong incentive for staying away from (G_2,*) and moving to G_3 in the long run. Variable T captures the stream of costs being in each group (marginal cost of following transitory technology) and hence fulfills the requirements of equation 3 of chapter II that is necessary for asset replacement. We now proceed to the case studies.

CHAPTER VI

CASE STUDIES

In this chapter, we apply the results of our conceptual analysis to the two case studies. Since this research work is being conducted under a project that is oriented toward Great Lakes NIS problems, one case study will address Great Lakes shipping. The second case study deals with the Chesapeake Bay. We begin this chapter with a brief introduction of both the regions of the case studies - the Great Lakes and Chesapeake Bay. Section 6.1 introduces the framework followed. Section 6.2 deals with the Great Lakes, whereas Section 6.3 deals with Chesapeake Bay case study.

The Great Lakes have some peculiarities which make it an interesting case. First, they have a single point of entry -all ocean-going vessels that are headed for the Great Lakes can enter only through the St. Lawrence Seaway; they are all fresh water ports, which makes monitoring (testing salinity of water) relatively easy; most ships that enter the Great Lakes deal in commodity-specific trade (such as grain,oil etc), so the fleet is fairly homogenous; lastly, MOE is mandatory in the Great Lakes and, hence, a monitoring mechanism is already in place which allows for a comparison between the proposed mechanism and the one currently followed. Cost of monitoring is calculated under the proposed scheme and compared with the budget that is currently incurred for monitoring ships in the Great Lakes.

Ships that intend to enter the Great Lakes are monitored by the Coast Guard which has a monitoring unit at Mesenna, New York. Every ship that has completed trans-oceanic voyage is contacted by the Coast Guard through its agent. If a ship does not have ballast water (No Ballast on Board or "NOBOB") then it is free to enter the Great Lakes without any further monitoring. On the other hand, if a ship has ballast water (Ballast on Board or "BOB") and if it intends to exchange its ballast in the Great Lakes, then the ship is checked for compliance with MOE. This is done by randomly choosing two ballast tanks and sending down a probe to check for salinity levels. If the water is found to have a salinity level of 30 ‰ or above, it is deemed to have passed the salinity test and the ship is permitted to exchange water in the Great Lakes. The ballast tanks of those ships that do not intend to exchange water are sealed to prevent any accidental releases. The seals are checked as the ship leaves the Great Lakes to prevent tampering.

In the 1990 shipping season, 455 ships entered the Great Lakes. Out of these, there is no information on 44 ships (10%); 213 ships (47%) reported no ballast on board, "NOBOB"; 177 ships (39%) were in compliance and 21 ships (5%) were in non compliance. Two points to be noted here are: (i) ships in compliance include those ships that either passed the salinity test or had their ballast tanks sealed; (ii) compliance is calculated by the authorities as 95% { (213 + 177) / (455 - 44)}. Ships with "NOBOB" are taken to be in compliance (Canadian Technical Report of Fisheries, 1991). By 1994, the number of ships that entered the Great Lakes increased to 609 (by 39%). Out of these 564 ships (92.6%) reported no ballast on board, NOBOB; and 45 ships (7.4%) reported ballast water on board[1].

It is clear that ships are currently sorted into two different groups for the purposes of monitoring ("NOBOB" and "BOB"). NOBOB ships have 0% probability of monitoring, ships with BOB have 100% probability of monitoring. Only ships with "BOB" are considered for calculating compliance. It is surprising to note that in four years, the number of ships reporting 'No Ballast on Board' have increased from 47% to roughly 93%. There appears to be a moral hazard problem, in that ships can avoid monitoring by self-reporting "NOBOB". One of the important issues that must be brought

[1]Personal communication with Lt. Comm. Rhea Giacoma, US Coast Guard.

to attention here is that ships that report "NOBOB" may have large quantities of unpumpable[2] ballast water on board.

Chesapeake Bay consists of roughly twelve ports, including the ports of Baltimore, Norfolk, Newport, Portsmouth, Chesapeake, Hopewell, Richmond and Alexandria. Norfolk is the largest operating base for the U.S. Navy on the East Coast (NABISS,1995). Norfolk and Baltimore are two of the busiest ports on the East Coast with a combined traffic of over 4000 ships per year. As the following figure shows, Norfolk port receives over 9 million metric tons of ballast water from bulkers alone each year. In 1990-91, Richmond port received 125 ships (NABISS,1995). Unlike the Great Lakes, ships that enter Chesapeake Bay are more diverse. MOE is only a voluntary guideline here. This study assumes that MOE is made mandatory, suggests the proposed monitoring mechanism and calculates the approximate budget needed to carry out the scheme. The applications are as extensive as the data permits.

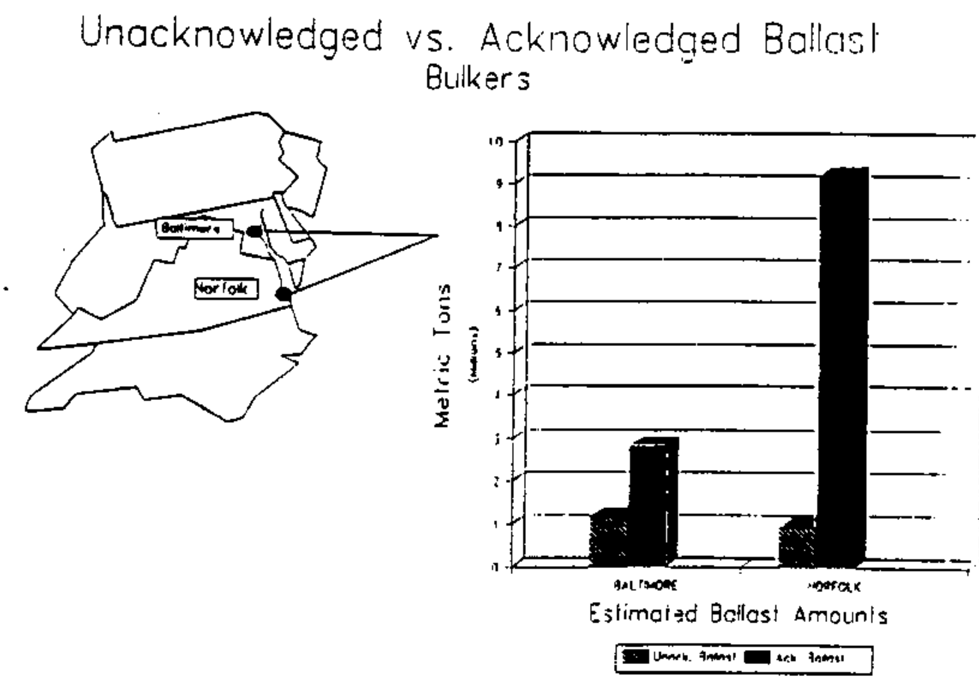

Figure 6 : Ballast Water from Bulkers arriving at Chesapeake Bay

[2]Water at the bottom of ballast tanks which cannot be pumped out but which is generally rich in marine organisms.

