



On the optimal environmental liability limit for marine oil transport

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Abstract

Recent changes in the US liability regime for oil pollution damage have intensified a policy debate about environmental liability limits. Economic theory suggests that some type of limit may be needed under certain conditions, and that such a limit should be set so that the marginal social benefit and cost are equal. However, it is unclear how a liability limit may be determined specifically for tanker shipping in US waters. We first examine conditions under which corner solutions (no liability or unlimited liability) are desirable. We then formulate a model to determine a socially optimal liability limit for oil pollution damage in US waters when a non-zero, finite liability limit is desirable. The model captures the tradeoff between less expensive energy supply and more stringent protection of the marine environment. Numerical simulations illustrate the properties of the model and major factors affecting the public policy decision regarding a liability limit. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Recent changes in the US liability regime for oil pollution damage have intensified a policy debate about limits on environmental liability (Garick, 1993; Gauci, 1995; Ketkar, 1995; Jin and Kite-Powell, 1995). Economic theory suggests that some type of limit may be needed under certain conditions, and that such a limit should be set so that the marginal social benefit and cost are equal. However, it is unclear under which conditions no liability, limited liability or unlimited liability is desirable. Furthermore, it is unclear specifically how a liability limit may be determined for tanker shipping in US waters when a limit is desirable.

The United States imports about 8.5 million barrels of oil per day, which accounts for nearly 50% of its total consumption (US Department of the Interior, 1995). Seventy percent of the

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imports are carried in foreign independent tankers (US Department of Transportation, 1993). Marine transportation of crude oil and petroleum products creates risks to private property and the common environment. In US waters, environmental damages due to a single large spill in an environmentally sensitive area can amount to billions of dollars (Anastasion et al., 1993).

The Oil Pollution Act of 1990 (OPA 90; P.L. 101-380) attempts to provide a comprehensive system of liability for damages resulting from oil spills. Under this legislation, shipowners are liable for removal costs¹ and damages in amounts up to US\$ 1200 per gross ton. However, the limit is lifted in a number of circumstances, including gross negligence, willful misconduct, or violation of a safety regulation. In addition, under OPA's legal framework, unlimited liability is available separately to the federal government, to state and local governments, and to private interests. As of 1998, at least 21 coastal states imposed unlimited liability through state law on the responsible party for damages and cleanup costs resulting from a spill (Crick, 1992; Crick-Sa-hatjian, 1998). Shipowners therefore must assume that their liability for spills in US waters will be unlimited in most, if not all, cases. This liability makes shipowners wary of committing their tankers to the US trade (Anastasion et al., 1993).

Rationally, society should manage the risk of marine oil spills by maximizing the benefits of importing oil, net of costs due to accidents. To date, much of the practical debate over the implementation of OPA 90 liability provisions has taken place between the US Coast Guard (the regulatory agency) and the foreign tanker industry. The industry is represented by shipowners associations (for example, see Dyer et al., 1994) and the protection and indemnity (P&I) clubs² (Leader, 1985).

A liability limit for the foreign tanker industry presents an interesting problem in the economics of liability. For example, unlike most liability problems, in which both injurers and victims are members of the same society (see Shavell, 1987), the tankers calling on US ports are predominantly foreign-owned. The oil transport industry is international and foreign tankers are highly mobile. Also, most foreign shipowners obtain liability insurance through their membership in P&I clubs.³ Liability from shipping operations has long been limited according to the size of the vessel. Historically, this limit has been set through negotiations.

This paper has three objectives: to develop an analytical framework for the oil transportation problem; to identify conditions under which liability should be zero, unlimited, or finite (limited); and to formulate a risk sharing model that captures tradeoffs between social welfare and liability

¹ These include costs associated with various oil spill response activities such as containment, cleanup, disposal, monitoring, and mitigation.

² About 95% of the world's ocean tonnage is insured through membership in one of 17 P&I clubs in the International Group (Harrod, 1993). The P&I clubs are mutual clubs, in which members (owners, charterers, managers, and operators of ships) agree to share each other's liabilities. When the liability limit of the club-level coverage has been exhausted for an accident, excess coverage provisions (through pooling and reinsurance) go into effect. P&I clubs differ from commercial insurance companies in that they are mutual self-insurance pools, and not designed to produce profits from premiums. However, this insurance system is not actuarially fair due, in a strict sense, to multiple layers of reinsurance.

³ Although with insurance shipowners may act as though they are risk neutral when making production decisions, we model the shipowners as risk averse. This is because the entire P&I insurance regime has been severely challenged under OPA 90. Modelling the shipping industry as risk averse provides useful information regarding their position in policy debates about liability limits and insurance arrangements.

limits in US waters. In our model, the foreign tanker industry has monopoly power and considers liability exposure and freight rates in determining the amount of tonnage committed to the US oil trade. US society's utility is a function of the benefits of oil imports and of environmental costs. We show that the liability limit should be set so that the marginal reduction in net social benefit from shipping services is equal to the marginal reduction in the social cost of risk-bearing associated with oil spills plus the marginal increase in the tanker industry's liability payments. We illustrate the properties of the model using numerical simulation techniques. We show how benefits and costs may be calculated, how a numerical estimate for an optimal liability limit may be developed, and how this estimate changes with respect to economic and social factors.

These is a substantial literature on the effect of liability laws on firms' behavior, and on social benefits and costs when both polluters and victims belong to the same society, where firms' decisions are based on operating costs and liability rules (Shavell, 1982, 1984, 1986; Segerson, 1987, 1989). The model described in this paper extends earlier studies by analyzing the effect of US liability law on the foreign tanker industry. We show that the socially optimal liability limit is lower when the tanker industry is US-owned. Our models captures four important aspects of the problem: the oil import market and US monopsony power, the tanker shipping market conditions, externalities from oil spills, and the allocation of risk. We examine the impact of liability laws at the aggregate industry level. We consider the alternative markets for the industry in other parts of the world. We show that the elasticities of oil supply and demand and the competitiveness of shipping markets are key factors affecting liability policy. For example, when the US has monopsony power and the tanker market is competitive, the optimal policy is to increase liability to extract monopsony rent from the oil market. Furthermore, an extra penalty (e.g., tax) may be needed to achieve this objective.

The remainder of this paper is organized as follows. Section 2 describes an analytical framework for the oil import problem. We construct theoretical models setting socially optimal liability policy under different market conditions. The main results of our analysis are summarized in four propositions. Section 3 develops methods to generate numerical results for the theoretical model. In Section 4, data for the simulations and selected results are presented. Section 5 illustrates a comparison of preliminary results and the liability limit set by OPA 90. Conclusions are summarized in Section 6.

2. Theoretical model

We start our analysis by developing a graphical description of the oil market and the shipping market. We then examine the optimal liability policy under different market conditions. As noted, the theoretical results are then summarized in four propositions.

2.1. *Oil market and demand for shipping*

Fig. 1 is a 'back-to-back' diagram with quantity of exporting and importing countries measured from left to right and right to left, respectively. This type of graph was used by Shneerson (1977) to discuss benefit measurement of shipping services.

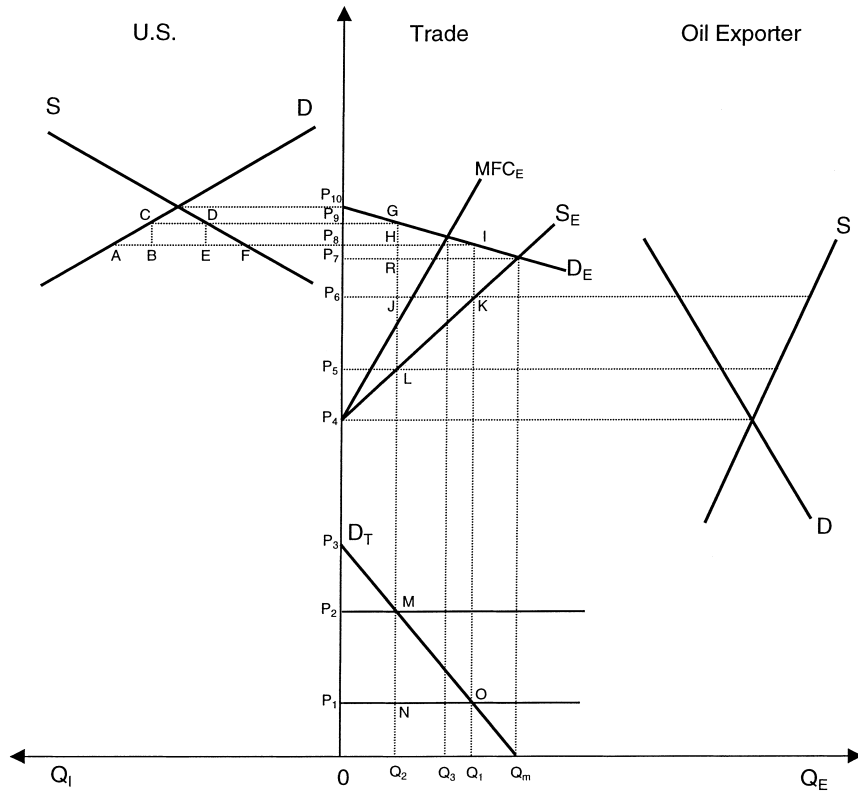


Fig. 1. Linkage between US oil imports and the shipping market.

