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Assessing the Environmental Performance of Tankers in Accidental Grounding and Collision

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ABSTRACT

Current regulatory methods for predicting tanker performance in accidental grounding and collision do not properly consider environmental risk or account for variations in ship structural design. This paper investigates alternatives for a tanker environmental risk index, and proposes a performance assessment methodology which includes methods for estimating damage extents based on ship structural design and accident scenario probabilities. This methodology is used to assess the environmental performance of representative single hull, double hull and mid-deck tankers.

1 INTRODUCTION

The International Maritime Organization (IMO) "Interim Guidelines for the Approval of Alternative Methods of Design and Construction of Oil Tankers Under Regulation 13F(5) of Annex I of MARPOL 73/78" [1], hereunder referred to as the Guidelines, provide a probabilistic method to compute oil outflow in accidental grounding and collision. The Guidelines use probability density functions (pdfs) to describe extents of damage. They also define a "pollution prevention index" to compare alternative tanker designs to a series of "reference" double hull tankers.

The IMO methodology considers the effect of subdivision on oil outflow, but does not account for the ability of a particular structural design to minimize cargo loss. Specific deficiencies in the IMO Guidelines include:

- A single set of damage extent pdfs derived from limited single hull tanker data are applied to all ships independent of structural design. These pdfs are based on a statistical analysis conducted by Lloyd's Register in support of the IMO Comparative Study on Tanker Design [2,3].
- The IMO damage extent pdfs only consider data where the outer hull is ruptured. They are conditional on grounding or collision and hull rupture, but do not explicitly calculate and apply the probability of hull rupture. This penalizes structural designs which are better able to resist rupture.
- Damage extents are defined using independent random variables when significant interdependence may exist between these variables.
- Damage extents are normalized with respect to ship length, breadth and depth when they may depend as much on local structural scantlings as on global ship dimensions.
- The IMO "pollution prevention index" is not based on a rational definition of risk.

To correct these deficiencies, this paper proposes a probabilistic methodology for evaluating the environmental risk of tankers using theoretical models to predict damage extents rather than historical data. It also proposes to use the mean outflow parameter (mean outflow divided by cargo capacity) as the best single outflow risk index until sufficient cost data can be collected to calculate mean outflow cost.

The original plan for this research was to develop a set of damage extent pdf equations and/or tables which depend on ship structural design [4,5]. This would enable the use of the "Simplified" method developed by the SNAME Ad Hoc Panel on the Environmental Performance of Tankers to calculate oil outflow [5]. Given the wide variety of potential global and local structural design parameters, this plan was temporarily abandoned in favor of a more general approach using a standard set of scenario pdfs and a Monte Carlo simulation with grounding and collision models to develop damage cases and damage case probabilities. Once the relationship of damage extents to structural design is better understood, the use of equations and the "Simplified" method will be revisited.

The initial step in this research is to develop and calibrate a set of standard scenario pdfs. This is a one time process, and is not part of the proposed regulatory methodology. Once approved by IMO, the standard scenarios could be specified in the regulation for estimating damage extents. In this research the program *DAMAGE* [6,7] is used to predict bottom damage extents following a grounding, and a modified-Minorsky method is used to predict side damage in collision [8]. Scenario pdfs are calibrated by matching damage extent pdfs predicted by the models to the IMO pdfs.

Once the standard scenario pdfs are developed, the proposed regulatory methodology would be as follows:

- Apply the standard scenario pdfs (specified in the regulation) in a Monte Carlo simulation to a specific ship design using damage models approved by the IMO, classification societies or cognizant administration. Develop damage cases and damage case probabilities.
- Calculate oil outflow for each damage case as specified in the current IMO Guidelines. See Section 2, Step 2 in this paper. Damage pdfs are not required or used.
- Calculate the mean outflow parameter. See Section 2, Step 3 in this paper.
- Evaluate environmental risk. Compare the mean outflow parameter to required values that vary as a function of cargo capacity.

As an initial demonstration of the proposed methodology, it is applied to a notional single hull tanker, a series of double hull tankers and an intermediate oil-tight deck tanker of comparable size designed for this research. These designs are described in Section 4. Structural scantlings are varied in the double hull tanker series to evaluate their effect on oil outflow.