6.1 Framework for case studies:

The goal of the policy maker is to prevent NIS invasion with minimum social costs. This goal is partly achieved by minimizing monitoring budget with maximum compliance from ships. In these case studies a comparison between two scenarios is conducted to determine the scenario that minimizes monitoring costs.

Scenario 1: Simple regulation with simple, static monitoring scheme(Current situation in the Great Lakes). The monitoring budget for the Great Lakes under this scenario is available from the benefit cost analysis of MOE study conducted by the Coast Guard (CGD 91-066). In the case of Chesapeake Bay, we calculate the monitoring pressure required to attain >96% compliance in the region under the static monitoring scheme and the budget needed to achieve it. Such data is otherwise not available.

Scenario 2: The conceptual analysis developed in our study provides the needed monitoring scheme for this scenario. Data on cost of monitoring a ship is borrowed from the static case and used to calculate budgetary needs under this scheme.

6.2 A Case Study of the Great Lakes

The Great Lakes have been subject to invasion by the NIS since the 1800's. Over 40 NIS have been introduced since the 1960's (ANSP 1992). Some exotic species such as sea lamprey and the zebra mussel have caused enormous economic losses. To prevent future accidental introductions, in May 1993, MOE was made mandatory for all ships entering the Great Lakes after transoceanic voyages.

There are two cost numbers available in this regard. The BCA study (CGD 91-066) reports $1.141 million as the approximate amount needed to monitor ships. All cost calculations in this BCA study are based on 198 ships and not 455 ships. This gives us approximately $5705 per ship. A representative of the Coast Guard reports the cost of maintaining one monitoring unit at Mesenna, NY as $750,000 per annum[3]. This gives $3750 per ship. Analysis is conducted and reported for both the numbers. The Coast Guard expects the costs to be uniform over time and the same assumption is maintained in our study for the purpose of compatibility. The cost calculations do not seem to differentiate between 'salinity test' cost and 'sealing of ballast tank' cost. In this section monitoring budget under the current scheme is first calculated. Then it is compared with two sets of values that are calculated: (1) cost of monitoring under the proposed scheme with the cost of installing permanent technology, R_3 =$100,000; and (2) cost of monitoring under the proposed scheme with R_3 = $46,000. Analysis in chapter V showed that ships do not adopt permanent technology as long as $R_3 \geq \$50,000$. The values R_3=$46,000 and T=30 are taken as example to show movement of ships to G_3 group.

Monitoring costs under static monitoring scheme: All ships that intend to enter the Great Lakes are approached by the Coast Guard, but only those ships that have ballast on board are checked either for MOE or sealing of ballast tanks. Monitoring is not random but this scheme is neither efficient (because a moral hazard exists in that ships self-reporting "NOBOB" are not inspected; and the number of such ships has grown rapidly), nor is it cost effective as will be shown in this analysis. It incurs a cost of either $750,000 or $1.14 million per annum, i.e. approximately $21 million or $34 million for a 30 year period (without considering problems of inflation and present value calculations).

Monitoring costs under the proposed scheme: The proposed game is applied to all 455 ships in the Great Lakes. Thus the implicit assumption is that all ships have ballast water and must, therefore, conduct MOE. (Alternatively one can devise a scheme where every ship is monitored at two levels - checking for presence of ballast water and if ballast water does exist, then check for salinity levels to ensure MOE has been conduced). On the other hand, if there is a strong preference for maintaining the current mechanism of

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[3]Presentation at the Chesapeake Bay Commission Sub-committee Hearing, Oct 24, 1994, Washington, D.C.

monitoring only those ships that have ballast water, (Eg: 48% in 1990, (198 /411)), then the monitoring costs arrived at, can be proportionately reduced leading to further cost savings. R_3, the cost of installing permanent technology, is initially maintained at $100,000. Our results in chapter V give the optimal combinations of (p_1,p_2) of which (.2,.8) and (.3,.3) are applied here. The method of budget calculation as discussed in Chapter V is followed.

The following table gives the budget requirements for the Great Lakes for 30 time periods under the proposed scheme. It is shown for two sets of (p_1,p_2) combinations - (.2,.8) and (.3,.3) for two cost figures- $5705 and $3750. Cases 'a','b', and 'c' of the following table refer to table 5 of Chapter V. All values are for T=30 time periods. As cost of monitoring values change, the value of the variable, c_2, is also changed. c_2 represents the cost of monitoring transferred to ships in (G_2,*). The reported numbers are in millions of dollars.

Table 9 Monitoring Budget for the Great Lakes under the proposed scheme for R_3=$100,000 ($ millions)

	case a		case b		case c	
	$3750	$5705	$3750	$5705	$3750	$5705
.2,.8	14.43	19.21	14.43	19.21	11.97	17.18
.3,.3	15.87	24.14	15.87	24.14	15.87	24.14

In the above table, notice that all values under $3750 are less than $21 million, and all values under $5705 are less than $34 million, the costs of monitoring under the static system. This implies that the agency can save costs anywhere from 24% (from $21 million to $16 million) to 43% (from $21 to $12 million) for $3750, and from 30% (from $34 million to $24 million) to 50% (from $34 million to $17 million) for $5705 with this scheme. Clearly, the proposed scheme is cost effective than the one currently followed in the Great Lakes. Simulations show that 20 periods later, 396 ships (87%) are in G_1, 60 ships (13%) in (G_2,*)and none in G_3. Figure 7 shows the same.

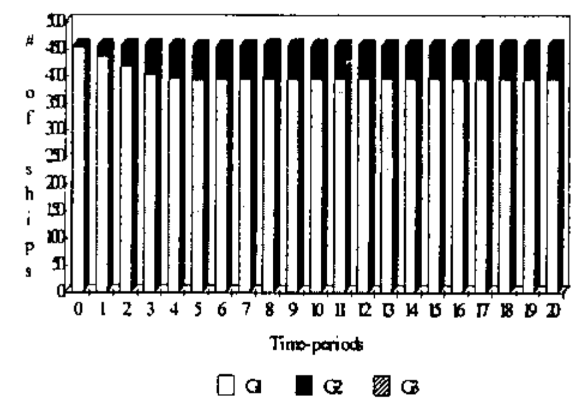

Fig 7:Composition of Bulkers arriving into the G L with R_3= \$100,000

Case 'a' is the base line case. Case 'b' has higher f_2 (fine in (G_2,*)), but notice that the budget needs are the same for case 'a' and 'b', implying that f_2 does not affect ships compliance or monitoring costs. Under case 'c' (R_2 =\$16050, c_1=0) costs are the lowest. One explanation could be that as R_2 increases, compliance increases resulting in decreased costs. High value of R_2 (\$16050, in our case) is accompanied by low c_1 (c_1=0) for optimal compliance. As expected, monitoring costs increase as p_1 increases. It is interesting to note that the differences among the various cases holds for (.2,.8) combination of (p_1,p_2) only. The cost of monitoring is minimum under case 'c', and therefore it can be concluded that it is most cost-effective to have a high R_2 value.