Following Shneerson, we see that US demand for oil imports (D_E) and the oil exporter's supply of oil exports (S_E) are derived by subtracting horizontally the domestic supply (S) from demand (D) in the two markets, respectively.⁴ The demand for shipping oil to the US (D_T) can be traced by subtracting vertically the supply of exports (S_E) from demand for imports (D_E). If the shipping charge (freight rate) is zero, the free trade equilibrium price and quantity are Q_m and P_7 , respectively. If freight rates exceed $P_3 (= P_{10} - P_4)$, no trade will take place and the quantity shipped is zero. If freight rates are between 0 and P_3 , the quantity shipped will be in the range between 0 and Q_m . For example, if the freight rate is $P_2 (= Q_2M = GL)$, then the quantity is Q_2 .

When the freight rate is $P_2 (= P_9 - P_5)$, the total transport cost is P_2Q_2 , or the area P_9GLP_5 . Although this is paid by the shipper,⁵ the total cost is in fact shared by importer and exporter. The payment by importer and exporter is area P_9GRP_7 and P_7RLP_5 , respectively (Marlow, 1976). This is because, although the importer pays freight rate $P_9 - P_5 (= P_2)$, it pays a lower price for

⁴ We assume that in Fig. 1 the oil exporter's market represents the world oil market.

⁵ The exporter for oil shipped c.i.f. ('cost, insurance and freight' or 'charged in full'), or the importer for oil shipped f.o.b. ('free on board').

oil (P_7 reduced to P_5). This fraction of the freight rate ($P_7 - P_5$) is effectively paid by the exporter as oil price is lowered by the same amount.

Fig. 1 can also be used to analyze welfare changes associated with changes in freight rates. Suppose the cost of shipping is P_1 , but the firms overcharge and increase the freight rate from P_1 to P_2 . Quantity imported declines from Q_1 to Q_2 , and oil price in the US market rises from P_8 to P_9 . Noting that $Q_1 = AF$ and $Q_2 = CD$, the reduction in imports ($Q_1 - Q_2$) leads to an increase in US domestic oil production (EF) and a decrease in consumption (AB). Welfare losses to the US are the area ACDF (= P_9GIP_8), when transportation is provided by a foreign tanker fleet. However, if oil is transported by a US tanker fleet, then payment BCDE (rent) goes to the US tanker industry and the net losses are the sum of ABC and DEF (= GHI).⁶

The increase in freight rate also affects the exporter. The net losses are JKL. The total net loss of importer and exporter is captured by the area MNO under the demand curve for shipping service.

Now, suppose the freight rate is zero and the US has monopsony power in the international oil market. The optimal import level will be determined by marginal factor costs (MFC_E). As a result, $Q_3 (< Q_m)$ should be the quantity imported.

Since D_T captures the demand for shipping by both importer and exporter, welfare changes in the US cannot be analyzed by examining D_T alone. However, if the supply of exports (S_E) is perfectly elastic (a horizontal line), D_T can be used for such analyses.

The demand for imports (D_E) and supply of oil (S_E) can be modeled as

$$p_d = p_d^0 - k_d q, \tag{1}$$

$$p_s = p_s^0 + k_s q, \tag{2}$$

where p_d^0 and p_s^0 are choke prices and k_d and k_s are slopes of the demand and supply functions, respectively. Thus, the demand for shipping is

$$p_t = p_t^0 - k_t q \tag{3}$$

with $p_t^0 = p_d^0 - p_s^0$ and $k_t = k_d + k_s$.

2.2. Externalities and liability limit

Liability rules are designed to force shipping firms to internalize the social cost associated with oil spills, such as environmental damage and cleanup cost. The internalization of environmental externalities will lead to higher shipping costs and thus a lower level of imports. For example, in Fig. 1, if the marginal cost of shipping increases from P_1 to P_2 due to internalization, the quantity will be reduced from Q_1 to Q_2 . If oil spill damages are greater than P_3 , there should be no imports.

We define ‘liability limit’ as the limit on industry’s payment for environmental damage associated with oil spills per unit of oil transported to society.⁷ Let x be the environmental damage per

⁶ In fact, the tanker industry gets additional rent P_6JLP_5 .

⁷ Although the liability limit is commonly specified in terms of vessel tonnage in laws such as OPA 90, we prefer to specify it in terms of tons of oil transported, which is linked directly to the social benefit of oil supply. If vessel tonnage were used instead, we would have to convert the tonnage to transport quantity through fleet size and vessel size assumptions. This introduces unnecessary complexity to this analysis.

unit of oil transported (e.g., dollars per ton). x is a stochastic variable that follows a probability density function $\varphi(x)$ with $x_{\min} \leq x \leq x_{\max}$. m and σ^2 are the mean and variance of x , respectively.⁸ Then, for a liability limit (x_1), the unit damage absorbed by industry (x_i) is x if $x \leq x_1$ and x_1 if $x > x_1$.⁹ The mean (m_i) and variance (σ_i^2) can be calculated as

$$m_i = \int_{x_{\min}}^{x_1} x\varphi(x) dx + x_1 \int_{x_1}^{x_{\max}} \varphi(x) dx, \quad (4)$$

$$\sigma_i^2 = \int_{x_{\min}}^{x_1} x^2\varphi(x) dx + x_1^2 \int_{x_1}^{x_{\max}} \varphi(x) dx - m_i^2. \quad (5)$$

For the same liability limit (x_1), the unit damage borne by society (x_s) is 0 if $x \leq x_1$ and $x - x_1$ if $x > x_1$. The mean (m_s) and variance (σ_s^2) can be calculated as

$$m_s = \int_{x_1}^{x_{\max}} (x - x_1)\varphi(x) dx, \quad (6)$$

$$\sigma_s^2 = \int_{x_1}^{x_{\max}} (x - x_1)^2\varphi(x) dx - m_s^2. \quad (7)$$

Generally, $x_{\min} = 0$ and $x_{\max} = \infty$. In the two extreme cases, no liability implies that $x_1 = 0$ with $m_i = \sigma_i^2 = 0$, $m_s = m$ and $\sigma_s^2 = \sigma^2$. By contrast, full (unlimited) liability means that $x_1 = \infty$ with $m_i = m$, $\sigma_i^2 = \sigma^2$, and $m_s = \sigma_s^2 = 0$.

An important function of oil spill liability laws is to provide firms with incentives to take care to avoid spills. The socially optimal level of care under different liability regimes has been examined by Shavell (1987) and Segerson (1987). To ensure mathematical tractability, the model we present in the paper does not include the level of care as a choice variable. When both the shipping activity level and level of care are endogenous variables, they will be adjusted simultaneously by the industry in response to a change in x_1 . Analytical solutions of the model will be much more complicated (Jin and Kite-Powell, 1995).

OPA 90 prescribes double hulls for tanker operating in US waters. This imposes a high fixed level of care on the foreign tanker industry. Thus, the range of preventative activities for the tanker industry is somewhat limited, and the most flexible choice variable is the activity level.

⁸ For simplicity, we do not examine the level of care (e.g., investment in pollution prevention technologies) in this study. To consider the level of care (y), we may modify the probability density function as $\varphi(x, y)$. See Jin and Kite-Powell (1995).

⁹ Our analysis is based on the assumptions that all spills are detected, the associated damage is known, and the court system functions perfectly. These assumptions are reasonable as most spills are detected and documented by the Coast Guard, and damage assessment is required by relevant laws. Also, the court system has processed many oil spill cases. See Grigalunas et al. (1998) for an excellent discussion of relevant issues and a summary of representative cases.

