International Hydrographic Review, Monaco, LXXII(2), September 1995

DYNAMIC ECONOMIC ANALYSIS OF MARINE POLLUTION PREVENTION TECHNOLOGIES: AN APPLICATION TO DOUBLE HULLS AND ELECTRONIC CHARTS

by DI JIN, HAUKE L. KITE-POWELL and James M. BROADUS [1]

Published in ENVIRONMENTAL AND RESOURCE ECONOMICS 4: 555-580. 1994. Kluwer Academic Publishers. Printed in the Netherlands.

Abstract

Marine pollution associated with shipping accidents has resulted in a Congressional mandate for double hulls on tankers in U.S. waters. In this paper, we formulate a social planner's problem using optimal control theory to examine the relative cost-effectiveness of double hulls and alternative pollution retention technologies, and the optimal installation strategy for such technologies. The model encompasses the costs and benefits associated with shipping operations, damage to the marine environment, and investment in each technology. A computer simulation of the model is used to evaluate investment strategies for two technological options: double hulls and electronic chart systems. Results indicate that electronic charts may be a far more cost-effective approach to marine pollution control.

1. INTRODUCTION

Marine pollution associated with shipping operations and accidents has received increased attention in recent years. Following the EXXON VALDEZ oil spill, the United States Congress mandated double hulls for oil tankers in U.S. waters in the Oil Pollution Act of 1990 (OPA90) (P.L. 101-380). However, economic and engineering analyses needed to identify the socially optimal choice of marine

[1] Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA.

pollution prevention technologies remain to be performed (see NRC, 1991; HOPKINS, 1992; ALCOCK, 1992; COHEN, 1986).

Marine pollution associated with shipping operations can be prevented through the use of several alternative technologies, among them double hulls and electronic chart systems. These two technologies are of special interest. Neither is widely employed in current shipping practice, and their introduction to the world fleet will be a significant innovation. Double hulls were selected as one of the most cost-effective pollution prevention design options by the Marine Board Committee on Tank Vessel Design (NRC, 1991), and they are mandated in OPA90. Electronic chart systems have great potential for preventing maritime accidents, and they represent a fundamentally different (and possibly complementary) approach to pollution reduction.

While the installation of double hulls in oil tankers can reduce the volume of oil spilled in an accident, it greatly increases capital cost and reduces cargo capacity. Similarly, the use of less costly electronic charts in navigation can reduce damages to the marine environment through a reduction in the incidence of groundings and other accidents.

Using double hulls and electronic charts as examples, this paper develops an economic analysis of alternative marine pollution prevention technologies and their policy implications. A social planner's problem is formulated using optimal control theory to examine the effectiveness of and the optimal rate for introducing each alternative technology. The model encompasses the costs and benefits associated with shipping operations, damage to the marine environment, and investment in each technology.

The remainder of this paper is organized as follows. Section 2 provides a brief description of the marine pollution prevention technologies examined in the study. In Section 3, the model is presented. Relevant data and assumptions used for simulations and selected simulation results are reported in Section 4. Policy implications and concluding comments are presented in Section 5.

2. MARINE POLLUTION PREVENTION TECHNOLOGIES

2.1 Double Hulls

The conventional oil tanker design is a single hull vessel with steel plate about an inch thick. Large tankers such as ultra large crude carriers (ULCCs) can carry more than one half million tons of crude oil. Oil tankers often remain in service for more than 20 years. In a conventional single hull vessel, virtually any accidental breaching of the hull will result in oil outflow. To lessen oil spill risks, several alternative designs have been developed to provide oil tankers with an added layer of protection. The NRC (1991) study examined eight design alternatives including double hulls, double bottoms, and intermediate oil-tight decks with double sides. The double hull design features two hulls about 2 meters apart on both sides and the bottom of the vessel.

The NRC (1991) report concluded that double hulls are effective in preventing oil spills or lessening their severity, and that they may reduce the volume of oil spilled by as much as 70 percent compared with the baseline (single hull) case. However, this design alternative requires substantial changes in ship construction, and in turn leads to large cost increases.

Currently, the vast majority of tankers calling on the United States (and most of those in the Valdez/West Coast crude oil trade) have a single hull (NRC 1991). To meet the Congressional mandate for double hulls, new tankers with improved designs will have to be built.

2.2 Electronic Chart Systems

Electronic charts [1] and integrated, computer-based navigation systems are designed to increase safety and efficiency of navigation by automating traditional functions such as position plotting. A typical electronic chart consists of a computer with a database of hydrographic information (roughly the same data traditionally represented in the paper chart) and software to allow route planning and route monitoring. Interfaces to navigational equipment allow the vessel's position to be displayed and monitored on the screen in real time. As well, the computer can analyze the hydrographic database for potential grounding dangers based on current course and speed. With a radar interface, collision targets can be added to the display and to the computer analysis.

Electronic charts today are being utilized on a small but growing percentage of merchant vessels. The introduction of this technology is relatively easy and less costly compared to double hulls, since electronic charts can be installed on existing ships.

3. THE MODEL

The social planner's problem is constructed as follows. The planning region is assumed to have one fleet, which has an effective cargo-carrying capacity of q (measured in metric tons) in a given period of time (e.g., one year) [2]. It is further assumed that the fleet capacity is always fully utilized, so q also represents the regional freight volume in the period. The size of the fleet is denoted by S_f, which can be either the total deadweight tonnage (dwt) of the fleet or the total number of ships in the fleet. The shipping operation generates social benefit, and also incurs associated capital and operating costs. At the same time, the operation causes damage to the marine environment. Pollution prevention technologies may be employed to reduce environmental damage (COHEN, 1986; GRIGALUNAS and OPALUCH, 1990). There are costs associated with each of these technologies. The planner internalizes the externality of shipping operations and treats environmental damage due to oil spills as part of the operating costs. The planner is to determine the rate of investment in each of the available pollution prevention technologies that maximizes the sum of discounted net social benefits. The model we specify here is deterministic. [3]. The planner is assumed to examine one technology at a time, and the model does not include joint introduction of different technologies. In the general case, the tariff (freight rate) is influenced by the total cargo volume shipped in a unit of time.

The planner is to

$$\max \int_0^T [B(q(S)) - c(S)q(S) - g(S)q(S) - I(z)]e^{-\delta t}dt \tag{1}$$

with

$$B(q(S)) = \int_0^q p(\eta)\, d\eta \tag{2}$$

subject to

$$\dot{S} = z \tag{3}$$

$$0 \leq z \leq S_f \tag{4}$$

$$0 \leq S \leq S_f \tag{5}$$

$$S(0) = S_0 \tag{6}$$

where B is the social benefit associated with shipping services;
p is the inverse demand function (tariff);
q is the cargo shipped at t;
c is the unit cost of shipping operations at t;
g is the unit damage to the marine environment from shipping operations at t;
I is the investment in pollution prevention technology at t;
z is the tonnage (or number of ships) of the fleet on which the technology gets installed at t; [4]
S is the cumulative tonnage (or number of vessels) of the fleet equipped with the technology at t;
δ is the discount rate;
t is time; and
T is the planning horizon.

Several features of the model are noteworthy. The model captures efficiency gains or losses in terms of effective cargo capacity q (the first terms in (1)) and operating cost changes (the second terms in (1)) associated with a new technology. For example, the installation of electronic charts enables the mariner to execute more easily and reliably the navigational routines currently performed on paper charts; and it improves the efficiency of vessel operations through reduced navigation workload, improved planning and track keeping (GONIN and CROWELL, 1992), and reduced manning needs. Thus, as more ships are equipped with electronic charts, the effective cargo-carrying capacity of the fleet (q) increases. The installation of double hulls has the opposite effect (a reduction in q) for a given vessel displacement [5] due to a reduction in cargo capacity. In this sense, electronic charts are a capacity-augmenting innovation, while double hulls are capacity-reducing.