2 IMO GUIDELINES - PROBABILISTIC OIL OUTFLOW CALCULATION

There are four main steps in the IMO Guidelines methodology [1]:

Step 1: Assemble Damage Cases

Application of the IMO damage extent pdfs to the ship's subdivision provides the probability of occurrence for a series of damage cases. The IMO Guidelines provide pdfs describing the location, extent and penetration of side and bottom damage. The locations and extents are normalized by the ship length for longitudinal location and extent, by ship breadth for transverse location and extent, and by ship depth for vertical location and extent. The pdf variables are treated independently for lack of adequate data to define their dependency. Figure 1 illustrates the IMO probability density function for the longitudinal extent of damage in grounding. The histogram represents statistical data collected by the classification societies [2,3] and the linear plot represents IMO's piece-wise linear fit of the data. The other pdfs are constructed in a similar manner.

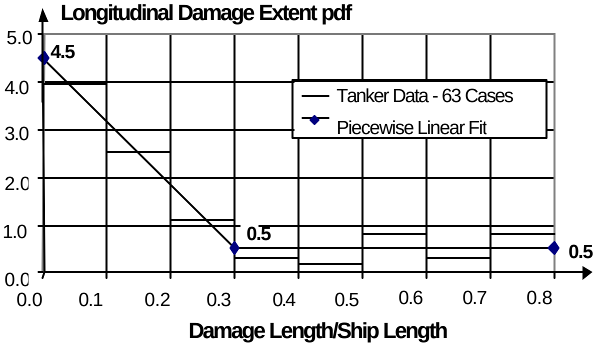


Figure 1. Damage probability density function (pdf)

Step 2: Calculate Oil Outflow

The next step is to compute the oil outflow associated with each unique side damage and bottom damage case. For side damage, total (100%) outflow is assumed for each damaged cargo tank. For bottom damage, oil loss is calculated based on pressure balance principles for tide reductions of 0, 2 and 6 meters. The following assumptions apply when calculating the oil outflow due to bottom damage:

- An inert gas pressure of 0.05 bar.
- The flooded volume of double bottom ballast tanks or voids located below ruptured cargo tanks retain up to 50% oil by volume.
- Ruptured cargo tanks which bound the outer shell have a minimum outflow of 1% of the cargo tank volume. This is intended to account for the expected oil loss at initial impact and through dynamic effects such as currents and waves.

By assigning an outflow value to each damage case, sufficient data exists to construct an outflow pdf from which global outflow parameters may be calculated.

Step 3: Calculate Oil Outflow Parameters

Three outflow parameters are computed:

- The *probability of zero outflow*, P_0, represents the likelihood that no oil will be released into the environment. P_0 equals the cumulative probability of all damage cases with no outflow.
- The *mean outflow parameter*, O_M, is the non-dimensionalized mean or expected outflow. The mean outflow equals the sum of the products of each damage case probability and their associated outflow. O_M equals the mean outflow, μ, divided by the total quantity of cargo oil onboard the vessel.

- The *extreme outflow parameter*, O_E, is the non-dimensionalized extreme outflow, and provides an indication of the expected oil outflow from particularly severe casualties. Extreme outflow is the mean of the largest 10% of all cases (i.e. all damage cases with outflow within the cumulative probability range from 0.9 to 1.0).

The bottom damage outflow parameters for the 0, 2 and 6 meter tides are combined in the ratio of 0.4: 0.5: 0.1 respectively. Collision (side damage) and stranding (bottom damage) parameters are then combined in a ratio of 0.4: 0.6. In this way, overall values for P_0, O_M, and O_E are obtained.

Step 4: Compute the Pollution Prevention Index "E"

Alternative designs are compared to reference double hull designs by substituting the outflow parameters for the appropriate reference design and the alternative design into the following formula:

$$E = \frac{(0.5)(P_O)}{P_{OR}} + \frac{(0.4)(0.01 + O_{MR})}{0.01 + O_M} + \frac{(0.1)(0.025 + O_{ER})}{0.025 + O_E} \quad (1)$$

P_0, O_M, and O_E are the oil outflow parameters for the alternative design, and P_{0R}, O_{MR}, and O_{ER} are the oil outflow parameters for the IMO reference ship of equivalent size.