2.3. Competitive tanker supply

As noted, the optimal policy regarding a liability limit will depend largely on the characteristics of the shipping market. There has been a small number of studies on the market structure of the tanker industry. While the majority of researchers believe that the market is competitive (Zanetos, 1966; Cockburn and Frank, 1992; Pirrong, 1992), others have shown that the market structure has changed over time and that the market has become differentiated by vessel size and trade route (Glen, 1990; see also Pirrong, 1993). In our study, we examine two scenarios: competitive market and monopoly.¹⁰ The competitive case is examined first in this section.

Suppose that there are a number of *identical* shipping firms. All tankers are foreign-owned. When the market is competitive, an individual shipping firm (j) chooses the volume of oil to transport (q_j) that maximize its expected utility ($E(U_j(\pi_j))$), where π_j is the net revenue:

$$\pi_j = p_t q_j - c q_j - x_i q_j \quad (8)$$

Here, q_j is the volume carried by the firm, and c is the unit cost of transportation in the US trade. Applying the expected value-variance (EV) approach¹¹ and noting that x_i is the only stochastic variable in Eq. (8), firm j 's certainty-equivalent profit function is:

$$\pi_{jce} = p_t q_j - (c + m_i) q_j - \frac{\lambda_j}{2} q_j^2 \sigma_i^2, \quad (9)$$

where λ_j is the Pratt–Arrow risk aversion parameter ($\lambda = -U''/U'$) for the firm, assuming U displays constant absolute risk aversion. The last term in Eq. (9) is a ‘risk premium.’

The first order condition implies that

$$p_t = c + m_i + \lambda_j q_j \sigma_i^2. \quad (10)$$

Since the market is competitive, the freight rate (p_t) equals the sum of unit shipping cost (c), expected unit damage (m_i), and the marginal risk premium determined by the variance of damage (σ_i^2) and the firm's risk preference (λ_j).

Although we know that the sum of firms' shipments equals the total US import ($\sum q_j = q$), each individual q_j is indeterminate. For simplicity, we assume the number of firms is N and $q_j = q/N$. When there are many firms, q_j is much smaller than q . From Fig. 1, it is apparent that the level of US imports is (q^*):¹²

$$q^* = \frac{p_d^0 - p_s^0 - c - m_i}{k_d + k_s + \lambda_j \sigma_i^2 / N}. \quad (11)$$

¹⁰ Because of the existence of foreign tanker fleets and other fleets, the price leadership model that includes a leader (OPEC) and competitive fringe as described by Pindyck (1978) in study of cartelization of oil production may be relevant to this problem.

¹¹ This approach involves an approximation (see Robison and Barry, 1987).

¹² Here, we assume that the demand for tankers (D_T) will not shift down to reflect changes in liability rules regarding environmental damage. This is because the consumers do not have full knowledge of the damage and, in fact, most of consumers of oil will not be injured directly by oil spills. This is different from a typical product liability case in which the demand for a “risky” product (that may cause harm to users) shifts down to reflect potential damages; as a result, the allocation of liability between producer and consumer will have no effect on the equilibrium output level of the product (Shavell, 1987).

We now examine if this level of imports is socially optimal. Society attempts to maximize its expected welfare ($E(U_s(\pi_s))$). π_s is the net social benefit from the shipping service. Using the EV approach, society's certainty-equivalent benefit function is

$$\pi_{sce} = B(q) - p_s(q)q - m_s q - p_t q - \frac{\lambda_s}{2} q^2 \sigma_s^2, \quad (12)$$

where $B(q)$ is the area under the demand curve (D_E) defined in Eq. (1), $B(q) = p_d^0 q - k_d q^2/2$. Note that p_t is defined in Eq. (10). The first order condition provides:¹³

$$q^{**} = \frac{p_d^0 - p_s^0 - c - m_i - m_s}{k_d + 2k_s + 2\lambda_j \sigma_i^2/N + \lambda_s \sigma_s^2} \quad (13)$$

where m_s defined in Eq. (6) is the mean damage borne by the society.

Comparing Eq. (11) and Eq. (13), we see that the numerator of Eq. (13) is smaller than that of Eq. (11) and the denominator of Eq. (13) is greater than that of Eq. (11). Thus, the socially optimal level of imports (q^{**}) is smaller than the market equilibrium (q^*) when the importer wants to capture monopsony rent from the oil market, and when the external cost of oil spills is borne by the US society. Eqs. (11) and (13) lead to the following proposition:

Proposition 1. *If the shipping market is competitive, then full (unlimited) liability is desirable, regardless of the risk preferences of the shipping firms and the society.*

Proof. When $k_s = \lambda_i = \lambda_s = 0$, from Eqs. (11) and (13) we see that if $m_i = m$ and $m_s = 0$, then $q^* = q^{**}$. When $k_s = 0$, $\lambda_i \neq 0$, or $\lambda_s \neq 0$, the denominator of Eq. (13) is greater than that of Eq. (11). Thus, $q^* > q^{**}$ and the lowest level of q^* (closest to q^{**}) can be achieved only if $m_i = m$ and $m_s = 0$. When $k_s \neq 0$, the denominator of Eq. (13) is always greater than that of Eq. (11). Again, we have $q^* > q^{**}$. Similarly, the condition to make q^* closer to q^{**} is $m_i = m$ and $m_s = 0$ and $\sigma_i = \sigma$ and $\sigma_s = 0$.

Thus, we know that when the shipping market is competitive, the optimal import level can be achieved through liability policy only when the oil market supply is perfectly elastic ($k_s = 0$) and both the firms and society are risk neutral ($\lambda_i = \lambda_s = 0$). In other cases, although full liability can only lead to a lower level of imports (q^*) closer to the socially optimal level (q^{**}), q^* is still greater than q^{**} . Thus, to achieve $q^* = q^{**}$, other policy instruments are needed. Essentially, if the US is a price taker in the international oil market and if the industry faces the full cost of their activities, $q^* = q^{**}$. If the US has monopsony power, q^* will not equal q^{**} because US extracts rents by importing less than q^* .

Suppose it is feasible for the United States to levy an import tax. Then, a tax (T) set at

$$T = \frac{(k_s + \lambda_s \sigma_s^2 + \lambda_j \sigma_i^2/N)(P_d^0 - P_s^0 - c - m_i) + (k_d + k_s + \lambda_j \sigma_i^2/N)m_s}{k_d + 2k_s + 2\lambda_j \sigma_i^2/N + \lambda_s \sigma_s^2} \quad (14)$$

will set the level of imports q^* equal to q^{**} . In this case, the firms pay the tax and the higher cost (shipping cost plus the tax) leads to lower q^* . If the US is a price taker ($k_s = 0$), and both society

¹³ It can easily be shown that the second order condition is satisfied as $-k_d - 2k_s - 2\lambda_i \sigma_i^2/N - \lambda_s \sigma_s^2 < 0$.

and firms are risk neutral ($\lambda_i = \lambda_s = 0$), then the tax is equal to the damage borne by society ($T = m_s$).

Proposition 2. *If the US is a monopsony importer of oil, an import tax on tanker owners may be used to maximize the net social benefit defined in Eq. (12), and the tax rate is set in Eq. (14).*

Proof. With tax (T), Eq. (10) becomes

$$p_t = c + m_i + \lambda_j q_j \sigma_i^2 + T \quad (15)$$

and, in turn, Eq. (11) becomes

$$q^* = \frac{p_d^0 - p_s^0 - c - m_i - T}{k_d + k_s + \lambda_j \sigma_i^2 / N}. \quad (16)$$

Setting Eq. (16) equal to Eq. (13), and solving for T , we get Eq. (14).

From Eq. (14), we see that setting such a tax may involve significant administrative costs, to derive market demands, spill risks and costs. Hartwick and Olewiler (1986) discuss advantages and disadvantages of a tax on imported oil. The tax discourages consumption and encourages conservation, stimulates domestic oil production and exploration, and provides revenue to the federal treasury. However, the tax is not politically popular for several reasons. It increases the price of oil to consumers. The tax has possible adverse effects on world trade.¹⁴ Also, if new energy resources are not developed to replace the declining supply of US reserves of oil, the tax will speed up eventual dependence on imports as domestic supplies are depleted more rapidly. Thus, in practice, some combination of tax and a policy to encourage alternative energy supplies may be desirable.