Generally, in the case of electronic charts,

$$\frac{dq}{dS} > 0 \; ; \qquad \frac{d^2q}{dS^2} \leq 0 \tag{7}$$

$$\frac{dc}{dS} < 0 \; ; \qquad \frac{d^2c}{dS^2} \geq 0 \tag{8}$$

At this level, the model does not differentiate between individual vessels. However, we assume that, other things equal, the planner will install electronic charts first on vessels where they will most improve efficiency (7) and reduce costs (8). This assumption leads to the decreasing returns expressed by (7) and (8).

For double hulls,

$$\frac{dq}{dS} < 0 \tag{9}$$

Despite their differing effects on operating capacity, both electronic charts and double hulls may be used to prevent marine pollution. The application of electronic charts can limit environmental damage in marine transportation by reducing the incidence of groundings (DICKINS and KRAJCZAR, 1990). This reduction in environmental damage is captured by the third term in (1). Because the fleet is, in fact, heterogeneous, and the planner can take into account differences in vessels and operational risks, damage reduction also exhibits decreasing returns for both technologies:

$$\frac{dg}{dS} < 0 \; ; \qquad \frac{d^2g}{dS^2} \geq 0 \tag{10}$$

We assume that unit investment cost rises as investment increases. Constraints on the capacity of the most-effective shipyards suggest that multiple concurrent orders for double-hull vessels would necessitate utilization of more expensive shipbuilding capacity. The effect is likely to be less pronounced for electronic chart hardware, digital chart production, and associated operator training programmes. For either technology, however, the number of units required to serve a fleet is not likely to be large enough to produce significant increasing returns to learning or economies of scale. Therefore, we suggest that the process of investment exhibits decreasing returns with respect to capital, and that the investment cost (the last term in (1)) has the following properties:

$$\frac{dI}{dz} > 0 \; ; \qquad \frac{d^2I}{dz^2} > 0 \tag{11}$$

It should be pointed out that the following analysis on the optimal rate of introduction of marine pollution technologies is based on the assumption expressed in (11). If the installation of new technologies were instead to exhibit increasing or constant returns with respect to capital (a possibility with electronic charts), a similar analysis would lead to one of two possible outcomes: no installation at all if cost is greater than benefit, otherwise install on all vessels as soon as possible.

This model captures the trade-off between the social benefit associated with reductions in environmental damage from oil spills and the cost of investment in pollution prevention technologies. By specifying a convex investment cost function for the general case where unit investment cost escalates as investment rises, the dynamic model can determine not only the benefit and cost of each alternative technology under a variety of conditions, but also the rate at which each technology should be installed in the fleet over time. In addition, the model may specify diminishing return functions for both operating efficiency gains and environmental damage reductions, thereby implicitly taking into consideration the actual heterogeneity of vessels, the cargos they carry, and their geographic areas of operation.

The current value Hamiltonian is

$$\bar{H} = B(q(S)) - c(S)q(S) - g(S)q(S) - I(z) + \lambda z + \mu_1 (S_f - z) + \mu_2 z + \mu_3 (S_f - S) + \mu_4 S \tag{12}$$

where λ and μ_1 and μ_4 are multipliers associated with (3) through (5).

First order conditions include

$$\lambda = \frac{dI}{dz} + \mu_1 - \mu_2 \tag{13}$$

$$\dot{\lambda} - \delta\lambda = -p\frac{dq}{dS} + q\frac{dc}{dS} + c\frac{dq}{dS} + q\frac{dg}{dS} + g\frac{dq}{dS} + \mu_3 - \mu_4 \tag{14}$$

$$\mu_1 \geq 0 , \quad \mu_1(S_f - z) = 0 \tag{15}$$

$$\mu_2 \geq 0 , \quad \mu_2 z = 0 \tag{16}$$

$$\mu_3 \geq 0 , \quad \mu_3(S_f - S) = 0 \tag{17}$$

$$\mu_4 \geq 0 , \quad \mu_4 S = 0 \tag{18}$$

For an interior solution ($\mu_i = 0, i = 1, 2, 3, 4$), substituting (13) into (14) yields

$$\dot{z} = \frac{\delta \frac{dI}{dz} - (p - c - g) \frac{dq}{dS} + q \left(\frac{dc}{dS} + \frac{dg}{dS}\right)}{\frac{d^2I}{dz^2}} \tag{19}$$

Equations (3) and (19) describe the optimal investment rate.

As noted, z is the tonnage (or number of ships) of the fleet on which the technology gets installed at t (the installation rate). Thus , z-dot is the change in the installation rate with respect to time. Equation (19) indicates that z-dot is determined by several effects. In the numerator, the first term is the marginal cost of investment (which is equal to the marginal benefit); the second term represents the change in effective cargo capacity (q) with respect to cumulative installation (S); and the third term includes the changes in unit operating cost (c) and environmental damage (g) with respect to cumulative installation (S). z-dot is also influenced directly by other factors such as the discount rate (δ) and the tariff (p). The denominator of Equation (19) captures the effect of increasing marginal cost of investment (I) with respect to installation rate (z). Since the optimal investment path depends on initial and terminal conditions, it is rather complicated to discuss the direction and magnitude of each of these effects in general form. Instead, they can be elaborated using specific functional forms in the following two examples considering homogeneous and heterogeneous fleets.

3.1 Homogeneous Fleet

The problem can be analyzed further by specifying the functional forms for p, I, q, c and g. In this case, we assume that the regional demand for shipping services is a linear function

$$p(q) = p_0 - kq \tag{20}$$

where p_0 is the choke price, and k is the slope.

The convex investment cost function can be specified as

$$I(z) = mz^2 \tag{21}$$

where m is a constant.

For a homogeneous fleet, q is linear

$$q = q_0 + \frac{q_1}{S_f} S , \qquad \text{for } 0 \leq S \leq S_f \tag{22}$$

where q_0 is cargo shipped per unit time without investment in the new technology, q_1 is the total additional cargo capacity if the technology were installed in the entire fleet, and S_f is the size of the fleet. For electronic charts and double hulls, q_1 is positive and negative, respectively.

Functions c and g have similar properties (see (8) and (10)). Thus, to simplify the problem, c and g are merged into a single linear function, denoted as c, which includes both operating cost and environmental damage:

$$c = c_0 - \frac{c_1}{S_f} S , \qquad \text{for } 0 \leq S \leq S_f \tag{23}$$

where c_0 is unit cargo cost without the technology, and c_1 is the total reduction in unit cost if the technology were installed throughout the fleet. Without this model, c_1 is positive for all socially valuable pollution control technologies.

Equation (21) through (23) satisfy the relationships in (7) through (11).

After merging c and g, Equation (19) becomes

$$\dot{z} = \frac{\delta \frac{dI}{dz} - (p - c)\frac{dq}{dS} + q\frac{dc}{dS}}{\frac{d^2I}{dz^2}} \tag{24}$$

Substituting (20) through (23) into (24) yields

$$\dot{z} = \frac{1}{2m}\,[2\delta mz - ((p_0 - c_0 - kq_0)\,q_1 + c_1q_0)/ \\ S_f - q_1\,(2c_1 - kq_1)\,S/S_f^2\,] \tag{25}$$

In this simple case, the interior solution for installation rate (z) and cumulative installation (*S*) can be solved analytically as shown in Appendix I, and simulations in a continuous framework can then be performed. The solution of (25) (see Appendix I) indicates that the optimal investment path is influenced by changes in cargo volume (q_1), slope of the demand function (k), cost reduction (c_1), cost of capital (m), discount rate (δ), and fleet size (S_f).

The optimal investment decision can also be analyzed by examining Equations (3) and (25) on the z-*S* plane, as shown in Figure 1. In Figure 1, *A* is the intercept of the zero z-dot isocline on z; *S* is the intercept of the same isocline on *S*. *A* and *S* are defined as

$$A = \frac{(p_0 - c_0 - kq_0)\,q_1 + c_1q_0}{2\delta mS_f} \tag{26}$$

$$S. = \left[\frac{(p_0 - c_0 - kq_0)\,q_1 + c_1q_0}{q_1\,(kq_1 - 2c_1)}\right]S_f \tag{27}$$

Figure 1(a) shows the case where the slope of the zero z-dot isocline is negative. This illustrates the phase diagram for double hulls ($q_1 < 0$) and electronic charts ($q_1 > 0$ and $kq_1 > 2c_1$), the slope is positive as shown in Fig. 1(b). An optimal investment path, assuming conditions (1.10) in Appendix I and $z = 0$ as $t = T$, is illustrated by *Y*. When *S.* is positive, *S.* constitutes a saddle point, as shown in Fig. 1(a).