In Chapter V, it was found that for $R_3 \geq \$50,000$ permanent technology is not adopted. For $R_3 < \$50,000$ adoption is dictated by the variable T (number of visits to port). As T increases, adoption takes place at higher R_3 values. In this analysis so far, there has been no movement to G_3. R_3 values are now decreased to test the inference of Chapter V that decreased R_3 or increased T leads to adoption of y_3.

As expected, ships start adopting permanent technology as R_3 decreases. Ships in (G_2,*) adopt first, followed by ships in G_1. The results show that the model responds for values of R_3 <$50,000. We calculate the monitoring budget needed when R_3=$46,000 and T=30 which are reported below.

Table 10 Monitoring Budget under the proposed scheme for the Great Lakes with R_3 =$46,000 ($ millions)

	case a		case b		case c	
	$3750	$5705	$3750	$5705	$3750	$5705
.2,.8	3.91	6.06	3.91	6.06	4.7	7.1
.3,.3	3.88	6.24	3.88	6.24	1.38	2.1

The budget needed to monitor ships is much lower when ships start adopting permanent technology, y_3. Whereas $21 million is the current cost of monitoring over 30 periods, it falls down to $14 million with the proposed scheme. If the proposed scheme is combined with decreased R_3 values, then the cost of monitoring further decreases to as low as $1.38 million, (93% decrease). The monitoring budget is the least when R_2 is high (case 'c'). This is an important result as it brings out the importance of cost reducing innovations in R_3 technology. Therefore, with installation of permanent technology, losses due to NIS introductions and monitoring costs are both minimized, thus achieving some of the goals of the social planner. This analysis assumes that the cost of monitoring in G_3 is zero. The following figure is a simulation of bulk carriers (for case 'a'). for R_3 = $46,000, T =30. It should be noted that similar simulations can be obtained for a combination of $0 < R_3 < \$50,000$; and $0 < T < 50$.

Notice that at the end of 20 time periods, 442 ships (97%) are in G_3, 10 ships (2%) in G_1, and 3 ships (.7%) are in (G_2,*).

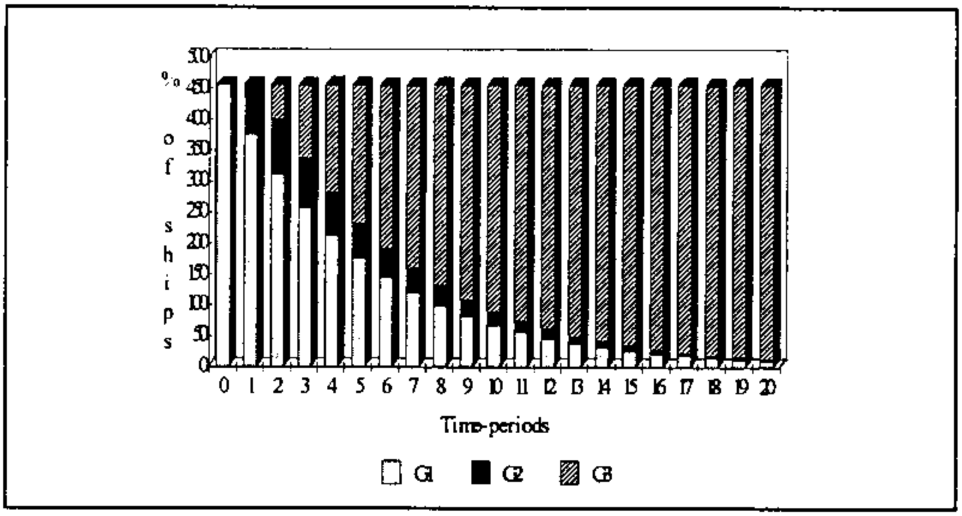

Figure 8 : Composition of Bulkers for R_3 = $46,000

6.3 Chesapeake Bay Case Study

Norfolk and Baltimore, the two major ports in the Chesapeake Bay, receive roughly 3.2. billion gallons of ballast water each year (Chesapeake Bay Commission Report, (CBC)). This region is considered to be one of the nation's "hot spots" for the release of NIS. In 1991 alone, 4390 ships entered the ports of Baltimore and Norfolk (CBC Report). Currently MOE is only a voluntary guideline in the Chesapeake Bay.

Monitoring at Chesapeake Bay may differ from that in the Great Lakes because of differences in salinity levels between the two regions. Each marine port has its own "natural" salinity level (around 30 ‰) which is lower than mid-oceans (around 35 ‰). Chesapeake Bay is not a fresh water system, and therefore the salinity level needs to be higher (for example, 35‰). Hence, salinity as the only criterion may be of greater challenge at Chesapeake Bay. Since the Bay receives ballast water from far more diverse ports than the Great Lakes, there should be greater focus on certain target species which have a higher probability of establishing in the Bay region. There are 12 ports in the Chesapeake Bay which implies that there will have to be multiple points of inspection.

In view of all these differences, it is not clear if monitoring will entail a greater cost per ship in the Chesapeake Bay. Section 6.3.1 assumes that the costs of monitoring at the Bay are the same as in the Great Lakes. Section 6.3.2 assumes that the costs of monitoring are 25% higher in Chesapeake Bay than at the Great Lakes.

Monitoring under a static monitoring scheme: In order to obtain the budget in case of static monitoring system, it is assumed that there is only one group (say G_1), and one probability of monitoring (p_1). A ship owner follows MOE only if ($p_1.f_1$) > R_1 (expected fine>cost of MOE). To achieve compliance, the relationship $p_1 > R_1/f_1$ must hold. We know that R_1 = \$3600 (from Chapter V). To achieve compliance, either p_1 or f_1 must be high since p_1 and f_1 have an inverse relationship. The following table gives the (p_1,f_1) combinations that will fetch compliance from ships with static monitoring system.

Table 11 (p_1,f_1) Combinations under static monitoring system for Chesapeake Bay

p_1	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1
f_1	∞	36,000	18,000	12,000	9,000	7,200	6,000	5,285	4,500	4,000	3,600

The minimum fine in this case is \$3,600 (with p_1=1). Since the intention of this paper is to provide policy incentives that are feasible, we restrict fines to under \$10,000. It is assumed that high fines are politically infeasible. For our analysis, p_1=.4 with f_1=\$9,000 is chosen as the probability of monitoring (and fine) at Chesapeake Bay.

6.3.1 Monitoring Budget under the proposed scheme when the costs of monitoring are the same as in Great Lakes.

Around 4390 ships entered Chesapeake Bay in 1991. Assuming that 40% of ships (1756 ships) are monitored each year, we obtain \$197.7 million (for monitoring cost

\$3750) and \$300.6 million (for monitoring cost \$5705) as cost of monitoring for 30 time periods. These are gross numbers and do not include the reduction in monitoring costs due to collection of fines.

Monitoring costs under proposed scheme: The proposed game is applied to 4390 ships that entered the Chesapeake Bay in 1991. The same procedure as in the Great Lakes case study is followed i.e. optimal combinations of (p_1,p_1) as given in Chapter V {(.2,.8),(.3,.3)} is applied and monitoring budget is calculated according to the formula given in that chapter. The following table gives the budget needed to monitor ships for 30 time periods, for the two cost numbers (\$3750 and \$5705).