2.4. Monopoly power in the tanker industry

As noted, since the foreign tanker industry is coordinated through shipowners' associations and P&I clubs, they may have market power (Pindyck, 1978). In this section, we consider the case when the foreign tanker industry has monopoly power in the US market. Under this scenario, there are two decision makers: the foreign tanker industry and US society. The industry chooses a level of activity (e.g., tonnage committed to the US trade) for any given liability limit. Society chooses an optimal liability limit subject to industry's response (activity level). An interior solution to this problem is an equilibrium at which industry's activity level and society's liability limit are jointly determined.

The industry determines the vessel capacity engaged in the US trade so that the industry's expected utility ($E(U_i(\pi_i))$) is maximized. π_i is the total worldwide net revenue the industry generates:

$$\pi_i = p_t(q)q - cq - x_i q + p_b(f - q), \quad (17)$$

¹⁴ Generally, a US import tariff would have several effects, including higher price in the US market, lower price on the export market, lower quantity of trade, and a negative welfare impact on the US economy (Richardson, 1980).

where $p_t (= p_d - p_s)$ is the freight rate in the US trade, q is the US trade volume (import quantity carried by foreign tankers), c is the unit cost of transportation in the US trade, x_i is the unit damage associated with q , p_b is the net unit revenue from tanker operations in other parts of the world,¹⁵ and f is the total transportation capacity of the industry.

Applying the EV approach and noting that x_i is the only stochastic variable in Eq. (17), and that p_t is defined in Eq. (3), the industry's optimal activity level for a given liability limit is

$$q = \frac{p_d^0 - p_s^0 - c - m_i - p_b}{2k_d + 2k_s + \lambda_i \sigma_i^2}, \quad (18)$$

where λ_i is the Pratt–Arrow risk aversion parameter ($\lambda = -U''/U'$), again assuming U displays constant absolute risk aversion.

Eq. (18) shows how industry's activity level (q) changes with respect to an exogenous liability limit (x_i). The equation indicates that if the US trade is riskier than other trades, then the net revenue from the US trade ($p_t^0 - c - m_i$) must be greater than the net revenue from alternative trades (p_b). p_b is determined by international shipping market conditions, including the supply of and demand for tankers. A lower p_b implies a greater q . Also, the more risk averse the industry (greater λ_i), the less capacity (q) will be engaged in the US trade. As the level of risk rises (σ_i^2), q will decline. With a liability limit (x_i), the level of risk is reduced. Finally, q is also affected by the slope of the demand curve for shipping ($k_t = k_d + k_s$). Other things being equal, if the demand is perfectly elastic ($k_t = 0$), q will be at the highest level.

Now, consider how society should set the liability limit. Society is to maximize its expected welfare ($E(U_s(\pi_s))$), subject to industry's response as described in Eq. (18). π_s is the net social benefit from the shipping service (q):

$$\pi_s = B(q) - p_s(q)q - p_t(q)q - x_s q = B(q) - p_d(q)q - x_s q, \quad (19)$$

where $B(\cdot)$ is the US social benefit from the shipping service provided by foreign tankers (q), society's payment includes the cost of oil ($p_s q$) and the cost of transport ($p_t q$, is the industry's revenue), and x_s is the unit damage associated with q borne by society. As shown in Fig. 1, $p_d = p_s + p_t$. Also, as in Eq. (12), we assume $B(q)$ is the area under the demand curve, so that $B(\cdot) = p_d^0 q - k_d q^2/2$. We will show in the next section (see Eq. (23)) that Eq. (19) is different from the standard specification of net social benefit in which both the public and the industry in question are part of the same society (see Shavell, 1987).

Applying the EV method to the social planner's problem, the solution is given by

$$-[k_d q - m_s - \lambda_s q \sigma_s^2] \frac{\partial q}{\partial x_1} = \frac{\partial m_i}{\partial x_1} q - \frac{\lambda_s}{2} q^2 \frac{\partial \sigma_s^2}{\partial x_1}, \quad (20)$$

where λ_s is the Pratt–Arrow risk aversion parameter for society. Using Eq. (18), it is easy to show that $\partial q/\partial x_1 < 0$. Also, since $\partial m_i/\partial x_1 > 0$ and $\partial \sigma_s^2/\partial x_1 < 0$, both sides of Eq. (20) are positive for an interior solution. For a marginal increase in x_1 , the left hand side of Eq. (20) captures the marginal social cost associated with a reduction in foreign tanker services (q) resulting from the increase in x_1 . The marginal cost is affected by the slope of the demand for oil (k_d) and the activity level (q). Larger k_d is associated with higher cost. The right-hand side of Eq. (20) has two terms. The first

¹⁵ We assume that p_b is deterministic relative to environmental damage in US waters (x).

term is the marginal increase in liability payments (industry's share of the damage).¹⁶ The second term is the marginal decrease in the social cost of risk-bearing associated with oil spills. The right-hand side thus represents the social benefit associated with an increase in the liability limit (x_1). Therefore, Eq. (20) provides a formula for determining the socially optimal level of liability limit: the liability limit (x_1) should be set so that the marginal social benefit equals the marginal social cost.

If society is risk-neutral, λ_s equals zero. Eq. (20) can still be used to determine x_1 , since x_1 will still affect the industry's activity level (q) and the share of damage borne by society (m_s). Because of the tradeoff between beneficial activity and damages, a socially optimal liability limit may still be desirable: $0 \leq x_1 \leq \infty$.

Generally, if $\lambda_i = 0$ (the industry is risk neutral), x_1 affects the activity level (q) through m_i , while if $\lambda_i \neq 0$, x_1 affects q through both m_i and σ_i^2 . Similarly, if $\lambda_s = 0$ (society is risk neutral), x_1 affects the industry activity level (q) through m_s , while if $\lambda_s \neq 0$, x_1 affects q through both m_s and σ_s^2 . Thus, although the liability limit (x_1) is affected by the risk preferences of the two sectors, x_1 is not solely dependent on the risk parameters.

Proposition 3. *When the foreign tanker industry has monopoly power, and demand for oil imports is not perfectly elastic ($k_d \neq 0$), limited liability may be desirable. The existence of corner solutions depends on the slope of the demand curve (k_d).*

Proof. From Eq. (20), it is apparent that a perfectly elastic demand ($k_d = 0$) leads to a corner solution. Also, since $p_d = p_s + p_t$ (see Fig. 1), when the foreign tanker industry has monopoly power, it will set marginal cost equal to marginal revenue to capture monopoly rent. As a result, society will not be able to capture monopsony rent. Any reduction in oil price (p_s) will be offset by a corresponding increase in freight rate (p_t). Thus, in this case the slope of the oil supply curve (k_s) will not directly affect the liability policy, although k_s affects industry's activity (q) in Eq. (18).

For corner solutions, the Kuhn–Tucker conditions suggest:

$$\frac{\partial \pi_{sce}}{\partial x_1} \leq 0, \quad x_1 \geq 0, \quad x_1 \frac{\partial \pi_{sce}}{\partial x_1} = 0 \quad (21)$$

with

$$\frac{\partial \pi_{sce}}{\partial x_1} = k_d q \frac{\partial q}{\partial x_1} - [m_s + \lambda_s q \sigma_s^2] \frac{\partial q}{\partial x_1} + \frac{\partial m_i}{\partial x_1} q - \frac{\lambda_s}{2} q^2 \frac{\partial \sigma_s^2}{\partial x_1}. \quad (22)$$

Thus, if $\partial \pi_{sce} / \partial x_1 > 0$ is always true, full liability ($x_1 = \infty$) is the solution. By contrast, if $\partial \pi_{sce} / \partial x_1 < 0$ then no liability ($x_1 = 0$) is the solution. There are four terms in Eq. (22). Only the sign of the first term is negative and others are positive. Thus, the magnitude of the first term is important. For example, we choose unlimited liability if the demand for oil is perfectly elastic ($k_d = 0$). And we may speculate that no liability is the solution if the demand is very inelastic (k_d is large so that $\partial \pi_{sce} / \partial x_1 < 0$).

¹⁶ Since $\partial m_i / \partial x_1 = -\partial m_s / \partial x_1$, it is the marginal reduction in society's share.

As to the second order condition, it can be shown that the condition for a maximum is likely to be met ($\partial^2 \pi_{\text{sce}} / \partial x_1^2 < 0$), although in theory, the sign of $\partial^2 \pi_{\text{sce}} / \partial x_1^2$ can be positive or negative.¹⁷ Thus, numerical simulation is needed to examine each specific case.