Because of inequality constraints (4) and (5), the initial investment (z_0) is influenced by *A*. Higher initial investment is associated with higher values of *A*. Since q_1 is positive and negative for electronic charts and double hulls, respectively, the initial investment will be different for the two cases. For electronic charts, *A* rises if shipping demand shifts outward (an increase in p_0), the demand slope (k) decreases, the fleet-wide cargo capacity (q_1) increases, or the reduction in cost and damage (c_1) increases. For double hulls, $q_1 < 0$, an increase in c_1 also leads to greater *A*, and the effects of demand on *A* are opposite to those for electronic charts. For both technologies, *A* decreases if the discount rate (δ), the coefficient of investment cost (m), or the fleet size (S_f) increases.

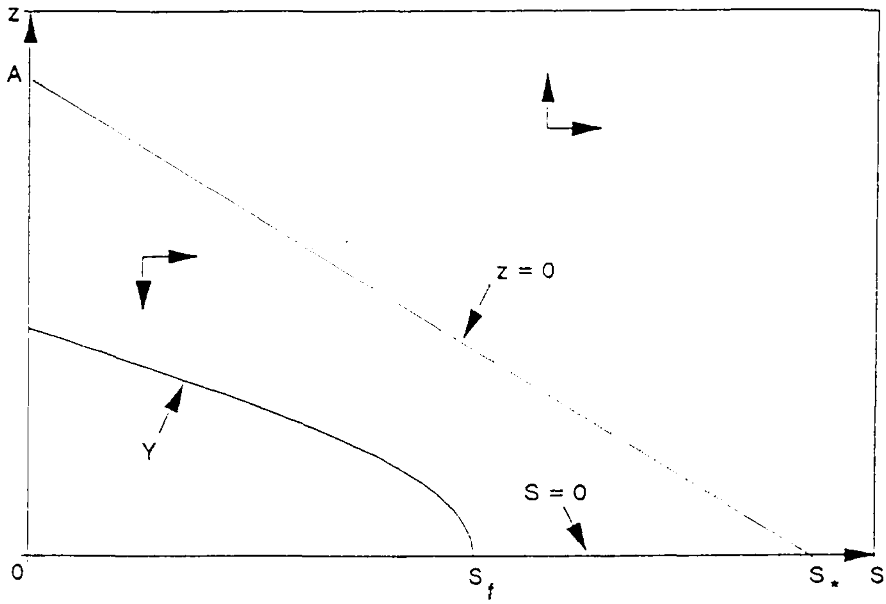

FIG. 1a.- Negatively Sloped Zero Z-dot Isocline.

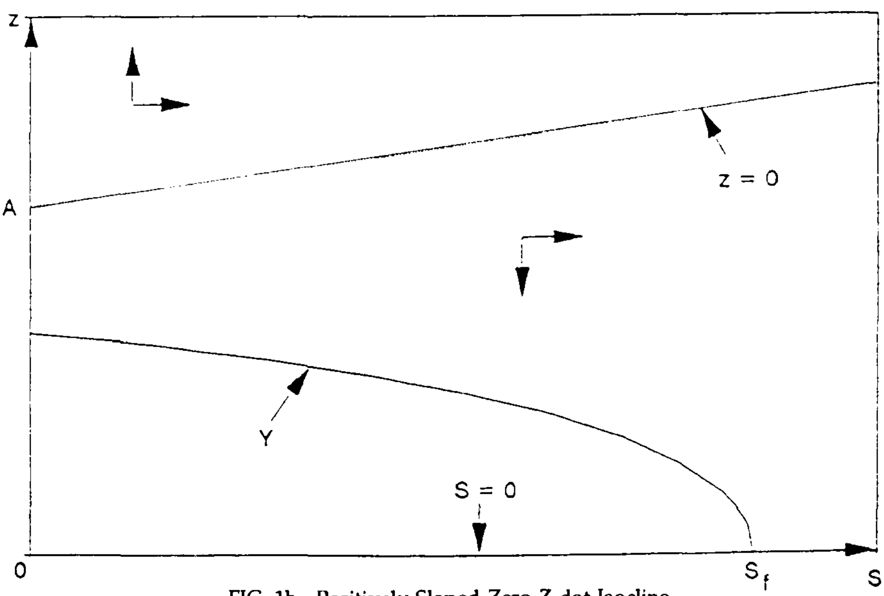

FIG. 1b.- Positively Sloped Zero Z-dot Isocline.

Equation (26) indicates that A can be negative. For double hulls ($q_1 < 0$), A is positive only if the reduction in total cost (c_1q_0) is greater than the reduction in benefit caused by reduced effective cargo capacity ($(p_0 - c_0 - kq_0)q_1$). Equation (27) shows that S_* can be either greater than, equal to, or smaller than S_f.

3.2 Heterogeneous Fleet

To treat implicitly the heterogeneity of the fleet, q can be specified as a quadratic function

$$q = -\frac{q_1}{S_f^2}(S - S_f)^2 + q_0 + q_1, \qquad \text{for } 0 \le S \le S_f \tag{28}$$

where q_0 is cargo shipped without the technology, q_1 is the total additional cargo shipped when the technology is installed in the entire fleet, and S_f is the size of the fleet. Again, q_1 is positive for electronic charts and negative for double hulls. [6]

Again, to simplify the problem, c and g are merged into a single quadratic function, denoted as c, which includes both operating cost and environmental damage:

$$c = \frac{c_1}{S_f^2}(S - S_f)^2 + c_0 - c_1, \qquad \text{for } 0 \le S \le S_f \tag{29}$$

where c_0 is unit cost without the technology, and c_1 is the total cost reduction if the technology is installed throughout the fleet. Equations (28) and (29) satisfy the relationships in (7) through (10).

Substituting (20), (21), (28) and (29) into (24) yields

$$\dot{z} = \frac{1}{m}[\delta mz + ((p_0 - c_0)\, q_1 + 2c_1q_1 + c_1q_0 - kq_1(q_0 + q_1))\\ (S - S_f)/S_f^2 - q_1(2c_1 - kq_1)(S - S_f)^3/S_f^4] \tag{30}$$

Again the optimal investment decision can be analyzed by examining Equations (3) and (30) on the z-S plane. In this case, the isocline of zero z-dot becomes concave or convex, while the shape of the optimal investment path is similar to Y in Figure 1.

4. SIMULATION DATA AND SELECTED RESULTS

In the theory section, we have developed a framework which can be used to examine two specific marine pollution prevention alternatives, electronic chart systems and double hulls. In this section, a simulation using empirical data is described and examples of simulation results are discussed. To define a study region, fleet and cargo for our analysis, we chose the tanker fleet serving the crude oil route from Valdez, Alaska to ports on the U.S. West Coast. This route is of interest because it encompasses almost one fifth of all petroleum movements through U.S. ports, and because it was the site of the EXXON VALDEZ accident in 1989. Ultimately, the model may be of greater interest for other regions in which double hull requirements have not yet been finalized, as they have for U.S. waters by OPA90.

Using dynamic programming, we developed a computer implementation of the model described in the previous section to solve for the optimal investment strategy for a specified transportation route/fleet and planning horizon. Among the advantages of a discrete model implementation are:

(a) It explicitly encompasses the inequality constraints (4) and (5) of the theoretical model.

(b) It allows for flexibility in functional specification. For example, we specify the investment cost function as $I(z) = mz^A$, where A is the cost-of-capital coefficient.

(c) It provides a range of useful results for real-world decision support.

The simulation assumes a homogeneous fleet and takes as input a set of parameters describing a particular technology investment decision scenario. The model is used to perform sensitivity analyses on the effect of each of these parameters on the fleet-wide optimal investment strategy. To compare alternative pollution-reduction technologies, we run the model with inputs describing each alternative, and compare the costs and benefits of the resulting optimal investment strategies.