Table 12 Monitoring budget under the proposed scheme for Chesapeake Bay for R_3=100,000 (\$ millions)

	case a		case b		case c	
	\$3750	\$5705	\$3750	\$5705	\$3750	\$5705
.2,.8	139.21	185.34	139.21	185.34	115.53	165.7
.3,.3	153.1	232.92	153.1	232.92	153.1	232.92

The results are similar to the results from the Great Lakes case study. Case 'c' has the least budget. Cases 'a' and 'b' have identical numbers. Again, we find differences in cost among cases for (p_1,p_2) values of (.2,.8), but no such differences appear for the other set of (p_1,p_2) values. For monitoring cost of \$3750, with (.2,.8) combination of (p_1,p_2), the minimum expenditure is \$115 million (case 'c') and the maximum expenditure is \$139 million (cases 'a' and 'b'). Both these numbers are lower than \$197.7 million, the cost under static system. If one considers \$5705 as the cost of monitoring per ship, this range for (.2,.8) combination is \$165 million to \$185 million, which is also less than \$300 million.

The costs under (.3,.3) combination are \$153 million (for \$3750) and \$233 million (for \$5705) which are also lower than \$197.7 million and \$300 million respectively. Hence it can be concluded that proposed system is more cost effective than the static system. One notices that ships do not adopt permanent technology as long as R_3 = \$100,000. Simulated figures show that 20 periods later, 3817 ships (87%) are in G_1 group, 573 ships (13%) are in (G_2,*) and none in G_3. Figure 9 shows the same.

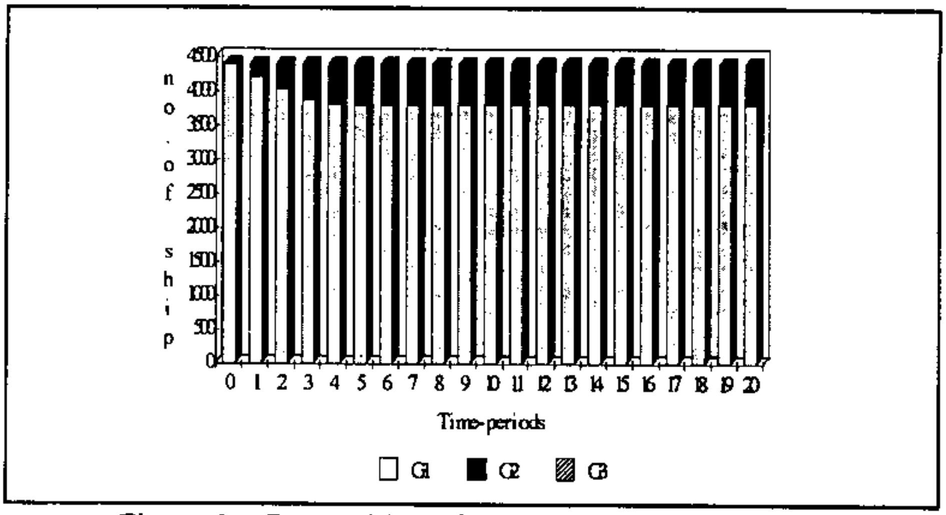

Figure 9 : Composition of Bulkers for R_3 = \$100,000

Values of R_3 are now reduced to check for movement to group G_3. The table below gives the monitoring budget needed for R_3=\$46,000 and T=30 case.

Table 13 : Monitoring budget under the proposed scheme for R_3=\$46,000 (\$ millions)

	case a		case b		case c	
	\$3750	\$5705	\$3750	\$5705	\$3750	\$5705
.2,.8	37.7	58.4	37.7	58.4	45.3	68.5
.3,.3	37.4	60.2	37.4	60.2	13	19.8

Notice that the costs are the least in case 'c' which has high R_2 value with c_1=0 for (.3,.3) combination of (p_1,p_2). The following figure gives the composition of bulk carriers arriving at Chesapeake Bay for 20 time periods.

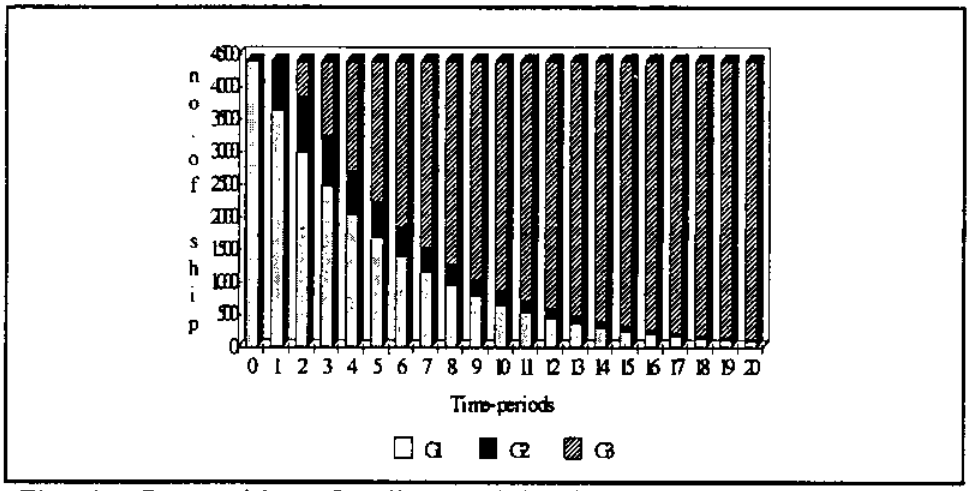

Fig 10 : Composition of Bulkers arriving into C.Bay for R_3 = \$46,000

At the end of 20 time periods, 98 ships (2%) are in G_1, 32 ships (.07%) in $(G_2,*)$ and 4260 ships (97%) are in G_3. These percentages are the same as in Figure 8.

6.3.2 Monitoring Budget under the proposed scheme when costs of monitoring are 25% higher than in the Great Lakes.

For reasons mentioned earlier, monitoring costs at Chesapeake Bay may be higher than those of the Great Lakes. Assuming that it is higher (by 25%), analysis is conducted for \$4688 (125% of \$3750) and \$7131 (125% of \$5705) values also. The cost of monitoring under the static scheme, for 30 time periods is approximately \$247 million and \$376 million respectively.

The results show that total costs increase less than proportionately as cost of monitoring per ship increases. It should be noted here that the cost of monitoring transferred to ships in $(G_2,*)$, the variable (c_2), is also \$4688 and \$7131 respectively. The following table shows the monitoring budget for these cases for (.2,.8) and (.3,.3) combinations of (p_1,p_2).