Development of the formula for "E" was an item of considerable discussion at IMO. It was recognized that the weighing factors for the outflow parameters should have a rational basis associated with the benefits of avoiding spills, and the relative financial and environmental impacts of smaller spills as compared to larger spills. However, IMO was unable to obtain such information, and it was necessary to develop "E" in a more arbitrary manner. Specifically, outflow calculations were carried out for a number of double hull tanker and mid-deck concept designs, all of which satisfied the requirements of the new MARPOL 13F regulations. The weighing factors were then selected to assure that the double hull and mid-deck concepts, both of which were considered acceptable by IMO, would be in conformance with the guidelines.

3 METHODOLOGY & MODEL DEVELOPMENT

In the proposed regulatory application of this methodology, administrations or classification societies would select and validate their own models for predicting damage given the standard scenario pdfs specified by IMO. Sufficient real data does not exist to predict damage extents empirically as a function of ship structural design. Model testing supports only one accident scenario per model, and constructing models is both time consuming and expensive. Analytical methods are required to define the probabilistic relationship between structural design and damage extents. These methods must be sensitive to at least the basic parameters defining unique structural designs while maintaining sufficient generality and simplicity to be applied by working engineers in a regulatory context for various designs in worldwide operation. They must evaluate thousands of damage cases required for a probabilistic analysis with reasonable speed. They must predict hull rupture, and should correct the scaling and statistical independence problems inherent in the IMO Guidelines.

Finite element methods (FEMs) are too time intensive, both in model definition and computation, for this application. "First principles" methods provide reasonable results in laboratory experiments, but have received only limited validation in real accidents. For this research, the simulation uses the program *DAMAGE* [6,7] to predict bottom damage in grounding, and a modified-Minorsky method to predict side damage in collision [8] as described in the following sections. *DAMAGE* uses "first principles" methods. The modified-Minorsky method combines the application of limited empirical data with some "first principles" analysis.

3.1 Extents of Damage in Grounding

In order to consider the effect of structural design or crash-worthiness on damage extents, it is necessary to model the interaction between local structural damage and global ship motion. The variety of structural details and potential accident scenarios makes this difficult. For predicting grounding damage, work by Wang, Ohtsubo and Liu [9], Ohtsubo and Wang [10], and Little, Pippenger and Simonsen [6] were considered. The computational model *DAMAGE* [6], developed at MIT by Professor Tomasz Wierzbicki under the Joint MIT-Industry Project on Tanker Safety provides the most mature and complete analysis of the grounding problem to date with some recent limited validation.

Recent efforts to validate *DAMAGE* indicate satisfactory accuracy with small and large scale model tests. In four 1:5 scale tests conducted by the Naval Surface Warfare Center, Carderock Division, *DAMAGE* demonstrates less than 10% error in energy absorption and similar error in predicting penetration to fracture of the inner shell. In three large scale tests conducted by the Association for Structural Improvement of Shipbuilding (ASIS), *DAMAGE* demonstrates similar degrees of accuracy in predicting horizontal forces and longitudinal length of damage. Instantaneous vertical penetration forces measured in these tests are not predicted well, indicating that the model for external dynamics should be modified to consider inertial effects. Steady state and mean vertical forces are predicted with accuracy similar to that for the horizontal forces.

The grounding scenario required as input is defined by a set of parameters that establish the initial conditions of the grounding event. *DAMAGE* then determines damage extents. The parameters defining the initial conditions are called "scenario inputs". They are determined by randomly selecting discrete values for each parameter using a pdf that describes the range and variability of that parameter. The scenario inputs for grounding are:

- Ship speed
- Ship trim angle
- Rock eccentricity (non-dimensional distance from the ship centerline)
- Rock elevation
- Rock tip radius
- Rock cone angle

The pdfs describing the range and variation for these scenario inputs are presented in Section 3.3.