4.1 Data

To facilitate a numerical simulation, we collected data from various sources. The primary data source is NRC (1991) which includes data on (a) the cargo volume (q_0); (b) other baseline data on the shipping operation, such as vessel size, speed and number of trips per year; (c) tanker capital and operating costs; (d) cost and technical data for double hulls; and (e) data on the range of oil spill volumes. The data on the effectiveness of electronic charts are from DICKINS and KRAJCZAR (1990).

Because tankers in the study region are owned by oil companies, tariff data for the study region are not commonly published. The shipping market data (p_0 and k) are derived from international tanker market information from CHAMPNESS and JENKINS (1985), adjusted for the nature of the study region. A detailed description of data sources, relevant assumptions, and data ranges is presented in Appendix II.

Although data on costs of the shipping operation and investment in the technologies are fairly accurate, the estimates of environmental damages due to oil spills are highly controversial, as indicated in NRC (1991). This is due to the fact that marine resources provide a variety of tangible and intangible goods and services to the public. Although most resource economists believe that marine resources generate both use and non-use values, there is no consensus with regard to damage assessment methodologies. Several economic methods have been developed to estimate the value of natural resources in general[7] and the damage of marine resources due to oil spills in particular (see GRIGALUNAS *et al.*, and DUNFORD, 1992).

The NRC (1991) study summarized earlier studies by COHEN (1986), GRIGALUNAS and OPALUCH (1990), and others, and concluded that the total cost of oil spills, including clean-up cost and environmental damage, ranges from $12 000 to $68 000 per ton of oil spilled, with the EXXON VALDEZ case possibly reaching $90 000 per ton. For our study, we use $40 000 per ton for the baseline case. Sensitivity analyses are performed to examine the range of damage figures from below $10 000 per ton to $90 000 per ton. In addition to the unit damage estimate, total damage is also affected by the volume of traffic and the probability of oil spills.[8] As shown in Appendix II, the baseline value of total annual damage is $61.2 million (estimated as the total oil spilled annually in U.S. waters (9 000 tons) times the percentage moved through Alaskan waters (17%) times the unit damage ($40 000/ton)).

Table I summarizes the baseline values for the simulation. Ranges for sensitivity analyses are given in Appendix II. As shown in Table I, the annual cargo volume in the study region is 100 million tons, and there are 19 tankers of 240 000 dwt in the fleet. According to NRC (1991), the volume spilled from large tankers may be reduced by 70% through double hulls. Using U.S. Coast Guard historical vessel accident data, DICKINS and KRAJCZAR (1990) estimated that vessel accident risk can be reduced by 14-19% with the application of electronic charts. We assume that this translates to a 14-19% reduction in total spill volume. The investment cost of double hulls is much greater ($23.81 million per vessel) than the cost of electronic chart systems ($58 730/vessel). A relatively high cost-of-capital coefficient (1.5) is assumed to capture the decreasing returns to capital described in the discussion of Equation (11).

It should be pointed out that although both of these technologies can reduce the risk of oil spills, their effectiveness may not be fully realized due to the offsetting effect of "revenge theory" (PERROW, 1984 and HIRSCHMAN, 1991): ship operators may navigate less cautiously, believing that they are safeguarded by the pollution prevention technologies. For example, excessive confidence in technology can lead to larger environmental costs, if it leads operators to underestimate the probabilities of spills (OPALUCH, 1984). Indeed, in response to reduced risks of certain accidental outcomes, operators may undertake an optimal readjustment (from their perspective) of the entire portfolio of risks associated with the activity. Such an effect may explain the absence of a clear decrease in collision and grounding probabilities following the introduction of radar (see KITE-POWELL, 1992).

Baseline values without (prior to) investment are based on operations with single hull vessels. The investment value (m) for double hulls incorporates a discounted stream of annual cost differentials associated with building (capital costs) and operating a new double hull vessel instead of a single hull vessel. Conversion of existing single hull vessels to double hull is not considered here ("grandfather" clauses in the Oil Pollution Act of 1990 make such conversion unlikely). The baseline change in cargo capacity with investment in double hull is zero, because it is assumed that double hull vessels will be built to the same cargo capacity (dwt) specifications as their predecessors. Investment costs for electronic charts represent equipment purchase and installation costs.[9]

Table I
Computer model input values for analysis of U.S. West Coast oil transport system *

Parameter	*Description*		*Baseline Value*
p_0	freight rate choke price		\$10/metric ton
k	slope of demand function		\$0.04/million (dwt)^2
δ	discount rate		10%
A	cost-of-capital coefficient		1.5
T	planning period/horizon		30 years
S_f	fleet size		19 tankers @ 240 k dwt †
D_s	maximum number of conversions per unit time		19 tankers/year (unconstrained)
S_{min}	minimum number of vessels converted by end of planning period		0 tankers (unconstrained)
S_{max}	maximum number of vessels converted by end of planning period		19 tankers (entire fleet)
q_0	cargo capacity of the fleet prior to investment		100 million tons/year
c_0	environmental cost prior to investment		\$61.2 million/year
OC	operating cost prior to investment		\$7.42 million/vessel/year
CC	capital cost without investment		\$89.6 million/vessel
q_1	change in cargo capacity due to investment		
		double hulls	0
		elec. charts	+1 percent of q_0
c_1	reduction in environmental cost due to investment		
		double hulls	70 percent of c_0
		elec. charts	15 percent of c_0
m	investment cost, including discounted stream of operating cost changes	double hulls	\$23.81 million/vessel
		elec. charts	\$58.730/vessel

* All monetary values are in 1989 U.S. dollars. See Appendix II for details and sources.

† In the Valdez/West Coast crude oil trade, the round-trip distance is 4 000 nautical miles. The average vessel size is 240 000 dwt, and at an average speed of 15 knots each vessel makes 22 trips per year.

We emphasize that while these data represent a reasonable "first cut" description of the U.S. West Coast oil transportation system, they are used as an example only and should not be assumed to reflect the actual transportation system with any specific degree of accuracy.

The investment schedule developed here is abstract in that it focuses on incremental costs associated with the two technologies and does not consider the actual fleet depreciation and replacement schedule. This is not a problem for the electronic chart case, since electronic charts can be added to existing vessels without altering the existing fleet replacement schedule. However, in the double hull case, introduction of the technology may in fact affect the underlying replacement schedule.

Table II
Cost, investment and social benefit: double hulls and electronic charts

M [1] $m/vessel	Cargo [2] tons	Invest [3] $m	Cost [4] $m	Damage [5] $m	Benefit [6] $m	L-Benefit [7] $m
			Double hulls			
5.00	3,000	169.17	3,535.45	472.66	4,118.41	4,388.88
10.00	3,000	219.96	3,535.45	554.79	3,985.50	4,255.97
15.00	3,000	235.91	3,535.45	628.92	3,895.41	4,165.88
20.00	3,000	184.03	3,535.45	742.09	3,834.12	4,104.60
25.00	3,000	230.04	3,535.45	742.09	3,788.11	4,058.59
30.00	3,000	276.04	3,535.45	742.09	3,742.11	4,012.58
35.00	3,000	322.05	3,535.45	742.09	3,696.10	3,966.57
40.00	3,000	0.00	3,535.45	1,036.96	3,723.28	3,949.62
			Electronic charts			
0.01	3,029	0.83	3,548.66	904.38	3,897.85	4,136.00
0.02	3,029	1.66	3,548.66	904.38	3,897.02	4,135.17
0.03	3,029	2.48	3,548.66	904.38	3,896.19	4,134.34
0.04	3,029	3.31	3,548.66	904.38	3,895.36	4,133.51
0.05	3,029	4.14	3,548.66	904.38	3,894.54	4,132.69
0.06	3,029	4.97	3,548.66	904.38	3,893.71	4,131.86
0.07	3,029	5.80	3,548.66	904.38	3,892.88	4,131.03
0.08	3,029	6.63	3,548.66	904.38	3,892.05	4,130.20
0.09	3,029	7.45	3,548.66	904.38	3,891.22	4,129.37
0.10	3,029	8.28	3,548.66	904.38	3,890.40	4,128.54

1. This is the investment cost (capital and operating cost differentials) associated with each technology. As shown in the text, the investment cost function is specified as $I(z) = mz^{\wedge}$.
2. The planning period specified for the simulation is 30 years. It is assumed that annual cargo movement is 100 million metric tons. The "Cargo" column in this table shows total cargo moved over the entire planning period. In the baseline cases, no change and one percent increase in cargo capacity are specified for double hulls and electronic charts, respectively. Thus, for the electronic charts case, the cargo volume is slightly higher.
3. This is the present value of total investment (I, see above Note 1) in the planning period.
4. This is the present value of total cost of the shipping operation (including both capital and operating cost) in the planning period.
5. This is the present value of total damage to the marine environment due to oil spills in the planning period.
6. This is the social benefit (present value of total net benefit, considering the costs of environmental damages; see objective function (1) in Section 3) in the planning period.
7. This is the long-run social benefit which is the benefit from Note 6 plus the terminal value of the fleet. We assume that conditions at the end of the planning period will prevail indefinitely.