Table 14 Monitoring budget under the proposed scheme, for higher monitoring cost, for R_3=\$100,000 (\$ millions)

	case a		case b		case c	
	\$4688	\$7131	\$4688	\$7131	\$4688	\$5705
.2,.8	159.8	231.7	159.8	231.7	144.4	207.1
.3,.3	191.4	291.4	191.4	291.4	191.4	291.1

Notice that similar to the earlier cases, cost of monitoring is identical for cases 'a' and 'b', and decreases to certain extent in case of 'c'. Simulations show that 20 periods later, there will be 3991 ships (91%) in G_1, 399 ships (9%) in $(G_2,*)$ with none in G_3.

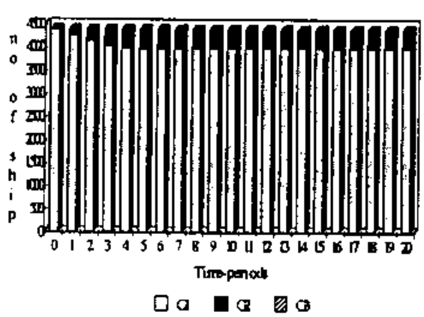

Figure 11: Composition of bulkers at Chesapeake Bay for higher cost values, R_3 = \$100,000

In Section 6.3.1 we obtained \$139 million as the monitoring budget needed (with \$3750). Here we obtained \$159 million (with \$4688). Notice that as costs increase by 25% (from \$3750 to \$4688), monitoring budget is increasing only by 15% (from \$139 to \$159 million). Hence it is cost minimizing for the agency to pass on the entire cost of monitoring to ships[4]. As cost of monitoring increases and as it is passed on to ships, compliance rates improve resulting in lower monitoring budget.

Similar to our result in Chapter V, we now reduce R_3 values at a \$1000 interval and notice the same pattern i.e. as R_3 increases or as T increases more and more ships adopt y_3. Since it is interesting to see what the monitoring costs will be when R_3=\$46,000, monitoring costs were calculated for costs \$4688 and \$7131, and c_2 = \$4688 and \$7131 respectively. The following table gives those results for (.2,.8) and (.3,.3) combinations.

Table 15 Monitoring budget under the proposed scheme for Chesapeake Bay, with higher monitoring costs, for R_3 =\$46,000 (\$ millions)

	case a		case b		case c	
	\$4688	\$7131	\$4688	\$7131	\$4688	\$5705
.2,.8	47.9	71.7	47.9	71.7	55.6	84.3
.3,.3	47.5	75.1	47.5	73.9	16.3	24.5

Notice that with R_3=\$46,000, monitoring costs decrease to less than a third (⅓) of the original costs (from \$159 to \$48 million). It is surprising to note that case 'c' does not give least budget values for (.2,.8) combination of (p_1,p_2) here. This phenomena needs further investigation before any conclusions are drawn. As in the earlier cases ,we are not assuming any monitoring costs once a ship adopts permanent technology. It should be remembered here that R_3=\$46000 is one particular values in a continuum of R_3 values $0 \le R_3 \le \$50,000$. One may conclude that since the policy maker is interested in minimizing social costs, it may be in the interests of society to decrease R_3 in which case monitoring costs would decrease more than proportionately.

[4]The analysis is conducted for \$4688, but with c_2 = \$3750 also. Then a proportional increase in monitoring budget is noticed i.e. monitoring budget increases from \$139 million to \$174 million, which is 125% of \$139 million. Similar results were noted for \$5705 cost values also.

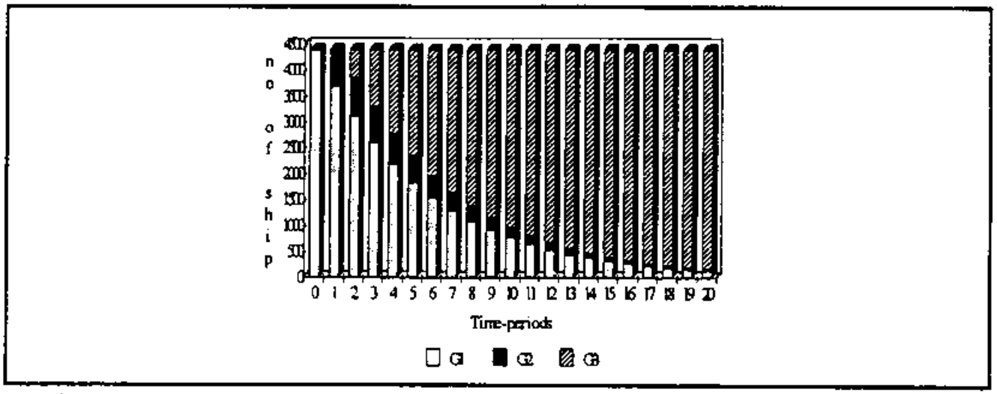

Fig 12: Composition of Bulkers for higher cost values, R_3 = \$46,000

The above figure shows simulated composition of bulk carriers arriving into Chesapeake Bay, for R_3=\$46,000 value. At the end of 20 time periods, 3% of ships are in G_1, .08 are in (G_2,*) and the rest 96% is in G_3 group.

Summary

In this chapter two case studies, one on the Great Lakes and the other on Chesapeake Bay, were conducted. Using two sets of cost numbers, the analysis was conducted for two sets of (p_1,p_2) values. Similar results are noticed for both the case studies. Several inferences that were made in Chapter V were tested here. Case 'b' showed that f_2, fines in (G_2,*) are not important in achieving compliance in G_1. Case 'c' shows that monitoring budget needed is minimum with high R_2 and low R_3 values. In chapter V we noticed that permanent technology y_3 is not adopted as long as R_3 is maintained at \$100,000. As R_3 decreases, and as T increases, adoption of permanent technology takes place. As t increases, the stream of costs associated with both G_1 and (G_2,*) increase. This acts as an incentive for adoption. Ships that frequent the port most will adopt permanent technology quicker than ships that do not frequent port.

We now move to chapter VII where we summarize the entire study and discuss the direction that future research in this area could take.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Invasion of non-indigenous species into domestic water systems has become an issue of serious concern because of the ecological disturbances brought about by these exotic species. In this thesis, a cost-effective policy framework to prevent introduction of NIS via shipping is proposed. The key elements in formulating this scheme are the replacement of ships with those that embody NIS-eliminating technology and a mechanism for monitoring the use of Mid Ocean Exchange (MOE).

7.1 The Problem

MOE has been made mandatory at the Great Lakes to prevent future NIS introductions. This study assumes that MOE is made mandatory in ports where the policy is implemented, and develops a cost effective monitoring scheme to ensure all ships comply with MOE. It also provides incentives for ships to adopt (ballast water) clean up technology in the long-run. To accelerate such an adoption, asset replacement principles are examined and certain crucial conditions identified. One such condition is that marginal cost of MOE (y_2) should be equal or greater than average cost of permanent technology (y_3) for an asset manager to replace y_2 by y_3 technology. Therefore, for cases where marginal cost of y_2 is less than the average cost of y_3, we devise a scheme that increases MC_{y2}.