2.5. US-Owned tanker industry

Suppose all tankers are owned by US firms.¹⁸ If the tanker market is competitive, the results of Section 2.3 hold. This is due to the zero-rent condition in a competitive shipping market. However, if the industry has monopoly power, the discussion in the previous section will change. Other things being equal, Eq. (19) becomes

$$\pi_s = B(q) - p_s(q)q - cq - xq + p_b(f - q). \quad (23)$$

The first order condition (22) becomes

$$\frac{\partial \pi_{\text{sce}}}{\partial x_1} = [p_d^0 - p_s^0 - k_d q - 2k_s q - c - m - p_b - \lambda_s q \sigma^2] \frac{\partial q}{\partial x_1} = 0. \quad (24)$$

Notice that m and σ^2 are the total mean and variance of x , respectively. Now only q is influenced by x_1 (see Eq. (18)). Generally, $\partial q / \partial x_1 \neq 0$. Thus, an interior solution requires the term in square brackets to be zero. A solution for Eq. (24) is

$$q = \frac{p_d^0 - p_s^0 - c - m - p_b}{k_d + 2k_s + \lambda_s \sigma^2}. \quad (25)$$

In determining the liability limit in this case, we choose x_1 to make Eq. (25) equal to Eq. (18).¹⁹ In this case, since the industry is part of the US economy, monopoly rent is considered benefit. Thus, in Eq. (23) the only shipping cost besides externalities is c .

Proposition 4. *When the tanker industry is US-owned and has monopoly power, zero liability (x_1) is likely the optimal policy when demand for shipping is high (p_t^0 is large). However, risk sharing and full liability may still be possible solutions.*

Proof. Since $\partial q / \partial x_1 < 0$, assuming the term in square brackets in Eq. (24) is positive, $\partial \pi_{\text{sce}} / \partial x_1 < 0$ and the solution is no liability ($x_1 = 0$). This is true when p_t^0 ($p_d^0 - p_s^0$) is large. Other factors that lead to zero liability include low environmental externality (m), risk neutral society ($\lambda_s = 0$), or perfectly elastic oil supply ($k_s = 0$). However, since the term in square brackets in Eq. (24) can be negative or zero, other scenarios cannot be excluded.

In our analysis, we assume that all agents in the economy can be fully compensated for any damage resulting from an oil spill. In practice, full compensation generally is not achieved. A

¹⁷ From Eq. (22), take the partial derivative with respect to x_1 . The resulting expression of $\partial^2 \pi_{\text{sce}} / \partial x_1^2$ includes several negative terms and one term whose sign depends on the sign of $\partial^2 q / \partial x_1^2$. Since the sign of $\partial^2 q / \partial x_1^2$ can be positive or negative, we cannot prove that $\partial^2 \pi_{\text{sce}} / \partial x_1^2 < 0$ is always true.

¹⁸ We use this case to illustrate the effect of fleet ownership. In reality, most tankers in the US trade are owned by foreign firms.

¹⁹ It can be easily shown that the second order condition for this problem is not always satisfied.

model that takes into account different agents within the society would identify the equity effects, but this is beyond the scope of our paper.

3. Numerical model

We have shown that when the tanker industry has market power, a liability limit may be desirable. However, since the second order condition for our model may not be satisfied, it is necessary to use numerical simulation to examine each specific case. In this section, we generate numerical estimates for liability limits under various conditions. We use the foreign tanker fleet as an example.

As noted, Eqs. (18) and (20) can be used to determine the socially optimal liability limit. To obtain numerical solutions, we need to specify a functional form for $\varphi(x)$ and calculate the corresponding $m_i, \partial m_i / \partial x_1, \sigma_i^2, \partial \sigma_i^2 / \partial x_1$ for the industry and $m_s, \partial m_s / \partial x_1, \sigma_s^2, \partial \sigma_s^2 / \partial x_1$ for society.

Suppose x follows a lognormal distribution:²⁰

$$\varphi(x) = \frac{1}{\sqrt{2\pi vx}} e^{-(\log x - \mu)^2 / (2v^2)} \tag{26}$$

with mean (m) and variance (σ^2):

$$m = e^{\mu + v^2/2}, \tag{27}$$

$$\sigma^2 = e^{2\mu + v^2} (e^{v^2} - 1). \tag{28}$$

$\text{Log}(x)$ then follows a normal distribution with mean (μ) and variance (v^2). The cumulative distribution function of x is

$$F(x) = \Phi\left(\frac{\log x - \mu}{v}\right), \tag{29}$$

where Φ is the standard normal distribution function:

$$\Phi(\xi) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\xi} e^{-x^2/2} dx. \tag{30}$$

For a liability limit (x_1), the truncated means and variances can be calculated (Johnson and Kotz, 1970) as

$$\alpha_r^+(x_1) = \alpha_r [1 - \Phi(w - rv)] / [1 - \Phi(w)] \tag{31}$$

with

$$w = \frac{\log x_1 - \mu}{v}, \tag{32}$$

²⁰ A study of oil spill costs indicates that the lognormal distribution provides the best fit of the empirical cost data (Monnier, 1995).

where α_r^+ is the r th moment of x about zero when x is truncated from below at x_1 , and α_r is the r th moment if not truncated.

It follows that

$$\alpha_r^-(x_1) = \frac{\alpha_r - [1 - F(x_1)]\alpha_r^+(x_1)}{F(x_1)}, \tag{33}$$

where α_r^- is the r th moment of x about zero when x is truncated from above at x_1 .

Now, let us define m_i , $\partial m_i / \partial x_1$, σ_i^2 , $\partial \sigma_i^2 / \partial x_1$, m_s , $\partial m_s / \partial x_1$, σ_s^2 , and $\partial \sigma_s^2 / \partial x_1$.

From Eq. (4), m_i is

$$\begin{aligned} m_i &= \int_0^{x_1} x\varphi(x) \, dx + x_1 \int_{x_1}^{\infty} \varphi(x) \, dx \\ &= \alpha_1^-(x_1)F(x_1) + x_1[1 - F(x_1)]. \end{aligned} \tag{34}$$

Note that α_1^- is calculated using Eq. (29) through Eq. (33) with $r = 1$ and $\alpha_1 = m$ (the mean).

$$\frac{\partial m_i}{\partial x_1} = 1 - F(x_1). \tag{35}$$

From Eq. (5)

$$\begin{aligned} \sigma_i^2 &= \int_0^{x_1} x^2\varphi(x^2) \, dx + x_1^2 \int_{x_1}^{\infty} \varphi(x) \, dx - m_i^2 \\ &= \alpha_2^-(x_1)F(x_1) + x_1^2[1 - F(x_1)] - m_i^2. \end{aligned} \tag{36}$$

Note that α_2^- is calculated using Eq. (29) through Eq. (33) with $r = 2$ and $\alpha_2 = \sigma^2 + m^2$ (see Eqs. (27) and (28)). m_i is defined in Eq. (34).

$$\frac{\partial \sigma_i^2}{\partial x_1} = 2[1 - F(x_1)](x_1 - m_i). \tag{37}$$

From Eqs. (4) and (6), $m_s = m - m_i$. Also,

$$\frac{\partial m_s}{\partial x_1} = F(x_1) - 1. \tag{38}$$

From Eq. (7)

$$\begin{aligned} \sigma_s^2 &= \int_{x_1}^{\infty} (x - x_1)^2 \varphi(x) \, dx - m_s^2 \\ &= [1 - F(x_1)][\alpha_2^+(x_1) - 2x_1\alpha_1^+(x_1) + x_1^2] - m_s^2. \end{aligned} \tag{39}$$

Note that α_1^+ and α_2^+ are calculated using Eq. (29) through Eq. (32) with r equal to 1 and 2, respectively. m_s is defined above.