4.2 Selected Simulation Results

Table II and Figures 2 through 5 summarize the results of the simulation using input data from Table I. Table II compares investment and benefit levels for double hulls and electronic charts under various cost assumptions. Figure 2 contrasts the total investment in the two technologies over a wide range of unit damage estimates. Figures 3, 4 and 5 illustrate the effect of changes in environmental damage levels, pollution prevention effectiveness, and investment cost on the optimal investment path for a particular technology.

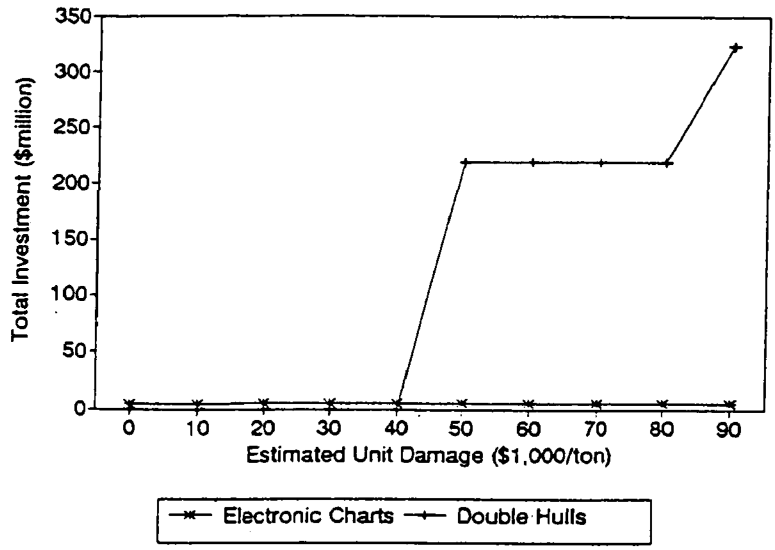

FIG. 2.- Total investment at different estimated unit damages.

These results should be interpreted with caution. Since they derive from input data that is at best an approximation of the actual transportation system, the results are themselves approximate. They require elaboration and revision before they could form the basis of investment or policy decisions. With this caveat, using the baseline values of Table I, the model runs suggest the following results.

The incremental cost of converting to double hulls is not justified by the resulting 70 percent reduction in environmental damage, although this rejection is marginal and highly sensitive to the specification of environmental damage. For example, increasing the baseline environmental damage figure (c_0) by less than seven percent (from $61.2 million (in Table I) to $65 million per year) justifies investment in double hulls. In contrast, the cost of electronic chart systems is unequivocally justified by its benefit (15 percent reduction in environmental damage and one percent increase in effective cargo capacity). Such a result holds even under conditions much less favorable for electronic charts than those of the baseline case (see Table I).

To contrast the two technologies, we conducted sensitivity analyses separately for double hulls and electronic charts with respect to their investment costs (m). The results, shown in Table II, assume an environmental damage level of $100 million per year (63 percent above the baseline value) [10]. The cost of double hulls is more than an order of magnitude higher ($5-40 million per vessel) than the cost of electronic chart systems ($10-100 000 per vessel); however, double hulls also

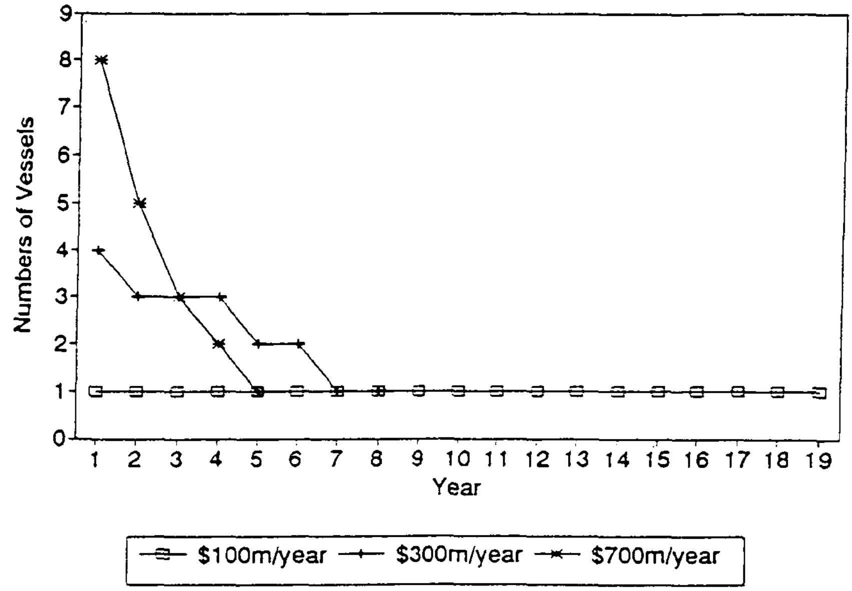

FIG. 3.- Optimal investment paths for different environmental damage levels.

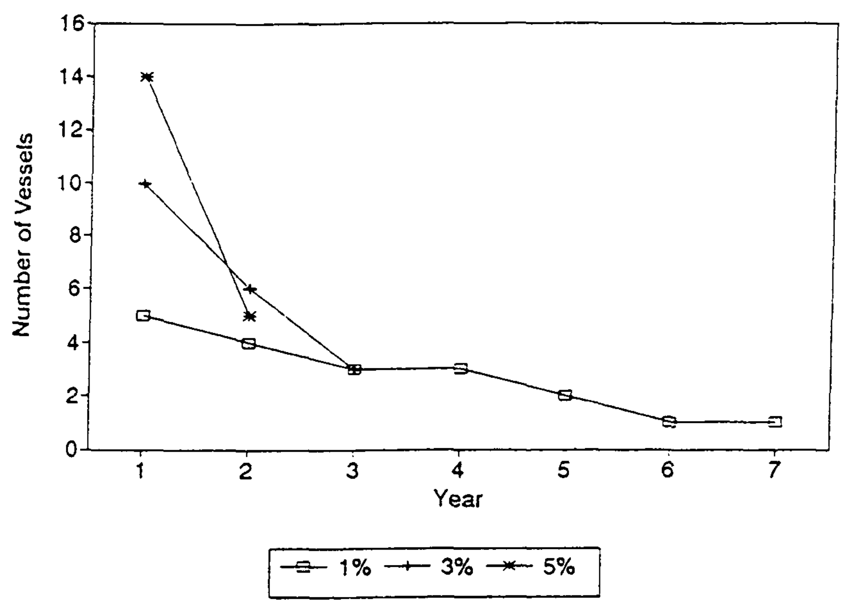

FIG. 4.- Optimal investment paths for different damage reduction levels.

lead to greater (four or five fold) reductions in environmental damage. If the cost of double hulls is $5 million per vessel, for example, the planner would follow a strategy of rapid installation, limiting environmental damage over the planning period to $473 million and achieving a total net social benefit of $4.4 billion. As the anticipated cost of double hulls increases, the planner would resort to less rapid installation strategies (see Fig. 5), with higher cumulative damage and lower benefit.