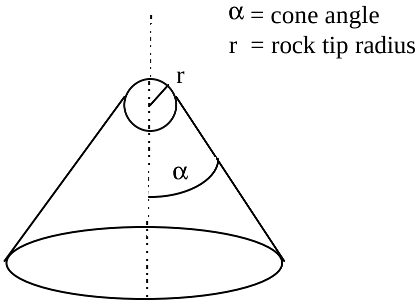


Figure 2. Rock Characteristics

One of the most difficult aspects of the MIT Tanker Safety Project was defining a "typical" grounding rock. There are an infinite number of possible rock shapes and reef formations. During the first two years of the project, the primary focus of research was on a sharp vertical wedge-type rock. As the project progressed, a more general type of grounding obstacle was necessary. A cone-shaped rock with varying cone apex angle and tip radius as shown in Figure 2 was selected. In this research, the rock is described using scenario input pdfs for cone angle and tip radius. Scenario pdfs are calibrated to best match predicted damage to the damage specified in the IMO damage pdfs. This obstacle is not intended to represent a real rock, but is a notional rock intended to give real results.

The primary mechanisms of energy dissipation in the rock grounding case are:

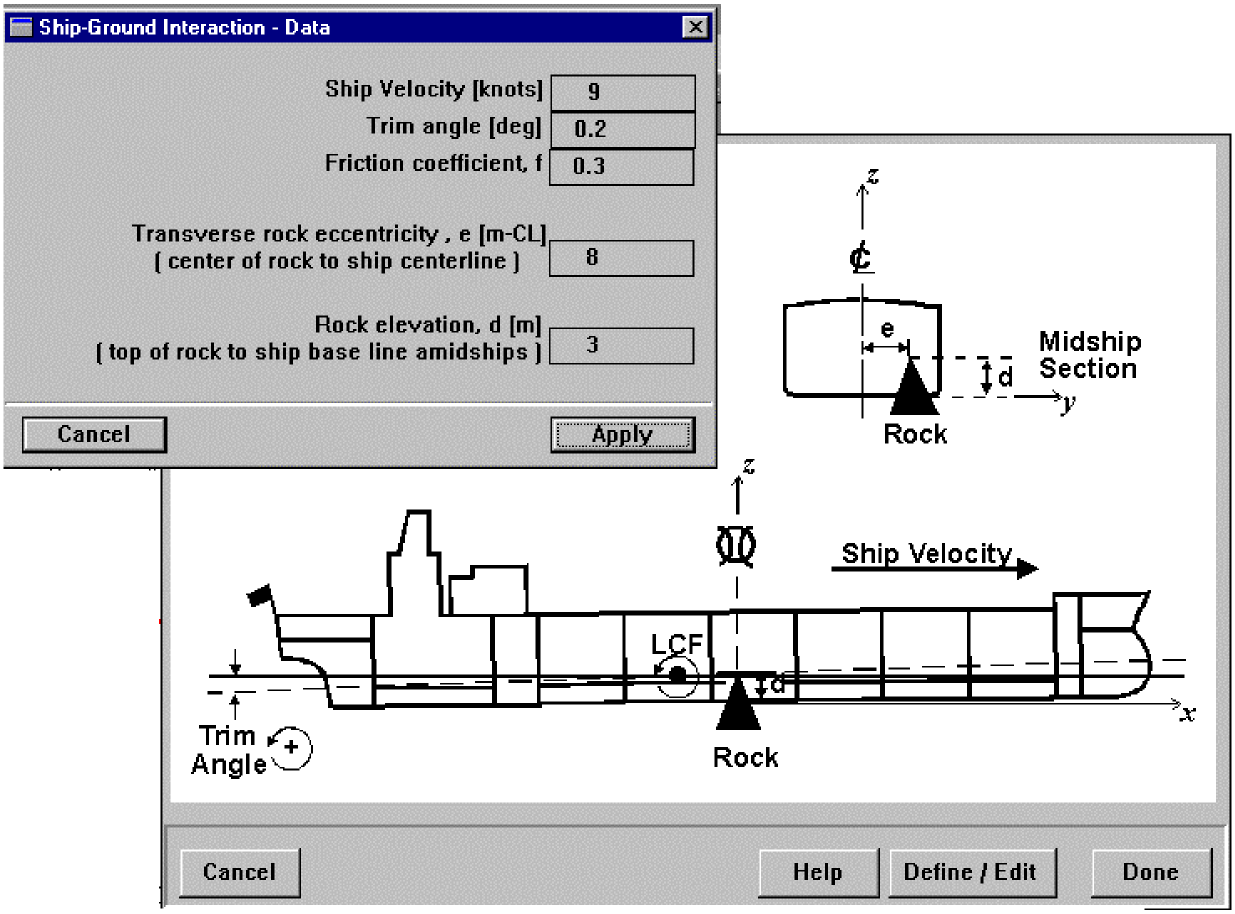
- A change in potential energy of the ship and surrounding water.
- Friction between the ground and hull.
- Deformation and fracture of the hull.