We propose that USCG monitor ships to ensure compliance of MOE. A state-dependent dynamic approach to monitoring is proposed which is framed in a game-theoretic set-up. Ships are divided among three groups based on their compliance record and the (ballast water) clean-up technology followed. Group G_1 comprises of ships with good compliance record, group G_2 has ships with poor compliance record, and group G_3 has ships with permanent technology. All ships start in G_1. Any ship in non-compliance is moved to G_2 where it must pass k consecutive inspections before it is moved back to G_1. The goal of the policy maker is to ensure that all ships either stay in G_1 or move to G_3. Probabilities of monitoring p_1,p_2 in the two groups G_1, and G_2 are different, (with $p_2 > p_1$). Fines on individual instances of non compliance with MOE are kept low to attain political feasibility. However, 'effective fines' consist of cost of monitoring transferred to ships (c) and higher costs of alternate mechanism which every vessel in non compliance must conduct to its ballast water (R_2). These effective fines make the cost of being in G_2 higher than being in G_1 or G_3. All cost minimizing ship operators find it economical to stay away from G_2. The lesser the number of ships in G_2, the lesser the monitoring cost required since $p_2 > p_1$. In the long run, as the number of visits to port increase, cost of being in G_1 increases relative to G_3. This combined with decreased cost of permanent technology results in adoption of permanent technology.

This study focuses on bulk carriers in the range of 25,000 to 75,000 DWT only. Cost of MOE and time-delay costs associated with MOE (in dollar terms) are calculated using information from current literature. Cost of monitoring is obtained from the BCA study conducted by the US Coast Guard (CGD 91-066). The cost and profit structures of this industry are discussed to enable the reader understand the extent of costs the industry can absorb. It is not uncommon for the port authorities to transfer part of their costs to the vessels. This becomes the justification for transferring cost of monitoring to ships in G_2.

Many control options are being studied by the scientific community. Some of them are discussed in Chapter III. Some of the options under consideration are transferring waste heat from ship's engine, chemical biocides. At this juncture it is still not clear what the permanent technology will comprise of. The scientific community may eventually choose an array of permanent options to accommodate for the different types and sizes of vessels. In light of all these considerations, it is extremely difficult to identify capital and operational cost values for permanent technology. In this study R_3 is used as the annualized cost of installation and operation of permanent technology.

7.2 The Model

A well specified model for our proposed monitoring scheme is presented in chapter IV. Chapter V deals with analysis of the model. This chapter begins with calculation of relevant cost values such as cost of conducting MOE, time-delays associated with MOE (in dollar terms) and cost of monitoring. Bellman equations are formulated and solved for the model (using k=3). At each stage, t, the ship operator must decide which one of the three decisions must be taken: follow MOE (i=1), not follow MOE (i=0), or adopt permanent technology (i=3). Two key questions are raised and answered here: (1) Can the agency achieve compliance with low (p_1, f_1) ?, and (2) when will ships adopt permanent technology ?

The ship operator is assumed to be a cost minimizer and hence will choose that decision which minimizes his costs. Decisions in each state and for each stage are obtained using dynamic programming techniques. To maintain consistency, all results are reported with T=30. (T is number of trips to port). Compliance rate and installation (of permanent technology) rate are calculated to enable calculation of transition matrices which are then used to simulate the model to determine the future composition of (Bulk carrier) fleet.

7.3 Results

The analysis was conducted in three steps. Step I was further divided into four categories. Each category dealt with one set of variables. In Category 1 the effect of relative cost between R_1 and R_2 was studied. Category 2 dealt with impact of fines, f_1 and f_2. Category 3 dealt with changes in probabilities of monitoring, p_1 and p_2, combined with changes in f_1 and f_2. Category 4 shows the importance of having $R_2 > R_1$. Step II combines all the results from Step I and shows the conditions under which compliance can be obtained in G_1 with low p_1 and f_1. Step III analyzes the conditions under which ships adopt permanent technology.

The results show that in our model, most ships comply and stay in G_1 even with a low p_1 (probability of monitoring in G_1) and low f_1 (fines in G_1) when (i) $c_1 < c_2$, and (ii) cost of compliance is less than cost of non-compliance. The results are shown for $c_1=0$ case. Condition (ii) is achieved efficiently when $R_2>R_1$. [Here c_1 and c_2 refer to the cost of monitoring transferred to ships in compliance in G_1 and G_2 respectively; R_1 and R_2 refer to the cost of conducting MOE and alternate mechanism respectively].

It is noticed that ships do not adopt permanent technology as long as $R_3 \geq \$ 50{,}000$. As this value is reduced, ships start adopting y_3. However, as T increases, adoption takes place even at higher values of R_3.

Since one of the main objectives of this study is to minimize monitoring budget for the agency, a locus of (p_1, p_2) combinations that will achieve compliance is obtained; the corresponding minimum budget levels are also estimated.

7.4 Case Studies

Two case studies are conducted to test our results. The first is on the Great Lakes. The Coast Guard currently monitors ships for MOE in the Great Lakes. The current monitoring scheme is not random, but our results show that the proposed monitoring scheme is cost-effective and efficient. It is shown that the cost savings are in the range of 25% to 50%. If the cost of installation of permanent technology is brought down to <$50,000, then there are further savings - up to 93%. This assumes that monitoring costs under G_3 are zero.

A second case study is conducted for the Chesapeake Bay. This region is different from the Great Lakes in various aspects and hence it is suspected that the cost of monitoring is higher than in the Great Lakes. There is currently no information available in this regard. Hence the analysis is done for two sets of 'cost of monitoring' values - (i) same as the Great Lakes values, and (ii) values that are 25% higher than in the Great Lakes. Since no cost values exist for static monitoring, these are also calculated. Again the results show that there are substantial gains in adopting the proposed monitoring scheme. R_3 values are reduced to < $50,000 to show that in 20 periods, over 90% of the ships are in G_3, the group with permanent technology.

The results with 25% higher cost of monitoring are very interesting - it shows that as cost of monitoring is increased by 25%, the total monitoring budget is increased by only 15% (a 10% savings in cost) because more ships adopt permanent technology with higher monitoring costs (since monitoring costs are transferred to ships in G_2, this results in increased "effective fines").

7.5 Limitations and Suggestions for Future Research

The scope of our research is bounded to enable the problem to be more manageable. Our model can be extended in further research in a few areas. First, it deals only with minimizing agency costs with 'loss due to NIS' as a constraint only. But a social planner would like to minimize social costs in their entirety which includes (i) loss due to NIS entry, (ii) loss to trade due to resulting regulations, and (iii) monitoring costs. It would be extremely interesting and useful to estimate welfare losses using a trade model in this context. Any regulation of this nature will affect trade operations which in turn will affect consumer prices. A comprehensive study capturing all the forward and backward linkages is much needed.

Our study has not made use of all the information available on the cost and profit structure of the shipping industry. It only deals with one kind and one size (bulk carriers in 25,000 - 75,000 DWT) vessels when, in fact, the shipping industry is a very diverse industry. All simulations (of future composition of fleet) that are conducted in this study are for one cohort of ships only. But new ships that are built may have permanent technology on board, and hence, the movement to permanent technology by the entire fleet may be much quicker than what is modelled here. Future research could extend this model to all types of ships, and obtain the complete fleet composition.