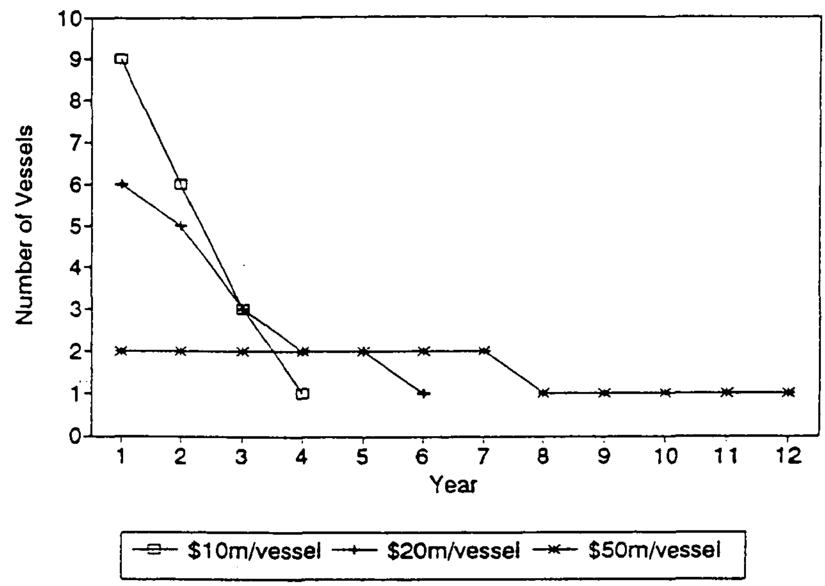

FIG. 5.- Optimal investment paths for different investment cost levels.

Under these assumptions, double hull technology would not be employed at all if its cost exceeds $40 million per vessel, which is about 40 percent of the cost of a 240 000 dwt tanker.

On the other hand, the cost of electronic charts is small, and at the specified damage level, the planner would install this technology on all ships as soon as possible (i.e., in the first year). The cumulative damage with electronic charts is a constant ($904 million), and the reduction in social benefit is small. The total cost of the shipping operation (column 4 of Table II) is slightly higher for the electronic chart case than for the double hull case because more cargo is shipped with electronic charts (column 2 of Table II).

To further examine the investment and damage figures (columns 3 and 5 of Table II), a benefit-cost ratio is defined as the reduction in total damage divided by the corresponding total investment.[11] As the investment cost (m) increases, this ratio changes from 3.34 to 0.92 for double hulls and 159.73 to 16.01 for electronic charts. In other words, in this example, for the least expensive double hulls ($5 million/vessel), a one million dollar investment leads to a $3.34 million reduction in environmental damage. In contrast, an investment of the same amount in the most expensive electronic charts ($0.1 million/vessel) is associated with a reduction of $16.01 million in damage. Also shown in Table II, if the incremental cost associated with double hulls (m) is greater than $20 million per vessel (the baseline estimate is $23.81 million per vessel, see Table I), the long-run net social benefit associated with double hulls is smaller than that associated with electronic charts (see column 7 of Table II).

As noted, estimates of environmental damages due to oil spills are highly controversial. Figure 2 contrasts the total investment in electronic charts and double hulls under different damage estimates. It is clear that the investment cost for electronic chart systems is much lower than that for double hulls. Because electronic charts are inexpensive, and also lead to an increase in effective cargo capacity, investment in this technology is justified over the entire range of unit damage estimates ($0-90 000 per ton). In contrast, the investment in double hulls is not justified if the unit damage is below about $40 000 per ton. In both cases, total investment increases as the damage estimates rise, since high damage levels call for rapid installation.

Based on these separate analyses of double hulls and electronic charts, we suggest that electronic charts may be far more cost-effective.

Figure 3 shows the optimal rate of conversion to double hulls under different environmental damage levels. As noted in Section 3, a rapid installation strategy is indicated when the reduction in damage (c_1) is high. In this simulation, we assume that conversion to double hulls leads to a 70 percent reduction in environmental damage; the higher the baseline damage value, the greater the value of this reduction. When annual damage is $700 million, eight vessels would be converted in the first year, and the entire fleet would be converted in five years. If the annual damage is only $100 million (close to, but still 63 percent higher than the baseline case), the conversion rate drops to one ship per year, and the fleet is not fully converted for 19 years.

Figure 4 shows the optimal rate of electronic chart installation for various levels of damage reduction (c_1), while assuming no increase in effective cargo capacity ($q_1 = 0$). Again, rapid installation strategies are associated with high damage reduction levels. The baseline data assume that electronic charts result in a 15 percent reduction in damage. With this level of reduction, the technology would be employed as soon as possible.

Figure 5 illustrates optimal investment rates for double hull under different cost assumptions. As shown by Equation (26), higher initial investment rates are associated with lower costs (m). Assuming annual environmental damage of $400 million and an investment cost of $10 million per vessel, nine vessels would be converted in the first year and the entire fleet would be converted after four years. As the cost increases to $50 million per vessel, fleet conversion stretches out over 12 years, with an initial conversion rate of two vessels per year.

5. CONCLUSIONS AND POLICY IMPLICATIONS

In the theoretical model presented in this paper, the net benefit of investment in a pollution reduction technology is influenced by changes in cargo capacity (q_1), by changes in operating and environmental damage/cleanup costs (c_1) and by the investment cost of introducing the technology (m). For a given cost of investment, high levels of benefit suggest that the social planner would promote a high initial rate of investment; low initial rates are more appropriate if benefits are low. Similarly, for a given level of benefits, high costs suggest slow initial rates of investment, while low costs indicate more rapid rates. In summary, the model illustrates the social planner's optimal investment strategy. It shows that (a) if the technology's benefit is much greater than its cost, it would be installed in the entire fleet as quickly as possible. More interestingly, (b) when benefit is marginally greater than cost, for a representative case, the optimal investment schedule is a high initial investment rate which decreases monotonically over time. (c) If the technology's benefit is smaller than its cost, it would of course not be utilized at all.

The computer simulation model provides illustrative numerical examples for the technological options of double hulls and electronic charts in the U.S. West Coast oil transportation system. There are three principal results:

(a) Comparison of double hull and electronic chart benefit/cost streams suggests that electronic charts may well be a far more cost-effective means of preventing oil pollution from marine transportation. For example, under given conditions, for the least expensive double hulls ($5 million/vessel), a one million dollar investment leads to a $3.34 million reduction in environmental damage. In contrast, an investment of the same amount in the most expensive electronic charts ($0.1 million/vessel) is associated with a reduction of $16.01 million in damage.

(b) The minimum benefit of spill reduction needed to justify investment in double hulls on the Alaska-U.S. West Coast route is about $42 300 per ton, assuming that double hulls reduce spills by 70 percent. Estimates of environmental damage and clean-up cost range from $12 000 to $68 000 per ton (NRC, 1991), which suggests that the social justification of investment in double hulls depends strongly on damage cost assumptions.

(c) In contrast, assuming a mean benefit from spill reduction of $40 000 per ton and no increase in effective cargo capacity, the minimum spill reduction to justify investment in electronic charts is only 0.2 percent. With a 15 percent reduction in spill volume, investment in electronic charts is socially justified even if damage is $500 per ton, which is much lower than estimates cited by NRC (1991).

The effect of investment on fleet cargo capacity, though considered by the model, turns out to be of little significance in these cases. Although these simulation results must be considered preliminary, they have potentially important implications both for regulatory efforts and for private investment strategies.

Our analysis is performed from the social planner's perspective. The planner maximizes the net social benefit of the shipping operation, incorporating the social cost of environmental damage caused by oil spills. Traditionally, the oil industry operating the tanker fleet may have had a different objective function. For example, in earlier years the industry may not have explicitly considered environmental damage (the third term in (1)) to be a cost of shipping operations.[13] As a result, it did not voluntarily employ marine pollution retention technologies, and shipping operations generated an externality: oil spills. However, current environmental legislation, such as the Clean Water Act and OPA90 in the United States, includes liability rules for oil spills, and is designed to direct the industry to internalize the cost of environmental damage from oil spills.[14] Legal liability is a useful economic instrument for environmental protection. For example, according to OPALUCH and GRIGALUNAS (1984), the oil industry reacted substantially to the cost of environmental risk from oil spills by lowering their bids for offshore oil and gas leases. In fact, current liability rules generate incentives for the application of marine pollution prevention technologies.[15] Without a mandate for a specific technology, the industry would select the most cost-effective option. For example, the results of this study suggest that the optimal approach may start with investment in electronic chart systems, possibly combined with low-cost double hulls if environmental damage is large and if society places a great premium on significant reduction of oil spills. This approach may encompass the advantages of both technologies, that is, the cost-effectiveness of electronic charts and the higher percentage reduction in environmental damages associated with double hulls.