Finally

$$\frac{\partial \sigma_s^2}{\partial x_1} = 2[F(x_1) - 1][\alpha_1^+(x_1) - m_s]. \tag{40}$$

Now, numerical simulations can be performed using Eqs. (18) and (20) with Eq. (34) through Eq. (40) for the liability limit (x_1). The computer program also calculates $\partial^2\pi_{\text{sce}}/\partial x_1^2$ so that the second order condition can be examined.²¹

4. Data and simulation

We need three types of data. First, we need to know tanker operating revenue and cost. We need to specify a US demand function for foreign oil tankers ($p_t^0 = p_d^0 - p_s^0$ and $k_t = k_d + k_s$) and net revenue from tanker operations in other parts of the world (p_b). From Eqs. (18) and (20), we see that we do not have to know p_d^0 and p_s^0 ; only $p_t^0 (= p_d^0 - p_s^0)$ is needed. Developing precise estimates of these variables is beyond the scope of this paper. To develop precise estimates, different trade routes and vessels sizes must be considered. Many other factors, such as flag and vessel age, further complicate the assessment. In this paper, we use preliminary estimates to illustrate the model. For simplicity, we assume that the world oil supply is perfectly elastic ($k_s = 0$) for the examined quantity (q) range. Thus, the slope of the shipping demand equals the slope of US demand for oil imports ($k_t = k_d$). The freight rate in the US trade is taken from US Coast Guard data, and import volume from the US Department of the Interior (1995). The slope is estimated based on the elasticity of US demand for crude oil (Choucri, 1981; Kalt, 1983) and tanker freight rate information (Champness and Jenkins, 1985). The fixed and variable cost of tanker operation (c) is from the National Research Council (1991).

Next, we need to specify the risk preference measures. The risk aversion parameter for the industry (λ_i) is calculated from a shipowners' utility function estimated by Cullinane (1991). Society's risk aversion parameter (λ_s) generally is considered to be smaller than individuals' or the industries' (Arrow and Lind, 1970; Chichilnisky and Heal, 1992).²²

Finally, we need to specify the parameters for the damage function. The mean (m) of the unit environmental damage (x) is calculated using estimates of average historical oil spill quantity and cost (dollars per ton spilled) in US waters (National Research Council, 1991) and total US oil imports (US Department of the Interior, 1995). The standard deviation of the unit damage (σ) is from a study of worldwide oil spill costs (Monnier, 1995). Baseline input data are summarized in Table 1.

²¹ This is constructed using Eqs. (18), (22) and (34) through Eq. (40).

²² Although a precise measure of individual or household risk perception is not an easy task (Anderson et al., 1977), several empirical studies have estimated risk aversion parameters (Binswanger, 1980) or factors affecting risk perceptions (Moses and Savage, 1989). Binswanger (1980) showed that at high payoff level, virtually all individuals are moderately risk-averse with little variation according to personal characteristics. Wealth tends to reduce risk aversion slightly, but its effect is not statistically significant. Although the absolute risk-aversion parameter (λ), which measures subjective risk preference, can be any value, the results of a study by King and Robison (1981) indicate that the absolute risk-aversion coefficient should be concentrated in the range from -10^{-4} to 10^{-3} . For a risk-averse decision maker, λ is a positive number. Decisions involving risks are affected by the value of λ . However, when λ is greater than 0.1 or very small (close to zero), the decisions are usually not sensitive to changes in λ .

Table 1
Input data

Parameters	Description	Baseline value
p_t^0	freight rate in the US trade (intercept of demand)	US \$43.32/ton
$k_t = k_d$	slope of demand for tankers	US \$0.06/10 ⁶ ton ²
c	unit cost of transportation in the US trade	US \$8.07/ton
p_b	net revenue for tankers in other parts of the world	US \$0.9/ton
λ_i	industry's Pratt–Arrow risk aversion parameter	0.0136
λ_s	society's Pratt–Arrow risk aversion parameter	0.00001
m	mean of the unit environmental damage (x)	US \$0.85/ton
σ	standard deviation of the unit environmental damage (x)	US \$2.55/ton

Using these empirical data, we develop a set of simulations to illustrate the properties of the model. Our simulations focus on sensitivity analyses with respect to key parameters such as λ_s , k_t , σ and m .

Results of five simulation cases are presented in Table 2 and Figs. 2–7. Fig. 2 shows the general features of this model using baseline data (see Table 1). The mean unit damage (x) is US \$0.85/ton. Fig. 2 shows how the tanker supply (q) declines and the certainty equivalent net social benefit ($\pi_{scc} = E(\pi_s) - \lambda_s q^2 \sigma_s^2 / 2$) changes as the liability limit (x_1) rises from US \$0.1/ton to US \$3.00/ton. At the optimal liability limit ($x_1 = \text{US } \$0.38/\text{ton}$), π_{scc} reaches the maximum.

Case 2 examines how the liability limit changes as society becomes more risk averse with regard to oil spill damages. As depicted in Fig. 3, the optimal liability limit rises from US \$0.38/ton to US \$0.69/ton (see Table 2) when λ_s increases from 10^{-5} to 10^{-3} . Declines in social benefit (π_{scc}) and oil imports (q) are observed.

Case 3 analyzes the effect of a change in the slope of US demand for oil imports (k_d) on the optimal liability limit. In this case, the slope decreases from 0.06 to 0.03 while the choke price remains the same ($p_t^0 = \text{US } \$43.32/\text{ton}$), representing an increase in demand. Compared with the baseline case (Case 1), there is a significant increase in tanker supply and oil imports ($q = 569$ million tons per year) due to higher freight rate (p_t). Social benefit also increases to US \$4.46 billion (see Table 2). Fig. 4 shows the changes in liability limit (x_1), imports (q), and social benefit (π_{scc}) for a wider range of k_d . Again, for the same p_t^0 , q and π_{scc} decrease and x_1 rises monotonously as k_d increases from 0.02 to 0.12.

Table 2
Selected simulation results

Variables	Description	Unit	Case 1	Case 2	Case 3	Case 4	Case 5
x_1	liability limit	US \$/ton	0.38	0.69	0.25	0.58	0.93
q	oil imports	10 ⁶ ton/year	283.62	281.25	568.53	281.67	277.96
m_i	mean damage borne by industry	US \$/ton	0.24	0.34	0.18	0.44	0.77
m_s	mean damage borne by society	US \$/ton	0.61	0.51	0.67	0.41	1.23
σ_i^2	variance of damage borne by industry	(US \$/ton) ²	0.02	0.07	0.01	0.03	0.06
σ_s^2	variance of damage borne by society	(US \$/ton) ²	6.31	6.08	6.40	0.86	6.06
π_{scc}	certainty-equivalent social benefit	10 ⁹ US \$	2.24	1.99	4.46	2.26	1.97

Notes: Case 1 uses baseline input values; Cases 2 through 5 also use baseline input values, but in each case, one variable's value is altered. Specifically, in Case 2 $\lambda_s = 0.001$, in Case 3 $k_d = 0.03$, in Case 4 $\sigma = 1$, and Case 5 $m = 2$.

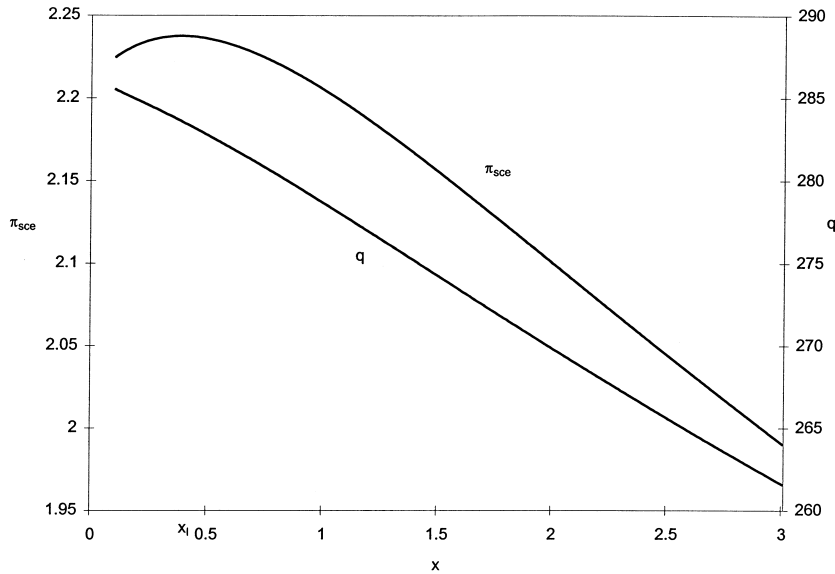


Fig. 2. Base case simulation of the effect of liability limit (x_1) on oil imports (q) and social benefit (π_{sce}).