The introduction of NIS is positively correlated with the extent of ballast water released, (as ballast water quantity increases, more numbers of the same species enter the ecosystem, thereby improving there chances of establishing in the alien environment). Under such circumstances, the size of the ship (more specifically, its ballast water) becomes an important variable. This aspect has not been considered in this study. However, the results of this study can be easily adjusted to any size and kinds of ships by re-specifying some of the parameters of the model.

Since the introduction of NIS affects welfare of society in several ways, a comprehensive model that bridges scientific, industrial, and economic modelling is needed. A dialogue between the various parties (such as biologists, economists, the industry, etc.) is crucial for a complete solution to this problem. It is also imperative to identify a permanent control option soon. It is extremely difficult to frame incentives for adoption of a technology when there is no information about that technology's cost structure. The scientific community must also find a solution to this problem as quickly as possible.

At the operational level, there are several issues that need to be addressed. Each port has its own unique characteristics - for instance Chesapeake Bay has at least 12 ports, with different salinity levels and different traffic rates. The possibility of a ship avoiding monitoring appears to be high in such a situation. Another example of an operational problem can be found in the Great Lakes region - ships that declare "no ballast on board" are free to exchange waters anywhere in the Great Lakes. Most of these vessels do carry unpumpable ballast which is rich in NIS. These ships generally deliver cargo in one Great Lakes port and pick cargo in another. They exchange ballast in transit. Currently there is no monitoring of these ships when, in fact they should be monitored. Several problems of these kind exist in different regions. Thus a uniform regulation in this matter must consider such operational problems when framing a policy.

Most studies involving NIS invasions are biology/zoology-based. The few studies that address monitoring of ships deal with other types of water contamination such as oil spills, toxic waste dumps etc. There are hardly any economic studies with NIS orientation. To our knowledge, this is the first study that addresses these issues, combining the principles of asset replacement and monitoring jointly. Our model is both cost effective and politically feasible. If devised properly, the proposed monitoring scheme will encourage installation of permanent technology and phase out MOE eventually.

APPENDIX A

Appendix A gives the computer output for Case 22. The first seven lines give the input parameters. The rest of the output gives the decisions, compliance rates, transition matrix, and aging of the ship. For further details refer to page 44.

```
p1 = 0.20 , p2 = 0.90 , p3 = 0.00
f1 = 5000 , f2 = 10000 , f3 = 0
T = 30 , k = 3 , beta = 0.90
R0 = 0 , R1 = 3600 , R2 = 3000 , R3 = 100000, r3 = 0
C1 = 3750 , D1 = 1700 , C2 = 3750 , D2 = 1700
c1 = 3750 , d1 = 1700 , c2 = 3750 , d2 = 1700
A = 20
```

DECISIONS:

Time	(G3,*)	(G1,*)	(G2,0)	(G2,1)	(G2,2)
30	4 [0.0]	0 [2690.0]	1 [8675.0]	1 [8675.0]	1 [8675.0]
29	4 [0.0]	0 [6188.3]	1 [16482.5]	1 [15943.8]	1 [11634.7]
28	4 [0.0]	0 [10112.4]	1 [23072.9]	1 [22582.3]	1 [14734.6]
27	4 [0.0]	0 [14124.1]	1 [29043.6]	1 [28274.2]	1 [18192.2]
26	4 [0.0]	0 [18087.2]	1 [34191.0]	1 [33471.5]	1 [21752.3]
25	4 [0.0]	0 [21867.2]	1 [38864.1]	1 [37997.6]	1 [25283.4]
24	4 [0.0]	0 [25429.3]	1 [42950.8]	1 [42123.0]	1 [28662.9]
23	4 [0.0]	0 [28730.7]	1 [46660.2]	1 [45753.8]	1 [31852.9]
22	4 [0.0]	0 [31774.9]	1 [49935.0]	1 [49055.5]	1 [34813.5]
21	4 [0.0]	0 [34556.2]	1 [52904.1]	1 [51982.1]	1 [37545.9]
20	4 [0.0]	0 [37093.2]	1 [55541.9]	1 [54637.4]	1 [40044.7]
19	4 [0.0]	0 [39394.7]	1 [57930.0]	1 [57002.3]	1 [42324.5]
18	4 [0.0]	0 [41481.6]	1 [60060.6]	1 [59143.9]	1 [44393.8]
17	4 [0.0]	0 [43367.6]	1 [61987.0]	1 [61057.4]	1 [46270.5]
16	4 [0.0]	0 [45072.3]	1 [63710.3]	1 [62787.5]	1 [47967.1]
15	4 [0.0]	0 [46609.9]	1 [65266.8]	1 [64336.9]	1 [49500.6]
14	4 [0.0]	0 [47997.2]	1 [66661.9]	1 [65735.0]	1 [50884.1]
13	4 [0.0]	0 [49247.1]	1 [67920.8]	1 [66990.9]	1 [52132.3]
12	4 [0.0]	1 [50372.4]	1 [69050.5]	1 [68123.0]	1 [53257.1]
11	4 [0.0]	1 [51385.2]	1 [70069.2]	1 [69139.4]	1 [54269.8]
10	4 [0.0]	1 [52296.6]	1 [70984.1]	1 [70055.7]	1 [55181.3]
9	4 [0.0]	1 [53117.0]	1 [71808.7]	1 [70878.8]	1 [56001.6]
8	4 [0.0]	1 [53855.3]	1 [72549.6]	1 [71620.6]	1 [56739.9]
7	4 [0.0]	1 [54519.3]	1 [73217.1]	1 [72287.2]	1 [57404.4]
6	4 [0.0]	1 [55117.8]	1 [73817.2]	1 [72887.7]	1 [58002.4]
5	4 [0.0]	1 [55656.0]	1 [74357.5]	1 [73427.5]	1 [58540.6]
4	4 [0.0]	1 [56140.4]	1 [74843.5]	1 [73913.5]	1 [59025.0]
3	4 [0.0]	1 [56576.4]	1 [75281.0]	1 [74350.8]	1 [59461.0]
2	4 [0.0]	1 [56968.7]	1 [75674.5]	1 [74744.4]	1 [59853.3]
1	4 [0.0]	1 [57321.8]	1 [76028.7]	1 [75098.5]	1 [60206.5]

```
COMPLIANCE: ro1 = 0.40  ro2 = 1.00  gamma1 = 0.00  gamm2 = 0.00
```

TRANSITION MATRIX

1.00	0.00	0.00	0.00	0.00
0.00	0.88	0.12	0.00	0.00
0.00	0.00	0.10	0.90	0.00
0.00	0.00	0.00	0.10	0.90
0.00	0.90	0.00	0.00	0.10

AGING:

Time	(G3,*)	(G1,*)	(G2,0)	(G2,1)	(G2,2)
0	0	100	0	0	0
1	0	88	12	0	0
2	0	77	12	11	0
3	0	68	10	12	10
4	0	69	9	11	11
5	0	71	9	9	11
6	0	72	9	9	9
7	0	72	10	9	9
8	0	71	10	10	9
9	0	71	10	10	10
10	0	71	10	10	10
11	0	71	10	10	10
12	0	71	10	10	10
13	0	71	10	10	10
14	0	71	10	10	10
15	0	71	10	10	10
16	0	71	10	10	10
17	0	71	10	10	10
18	0	71	10	10	10
19	0	71	10	10	10
20	0	71	10	10	10

APPENDIX B

Category 1
Table 16 $R_2<R_1$

	1	2	3	4
p_1	.2	.2	.2	.2
p_2	.8	8	.8	.8
f_1	5K	5K	5K	5K
f_2	10K	10K	10K	10K
T	150	30	30	30
k	3	3	3	3
β	.9	.9	.9	.9
R_1	3600	3600	3600	3600
R_2	3000	3000	3000	3000
R_3	100K	100K	100K	100K
C_1	3750	3750	3750	3750
D_1	1700	1700	1700	10200
C_2	3750	3750	3750	3750
D_2	1700	1700	1700	1700
c_1	3750	0	0	0
d_1	1700	1700	0	0
c_2	3750	0	0	0
d_2	1700	1700	0	0
A	20	20	20	20
COMPL	01114	01114	01114	11114
$P_1,P_2,$ C_1,C_2	0,1, 0,0	0,1 0,0	0,1 0,0	1,1 0,0
SIMUL	.57, 42,0	.57, 42,0	57, 42,0	100, 0,0

Category 1
Table 17 $R_2>R_1$

	5	6	7	8
p_1	2	2	.2	.2
p_2	.8	.8	.8	.8
f_1	5K	5K	5K	5K
f_2	20K	10K	10K	10K
T	30	30	30	30
k	3	3	3	3
β	.9	.9	9	.9
R_1	3600	3600	3500	3600
R_2	7550	16050	16050	7550
R_3	100K	100K	100K	100K
C_1	3750	3750	3750	3750
D_1	1700	1700	1700	1700
C_2	3750	3750	3750	3750
D_2	1700	1700	1700	1700
c_1	0	0	3750	3750
d_1	0	1700	1700	1700
c_2	0	0	3750	3750
d_2	0	1700	1700	1700
A	20	20	20	20
COMPL	11114	11114	11114	01114
$P_1,P_2,$ C_1,C_2	1,1 0,0	1,1 0,0	95,1 0,0	0,1 0,0
SIMUL	0, 100,0	0, 100,0	.95, .05,0	57, .42,0

Category 1
Table 18 $R_2 \geq 8255, c_1 = 0$

	9	10	11	12	13
p_1	.2	.2	.2	.2	.2
p_2	.3	.3	.3	.3	.3
f_1	5K	5K	5K	5K	5K
f_2	10K	10K	10K	10K	20K
T	30	30	30	30	30
k	3	3	3	3	3
β	9	9	9	9	9
R_1	3600	3600	3600	3600	3600
R_2	8255	8255	8255	8255	7550
R_3	100K	100K	100K	100K	100K
C_1	3750	3750	3750	3750	3750
D_1	1700	1700	3400	3400	1700
C_2	3750	3750	3750	3750	3750
D_2	1700	1700	3400	3400	1700
c_1	3750	0	0	0	0
d_1	1700	1700	1700	1700	1700
c_2	3750	0	0	3750	3750
d_2	1700	1700	1700	1700	1700
A	20	20	20	20	20
COMPL	11114	01114	01114	11114	11114
P_1, P_2, C_1, C_2	37.1, 0.0	0.1, 0.0	0.1, 0.0	93.1, 0.0	9.1, 0.0
SIMUL	68., 33.0	57., 42.0	57., 42.0	95., 06.0	93., 07.0

Category 2
Table 19 vary f

	14	15	16
p_1	.2	.2	.2
p_2	.3	.3	.3
f_1	5K	12795	5K
f_2	10K	10K	20K
T	30	30	30
k	3	3	3
β	9	9	9
R_1	3600	3600	3600
R_2	16050	8255	8255
R_3	100K	100K	100K
C_1	3750	3750	3750
D_1	1700	1700	1700
C_2	3750	3750	3750
D_2	1700	1700	1700
c_1	0	0	0
d_1	1700	1700	1700
c_2	3750	0	0
d_2	1700	1700	1700
A	20	20	20
COMPL	11114	11114	01114
P_1, P_2, C_1, C_2	3.1, 0.0	1.1, 0.0	0.1, 0.0
SIMUL	87., 13.0	0., 100.0	57., 42.0

Category 3
Table 20 vary p

	17	18	19	20	21
p_1	.1	.1	.1	.1	.2
p_2	.8	.8	.8	.9	.9
f_1	5K	23943	5K	5K	5K
f_2	10K	10K	200K	200K	200K
T	30	30	30	30	30
k	3	3	3	3	3
β	.9	.9	.9	.9	.9
R_1	3600	3600	3600	3600	3600
R_2	8255	8255	8255	8255	8255
R_3	100K	100K	100K	100K	100K
C_1	3750	3750	3750	3750	3750
D_1	1700	1700	1700	1700	1700
C_2	3750	3750	3750	3750	3750
D_2	1700	1700	1700	1700	1700
c_1	0	0	0	0	0
d_1	1700	1700	1700	1700	1700
c_2	3750	3750	3750	3750	0
d_2	1700	1700	1700	1700	1700
A	20	20	20	20	20
COMPL	01114	11114	01114	01114	01114
$P_1,P_2,$ C_1,C_2	0,1, 0,0	37,1 0,0	0,1 0,0	0,1 0,0	0,1 0,0
SIMUL	73, 27.0	81, 19.0	73, 27.0	75, 25.0	61, 39.0

Category 3
Table 21 vary f and p

	22	23	24	25	26	27
p_1	.2	.2	.2	.2	.1	.1
p_2	.9	.9	.9	.9	.9	.9
f_1	5K	8555	18050	5K	44550	2919
f_2	10K	10K	10K	200K	10K	10K
T	30	30	30	30	30	30
k	3	3	3	3	3	3
β	.9	.9	.9	.9	.9	.9
R_1	3600	3600	3600	3600	3600	3600
R_2	3000	3000	3000	3000	3000	3000
R_3	100K	100K	100K	100K	100K	100K
C_1	3750	3750	3750	3750	3750	3750
D_1	1700	1700	1700	1700	1700	1700
C_2	3750	3750	3750	3750	3750	3750
D_2	1700	1700	1700	1700	1700	1700
c_1	3750	0	0	0	0	0
d_1	1700	1700	1700	1700	1700	1700
c_2	3750	3750	0	0	0	3750
d_2	1700	1700	1700	1700	1700	1700
A	20	20	20	20	20	20
COMPL	11114	11114	11114	11114	11114	11114
$P_1,P_2,$ C_1,C_2	4,1 0,0	9,1 0,0	1,1 0,0	0,1 0,0	1,1 0,0	3,1, 0,0
SIMUL	71, 29.0	94, 06.0	0, 100.0	6, 39.0	0, 100.0	94, 06.0

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