From a social planner's point of view, the optimal rate for introducing the technology depends on the level of net social benefit. Except in extreme cases where net benefit is very large, a rapid fleet-wide installation of the technology is often not optimal. Depending on the level of net social benefit, legislation and regulation should provide the industry enough time to introduce the technology gradually.[16] The model presented here is helpful in determining an optimal schedule of implementation, and in guiding the development of regulations that may specify or influence such schedules.

The simulation model we have developed suggests several possibilities for extension. The model assumes a homogeneous fleet of discrete "ship units." It could be extended to consider distinct, individual vessels in a heterogeneous fleet, with individual cargo volume, cost, route-related damage values, and the life-cycle of vessels, and to take into account replacement schedules. The model could be extended further to allow consideration of specific costs/benefits arising from options such as vessel conversion, retirement, and movement or sale to other service, in addition to new-building and conversion. The freight rate (demand) function component of the model, presently based on world fleet capacity, would be considerably refined and tuned to the particular transportation route(s) under consideration.

The study can also be extended to examine the optimal schedule for joint introduction of several technologies. For example, given the double hull requirement in U.S. waters, what is the optimal strategy for the introduction of electronic charts? What would be the impact of electronic charts and other alternative pollution prevention technologies on the schedule for ordering new double hull tankers? Finally, the model could be extended to encompass the stochastic aspects of the occurrence and the damage costs of oil spills. Such an extension would examine the optimal strategy for a risk-averse decision maker (ROBISON and BARRY, 1987), and the effect of irreversibility of investment (PINDYCK, 1991 and VISCUSI, 1988). These possible extensions would certainly increase the complexity of the model, and could be realized through an integrated economic/engineering analysis.

Acknowledgment

The authors would like to thank Stephen POLASKY and two anonymous referees for their helpful comments on earlier drafts of this paper. We also benefitted from discussion with Yoshiaki KAORU on the issues associated with natural resource damage assessment. The study is supported by the Marine Policy Center of the Woods Hole Oceanographic Institution (WHOI Contribution No. 8669).

Notes

1. The abbreviation "ECDIS" (Electronic Chart Display and Information System) is often used to refer to electronic chart products compatible with emerging International Maritime Organization (IMO) standards for electronic charts. For our analysis, "electronic charts" includes a broader spectrum of navigation systems using digital hydrographic data.

2. In this study, the effective cargo-carrying capacity of the fleet is defined as the product of unit vessel cargo capacity (tons), number of trips per year and number of vessels in the fleet.

3. For a discussion of implications of uncertainty, see HARTL (1992).

4. In this formulation, the technology can be introduced in a continuous fashion; in the real world (and in the simulation later in the paper) installation happens in discrete units (ships).

5. While this assumption is theoretically valid, in practice it is unlikely to be significant because converting existing tankers to double hulls is expensive, and building a new double hull tanker removes the equal displacement constraint.

6. In the case of double hulls, the following inequality is assumed:

$$\frac{d^2q}{dS^2} > 0$$

7. These evaluation methods include (1) indirect methods such as Travel Cost Models (See BOCKSTAEL *et al.*, 1989 and KAORU, 1990) and Hedonic Property Value Models (See BROWN and POLLAKOWSKI, 1977 and PARSONS and WU, 1991), and (2) direct methods which are also called Contingent Valuation Methods (See BOCKSTAEL *et al.*, 1989 and SAMPLES *et al.*, 1986). Although contingent valuation methods provide an approach to estimating non-use values, the results are always controversial (See KAHNEMAN and KNETSCH, 1992a and 1992b; SMITH, 1992; HARRISON, 1992; and ARROW *et al.*, 1993).

8. For a recent study on this subject, see GOODSTEIN (1992).

9. Preliminary estimates indicate that the cost to create digital charts for the U.S. West Coast oil route is $1.3 million, with an annual maintenance cost of $130 000 (personal communications with Capt. Tom RICHARDS of NOAA's Nautical Charting Division, (1994). These charts would be utilized by other marine activities as well. A fraction of their cost may be allocated to the use of electronic chart systems on tankers.

10. We had to increase the damage valuation above baseline to force the model to consider non-zero investment in double hulls.

11. As shown in column 5 of Table II, total environmental damage without any pollution prevention technologies is $1.03696 billion. Thus, the reduction in damage is the differential between this figure and the other figures in column 5. The benefit-cost ratios are computed as these differentials divided by column 3.

12. In this and following figures, the steps in curves are the result of discrete modelling.

13. Also, the industry maximizes profit rather than social benefit.

14. There are, of course, enforcement and compliance issues. For a discussion of this topic, see TIETENBERG (1992).

15. There are many factors, such as inappropriate expectations concerning the probability of oil spills, which may lead to imperfect internalization (OPALUCH, 1984).

16. OPA90 does provide a schedule for compliance with the double-hull requirement based on the age structure of the tanker fleet.

References

ALCOCK, T.M. (1992), "Ecology Tankers" and the Oil Pollution Act of 1990: A History of Efforts to Require Double Hulls in Oil Tankers", *Ecology Law Quarterly* 19, 97-145.

ARROW, K., R. SOLOW, P.R. PORTNEY, E.E. LEAMER, R. RADNER and H. SCHUMAN (1993), "Report of the NOAA Panel on Contingent Valuation", Jan. 11, NOAA Damage Assessment Center, Rockville, MD.

BOCKSTAEL, N.E., K.E. MCCONNELL, and I.E. STRAND (1989) "Measuring the Benefits of Improvements in Water Quality: The Chesapeake Bay", *Marine Resource Economics* 6, 1-18.

BROWN, G.M. and H.O. POLLAKOWSKI (1977), "Economic Valuation of Shoreline", *Review of Economics and Statistics*, 272-278.

CHAMPNESS, M. and G. JENKINS (1985), *Oil Tanker Databook*, Elsevier Applied Science Publishers, London.

COHEN, M.A. (1986), "The Costs and Benefits of Oil Spill Prevention and Enforcement", *Journal of Environmental Economics and Management* 13, 167-188.

DICKINS, D. and K. KRAJCZAR (1990), "Review of tanker/barge safety", Report prepared for States/British Columbia Oil Spill Task Force. DF Dickins Associates Ltd., Vancouver, British Columbia.

DUNFORD, R. (1992) "Natural Resource Damages from Oil Spills" in T.H. TIETENBERG (ed.), *Innovation in Environmental Policy*, England: Edward Elgar Publishing Limited, Hants.

GOODSTEIN, E. (1992) "Saturday Effects in Tanker Oil Spills" *Journal of Environmental Economic and Management* 23(3), 276-288.

GONIN, I.M. and R.D. CROWELL (1992) "United States Coast Electronic Chart Display and Information System (ECDIS) Field Trials: Preliminary Results" Paper presented at ECDIS '92 Conference, Baltimore, MD. Feb. 28-29, Groton, CT: U.S. Coast Guard Research and Development Center.

GRIGALUNAS, T.A., J.J. OPALUCH, D. FRENCH, and M. REED (1988) "Measuring Damages to Marine Natural Resources from Pollution Incidents under CERCLA: Application of an Integrated Ocean System/Economic Model", *Marine Resource Economics* 5, 1-21.

GRIGALUNAS, T.A. and J.J. OPALUCH (1990) "The Environment", in R.S. FARROW *et al.* (eds.), *Managing the Outer Continental Shelf Lands: Oceans of controversy*. Taylor and Francis. New York.