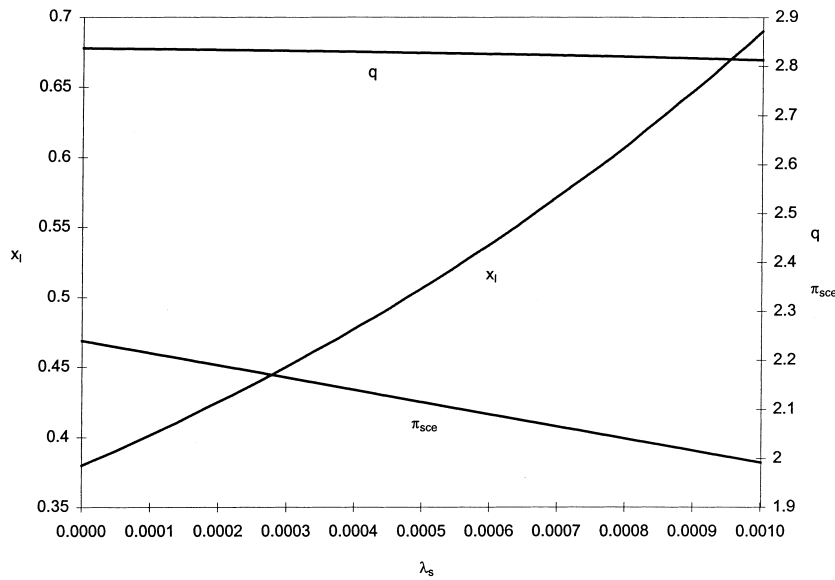


Fig. 3. The effect of increased social risk aversion (λ_s) on liability limit (x_1), oil imports (q) and social benefit (π_{sce}).

From Eq. (22), we know that k_d is an important factor in determining the existence of corner solutions. For example, when $k_d = 0$, $\partial\pi_{sce}/\partial x_1 > 0$ for all x_1 , making unlimited liability ($x_1 = \infty$) the optimal solution. Note that when $k_d = 0$, $\pi_{sce} < 0$; when the demand for import is perfect elastic, consumer surplus is zero. Excessive tanker supply (q , see Eq. (18)) will cause significant environmental damage. Our simulation for $k_d = 0$ indicates that when x_1 becomes very large (e.g., US \$2,000/ton), q becomes relatively small (e.g., 380 million tons/year) and π_{sce} is close to zero.

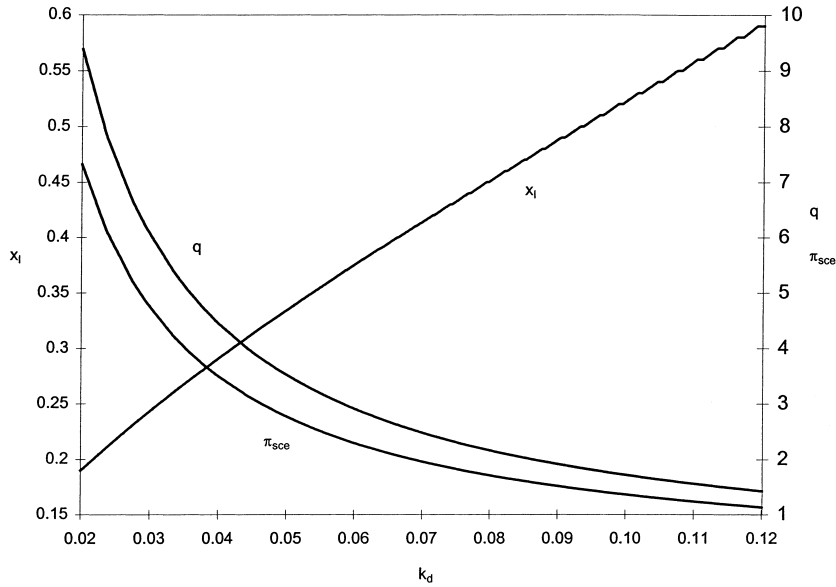


Fig. 4. Simulated effect of changing the slope of US demand for imports on liability limit (x_l), oil imports (q) and social benefits (π_{sce}).

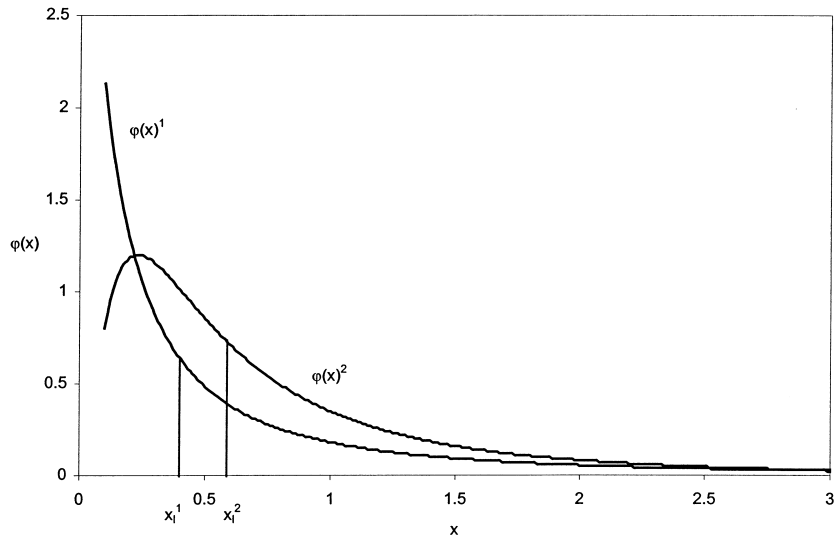


Fig. 5. Changes in the shape of probability density function of environmental damage ($\varphi(x)$) and liability limit (x_l) with respect to standard deviation (σ).

Although a corner solution exists for $k_d = 0$, our simulation suggests that limited liability is still optimal even when k_d is very large (e.g. $k_d = 8000$). We have speculated that when k_d is very large, $\partial \pi_{sce} / \partial x_l < 0$ (see Eq. (22)), and no liability ($x_l = 0$) is the optimal solution. However, our simulations indicate that $\partial \pi_{sce} / \partial x_l < 0$ will not happen: as k_d becomes larger, q and $\partial q / \partial x_l$ become smaller (see Eq. (22)).

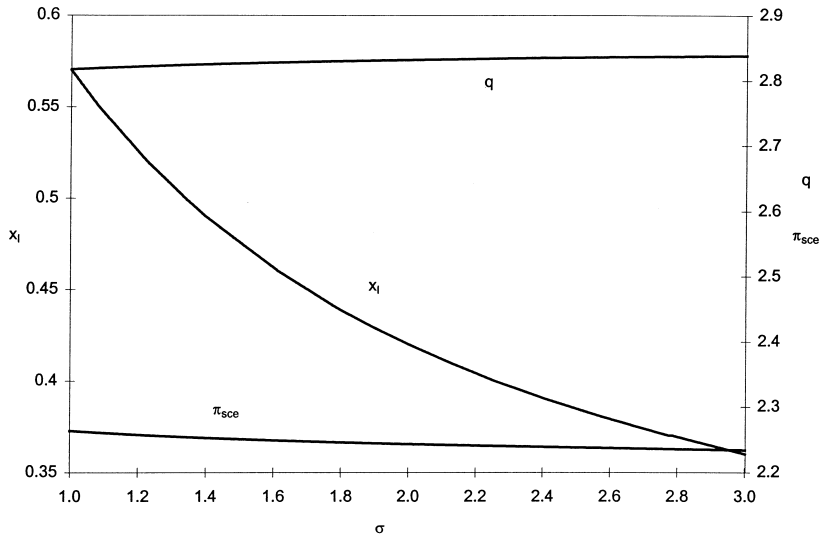


Fig. 6. The effect of decreased standard deviation of environmental damage (σ) on liability limit (x_1), oil imports (q) and social benefit (π_{sce}).