HARRISON, G.W. (1992), "Valuing Public Goods with the Contingent Valuation Method: A Critique of KAHNEMAN and KNETSCH", *Journal of Environmental Economics and Management* 23(3), 248-257.

HARTL, R.F. (1992) "Optimal Acquisition of Pollution Control Equipment Under Uncertainty", *Management Science* 38(5), 609-622.

HIRSCHMAN, A.O. (1991), *The Rhetoric of Reaction*, Harvard University Press.

HOPKINS, T.D. (1992) "Oil Spill Reduction and Costs of Ship Design Regulation", *Contemporary Policy Issues* 10, 59-70.

KAHNEMAN, D. and J.L. KNETSCH (1992a) "Valuing Public Goods: The Purchase of Moral Satisfaction", *Journal of Environmental Economics and Management* 22(1), 57-70.

KAHNEMAN, D. and J.L. KNETSCH (1992b) "Contingent Valuation and the Value of Public Goods: Reply" *Journal of Environmental Economics and Management* 22(1), 90-94.

KAORU, Y. (1990) "Key Problems in the Management of Sports Fisheries", *Ocean Development and International Law* 21, 317-333.

KITE-POWELL, H. (1992) "Rationale, Processes, and Effects of Technological Standards in Marine Electronics", Ph.D. Dissertation, MIT Ocean Systems Management Program.

National Research Council (NRC) (1991), *Tanker Spills: Prevention by Design*, National Academy Press, Washington, D.C.

OPALUCH, J.J. (1984) "The Use of Liability Rules in Controlling Hazardous Waste Accidents: Theory and Practice" *Northeast Journal of Agricultural and Resource Economics* 13(2). 210-217.

OPALUCH, J.J. and T.A. GRIGALUNAS (1984) "Controlling Stochastic Pollution Events through Liability Rules: Some Evidence from OCS Leasing", *The Rand Journal of Economics* 51(1), 142-151.

PARSONS, G.R. and Y. WU (1991) "The Opportunity Cost of Coastal Land-Use Controls: An Empirical Analysis", *Land Economics* 67(3), 308-316.

PERROW, C. (1984), *Normal Accidents: Living with High-Risk Technology*, Basic Books.

PINDYCK, R.S. (1991), "Irreversibility, Uncertainty, and Investment", *Journal of Economic Literature* 29(3), 1110-1148.

ROBISON, L.J. and P.J. BARRY (1987), *The Competitive Firm's Response to Risk*, Macmillan Publishing Company, New York.

SAMPLES, K.C., J.A. DIXON and M.M. GOWEN (1986) "Information Disclosure and Endangered Species Valuation", *Land Economics* 62(3), 306-312.

SMITH, V.K. (1992) "Arbitrary Values. Good Causes, and Premature Verdicts. *Journal of Environmental Economics and Management* 22(1), 71-89.

TIETENBERG, T.H. (1992) *Innovation in Environmental Policy*, Edward Elgar Publishing Limited, Hants, England.

VISCUSI, W.K. (1988) "Irreversible Environmental Investments with Uncertain Benefit Levels", *Journal of Environmental Economics and Management* 15, 147-157.

Appendix I: Analytical Solution of S

Substituting (3) into (25) yields

$$\ddot{S} + n_1\dot{S} + n_2S = n_3 \tag{1.1}$$

where

$$n_1 = -\delta \tag{1.2}$$

$$n_2 = \frac{q_1(2c_1 - kq_1)}{2mS_f} \tag{1.3}$$

$$n_3 = \frac{-(p_0 - c_0 - kq_0)q_1 - c_1q_0}{2mS_f} \tag{1.4}$$

The optimal investment rate can be obtained by solving (1.1). The roots of the auxiliary equation for (1.1) are

$$n_{4,5} = \frac{1}{2}\left(-n_1 \pm\sqrt{n_1^2 - 4n_2}\,\right) \tag{1.5}$$

n_4 and n_5 are determined by the sign and value of $n_1^2 - 4n_2$, or

$$\delta^2 - \frac{2q_1(2c_1 - kq_1)}{mS_f^2} \tag{1.6}$$

If (1.6) is greater than, equal to, or smaller than zero, then n_4 and n_5 are different real roots, equal real roots and conjugate complex roots, respectively.

Using N_1 through N_6 to represent constants which are determined by initial and terminal conditions, we have the following solutions.

If n_4 and n_5 are real roots, and not equal, then the general solution of (1.1) is

$$S = N_1e^{n_4t} + N_2e^{n_5t} + \frac{n_3}{n_2} \tag{1.7}$$

If n_4 and n_5 are conjugate complex roots, and n_6 and n_7 are the real and imaginary parts of n_4 and n_5, respectively, then the general solution of (1.1) becomes

$$S = e^{n_6t}\,[N_3\cos(n_7t) + N_4\sin(n_7t)] + \frac{n_3}{n_2} \tag{1.8}$$

If n_4 and n_5 are equal roots, the general solution of (1.1) is

$$S = e^{n_4t}\,(N_5 + N_6t) + \frac{n_3}{n_2} \tag{1.9}$$

For example, assuming initial and terminal conditions to be

$$t = 0 \ , \Leftrightarrow S = 0 \ ; \qquad t = T \ , \Leftrightarrow S = S_f \tag{1.10}$$

we obtain

$$N_1 = - \frac{S_f + \frac{n_3}{n_2} (e^{n_4 T} - 1)}{e^{n_5 T} - e^{n_4 T}} - \frac{n_3}{n_2} \tag{1.11}$$

$$N_2 = \frac{S_f + \frac{n_3}{n_2} (e^{n_4 T} - 1)}{e^{n_5 T} - e^{n_4 T}} \tag{1.12}$$

$$N_3 = - \frac{n_3}{n_2} \ , \tag{1.13}$$

$$N_4 = \frac{S_f + [e^{n_5 t} \cos(n_7 t) - 1] \frac{n_3}{n_2}}{e^{n_6 T} \sin(n_7 t)} \tag{1.14}$$

$$N_5 = - \frac{n_3}{n_2} \ , \tag{1.15}$$

$$N_6 = \frac{S_f + (e^{n_4 t} - 1) \frac{n_3}{n_2}}{T e^{n_4 t}} \tag{1.16}$$

Appendix II

Parameter	*Source and Derivation*
P_0	CHAMPNESS and JENKINS (1985), p. 267, adjusted according to shipping costs, NRC (1991), p. 170. Range examined: \$4-12 per metric ton.
k	A very rough estimate based on freight rate and dwt relationship from CHAMPNESS and JENKINS (1985), pp. 10-19 and 267. Values examined: 0 and \$0.04/(dwt)^2.
δ	Assumption. Range examined: 8-12 percent.
A	Assumption. Range examined: 1-2.
T	Assumption. Longer planning period does not change results greatly because of the discount rate used.
S_f	Based on 100 million tons/year, 22.7 voyages/vessel/year, and 240k dwt vessels; NRC (1991), p. 170 and 305.
q_0	NRC (1991), p. 170.
c_0	9 000 tons/year spilled in U.S. waters, NRC (1991), p. 161; 17% of U.S. oil movements involve Alaska, NRC (1991), p. 170. Environmental damage estimates range from \$12 000 to \$ 68 000 per ton, NRC (1991), p. 174. Oil spilled annually in U.S. waters ranges from 300 to 40 000 tons; EXXON VALDEZ spill cost \$90 000/ton, NRC (1991), p. 161 and 174. Range examined: \$0-700 million (at high-end: 40 000 tons x 17% x \$90 000/ton = \$612 million).
OC	NRC (1991), p. 305.
CC	NRC (1991), p. 305.
q_1	Double hulls: Range examined: 0 to 30 percent reduction. Electronic charts: Values examined: 0 and 1 percent increase.
c_1	Double hulls: NRC (1991), p. 166. Range examined: 30-70 percent. Electronic charts: DICKINS and KRAJCZAR (1990), p. 53. Range examined: 14-19 percent.
m	Double hulls: Capital and operating cost differentials from single hull to double hull for 240 k dwt tankers, NRC (1991), pp. 305-307. Range examined: \$5-50 million. Electronic charts: Estimate. Range examined: \$10 000 to \$100 000.