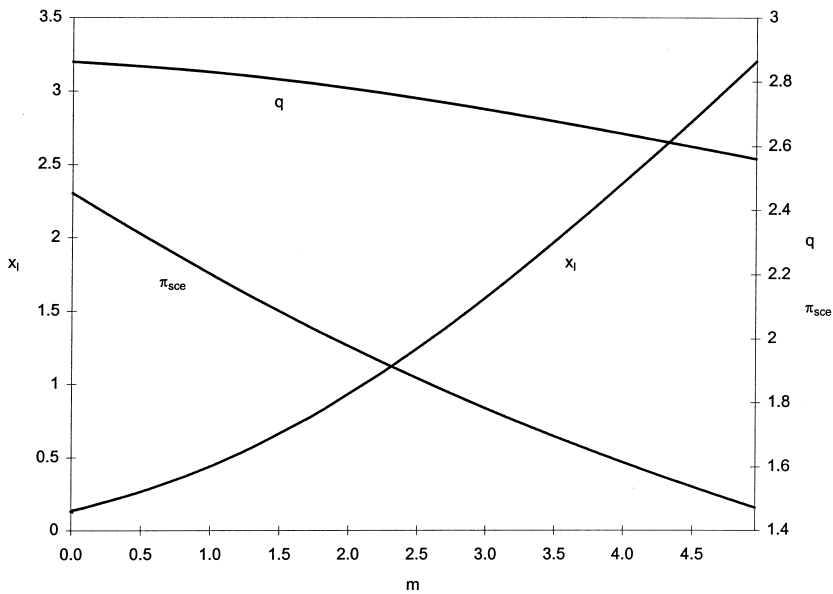


Fig. 7. Simulated effect of rising mean damage (m) on liability limit (x_1), oil imports (q) and social benefit (π_{sce}).

In Case 4, we change the standard deviation (σ) of the unit damage (x) from 2.55 to 1. As shown in Fig. 5, with the same mean (US \$0.85/ton), the shape of $\varphi(x)$ is skewed to the right (see $\varphi(x)^2$ in Fig. 5). The optimal liability limit increases to US \$0.58/ton (see x_1^2 in Fig. 5). This implies that even when the variance of unit damage becomes smaller, society may still want to set a higher limit (Table 2). Fig. 6 shows that as σ decreases, an increasing x_1 leads to higher social benefit (π_{sce}).

In the last case (Case 5), we change the mean (m) of the unit damage (x) from 0.85 to 2. As shown in Table 2, with the same standard deviation (US \$2.55/ton), the optimal liability increases to US \$0.93/ton. Fig. 7 shows the decrease in social benefit (π_{scc}) and imports (q) associated with rising mean damage. Table 2 also shows the mean and variance of the unit damage facing industry (m_i and σ_i) and society (m_s and σ_s) under different liability limits (x_l) in the five cases. In all simulations, the second order condition ($\partial^2 \pi_{scc} / \partial x_l^2 < 0$) is satisfied.

5. Comparison to OPA 90 liability limit

To illustrate one possible application of these results, we compare the baseline optimal limit suggested by our simulations to the limit set by OPA 90. We emphasize that this is strictly an illustration, since our simulation results are preliminary. Also, our simulations assume that the foreign tanker industry has monopoly power, while in reality the shipping market may be competitive. The exercise illustrates the assumptions required to translate liability limits from \$/ton spilled to \$/vessel tonnage terms in a static framework.

In this study, the mean ($m =$ US \$0.85/ton) of the unit environmental damage (x) is estimated based on total US imports (422 million tons per year) (US Department of the Interior, 1995), average volume spilled in US waters (9000 tons per year) (National Research Council, 1991), and average damage per ton spilled (US \$40 000) (National Research Council, 1991). Thus, the ratio of spillage to total shipments is roughly 2.13×10^{-5} ton spilled/ton shipped. If we assume that the ‘spill rate’ is constant for a range of import levels and that the average damage is US \$40 000 per ton spilled, the simulated optimal liability limit can be expressed in terms of damage per ton spilled. For example, in our baseline case (Case 1), the optimal liability limit (x_l) is US \$0.38 per ton shipped, or US \$17 818 per ton spilled. With this limit defined in these terms, industry pays no more than 45% of the average unit damage.

Current US law defines liability limits not in terms of tons shipped or tons spilled, but in terms of vessel tonnage. Under OPA 90, shipowners are liable for removal cost and damages in amounts up to US \$1200 per gross ton of a ship, or about US \$600 per dwt for large tankers (Institute of Shipping Economics and Logistics, 1990). We assume for the moment that this is a firm limit, like the limit in our model and simulation. According to the US Coast Guard, in most cases oil spill volumes are less than three tons (1000 gallons), much less than the total tonnage of a ship. For a 150 000 dwt tanker, the liability limit under OPA 90 might be about US \$90 million (US \$600/dwt \times 150 000 dwt). Even if 300 tons of oil were spilled from this vessel, the OPA 90 liability limit would amount to US \$300 000 per ton spilled. Thus, under ‘average’ (small) spill conditions, the OPA 90 liability limit is effectively higher than the optimal limit suggested by our simulation.

This relationship changes when we consider large spills. For example, in the *Exxon Valdez* case, the vessel tonnage was 215 000 dwt and spillage was 36 000 tons, or about 17% of the vessel tonnage (National Research Council, 1991). The OPA 90 liability limit for this vessel would be US \$129 million, or US \$3583 per ton spilled in the Prince William Sound accident. This is much lower than the optimal limit suggested by our baseline simulation (US \$17 818).

Thus, the liability limit defined by OPA 90 is higher than our hypothetical optimal limit for average (small) spills but falls short of the optimal limit for large spills. In fact, the OPA 90 limit is not firm, and the possibility of unlimited liability raises the ‘effective’ OPA 90 limit above US

\$1200 per gross ton. Whether this effective OPA 90 limit is above or below our hypothetical optimal limit for large spills is an unresolved question. A more detailed analysis could resolve this issue, and also take into account the dynamic nature of relationships between spill volumes and import levels, among others.

It is important to note that the implementation of OPA 90 regulations has not lead to any significant reduction in tanker supply or oil imports, although the industry predicted a disruption of oil supply prior to implementation. This suggests that the shipping market may be closer to the perfect competition scenario than the monopoly case. In that case, OPA 90's liability policy is an appropriate choice according to our analysis in Section 2.3.

6. Conclusions

Energy supply is crucial to the US economy. The United States imports nearly half of its total consumption. Most of the imports are carried in foreign tankers. Oil spills pose risks to the marine environment. Changes in the US liability regime, including the Oil Pollution Act of 1990 and implementing regulations, have had a major impact on the tanker industry. It is in the interest of society to manage the risk associated with marine oil spills so as to maximize the benefits of importing oil, net of costs from accidents.

We have formulated an analytical framework that incorporates the oil import market, tanker shipping market, environmental externalities, and risk allocation. Our analysis focuses on two extreme cases in the shipping market: perfect competition and monopoly. The results suggest that when the tanker supply is competitive, full (unlimited) liability is desirable regardless of the risk preferences of the shipping firms and the society. We also show that to maximize the net social benefit, a tax may be introduced, if the US is a monopsony importer of oil.

For the monopoly case, our model captures the tradeoffs between social welfare and liability limits in US waters. In this model, the foreign tanker industry has market power and considers liability exposure and freight rates in determining the amount of tonnage committed to the US oil trade. US society's utility is a function of benefit of oil imports and environmental costs. The results indicate that the liability limit should be set so that the marginal reduction in net social benefit from shipping services is equal to the marginal reduction in the social cost of risk-bearing associated with oil spills plus the marginal increase in the foreign tanker industry's liability payments to the society. We also discuss liability policy when all tankers are owned by US firms, and show that in this case, zero liability is likely desirable.²³

Based on these intuitive theoretical results for the monopoly case, we provide a procedure for quantifying the benefits and costs, and show how an optimal liability limit may be determined in practice. Assuming that the unit damage follows a lognormal distribution, we generate estimates of a socially optimal liability limit under various conditions using empirical data. For the baseline data, the simulation results show that unlimited liability ($x_1 = \infty$) is non-optimal and that a limit may be desirable, when the foreign tanker industry has market power. The socially optimal lia-

²³ This is supported by our simulation using baseline data.

bility limit is affected by risk perceptions of industry and society, the demand for foreign tankers, and the level of uncertainty associated with the unit damage. For example, as society becomes more risk averse regarding oil pollution, the liability limit should be set higher (Fig. 3), which will lead to a reduction in tanker supply (Table 2).

Because most of the baseline data are preliminary estimates, the results of our simulation can only be considered an illustration of the numerical model. A detailed analysis of the tanker market is needed to develop more accurate baseline data. Also, further work is required to develop realistic comparisons of optimal limits determined by our model and the limits effectively imposed by OPA 90. In summary, the analytical framework described in this paper provides a useful tool to inform the policy debate about tradeoffs between the benefits of oil import and environmental protection.

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