Initially, the ship is assumed to be on a straight course with a known velocity and trim. The rock is narrow compared with the beam of the ship. It is located at some distance, the rock eccentricity, to port or starboard of the ship's centerline, and reaches some height, the rock elevation, above the ship's baseline. During grounding, the grounding reaction induces heave, roll and pitch motion on the ship, and eventually causes the ship to stop. This motion is accompanied by large plastic deformation without fracture. As the rock approaches midship, the force becomes larger, and eventually the shell plating may rupture. First principles of mechanics and plasticity theory, without strong dependence on empirical relations, are used to predict damage forces and extents. The two basic damage mechanisms modeled are superfolding and supertearing. Damage forces and extents at any timestep are calculated in a closed-form solution.

DAMAGE models the grounding event as a series of stepwise incremental displacements resulting from the rock's interaction with the ship structure and global ship motion. At each step, the rock's penetration and resulting reaction force are calculated. Static equilibrium of global ship forces and local damage forces is assumed. This timestepping proceeds until the forward motion of the ship is stopped. When the calculation is complete, the heave, pitch, rock penetration, structural reaction force and plating status (rupture/no rupture) are known at each step.

DAMAGE is a Windows-based program that uses the graphical user interface capabilities of the personal computer as shown in Figure 3. Required input parameters are individually entered through a series of menu boxes and window dialogs. This configuration allows quick and simple input of model data, but makes repeated runs difficult as multiple dialog boxes must be accessed to alter the desired input parameters for each data run. A software testing program called *HighTest*, developed by Vermont Creative Software, is used to execute the batch runs without operator intervention. Input parameters are read from a prepared text file, substituted into the correct menu screen, and the calculations are completed. Output is then transferred from the standard screen outputs into an output file, where calculations on the data can be completed using other numerical analysis software.

The damage for each discrete grounding case is described using four *DAMAGE* outputs. These are the



Ship-Ground Interaction - Data

Ship Velocity [knots] 9

Trim angle [deg] 0.2

Friction coefficient, f 0.3

Transverse rock eccentricity , e [m-CL] (center of rock to ship centerline) 8

Rock elevation, d [m] (top of rock to ship base line amidships) 3

Figure 3. ***DAMAGE*** **User Interface**

longitudinal location of rupture start and end, the maximum rock penetration, and the maximum transverse width of damage. These outputs are used to describe the damage consistent with the probability density functions defined in the IMO Guidelines.

3.2 Extent of Damage in Collision

A thorough review of collision research and design methodologies was conducted by the Ship Structures Committee [11]. They concluded that the most promising simplified analysis alternative was to extend Minorsky's original analysis of high-energy collisions by including consideration of shell membrane energy absorption. This is the approach taken here.

V.U. Minorsky conducted the first and best known of the empirical collision studies [12]. His method relates the energy dissipated in a collision event to the volume of damaged structure. Actual collisions in which the ship speeds, collision angle, and extents of damage are known were used to empirically determine a proportionality constant. This constant relates damage volume to energy dissipation. In the original analysis the collision is assumed to be totally inelastic, and motion is limited to a single degree of freedom. Under these assumptions, a closed form solution for damaged volume can be obtained.

In order to support a probabilistic treatment of the collision process which includes a range of scenarios, the Minorsky method is generalized to allow three degrees of freedom (motion in the *x-y* plane, and yaw) for both the striking ship and the struck ship as shown in Figure 4. In this generalization, the final states of the ship velocities and relative positions cannot be determined by a simple closed form solution. Instead, a time-domain simulation is used to step through the collision process. In each small time step, the forces resulting from the collision are calculated, and the corresponding accelerations are used to update the ship velocities. These new velocities are used to determine the relative motions and resulting forces for the next time step. This process continues until the relative motions at the point of collision are sufficiently small to consider the collision process complete. The time domain process is illustrated in Figure 5.

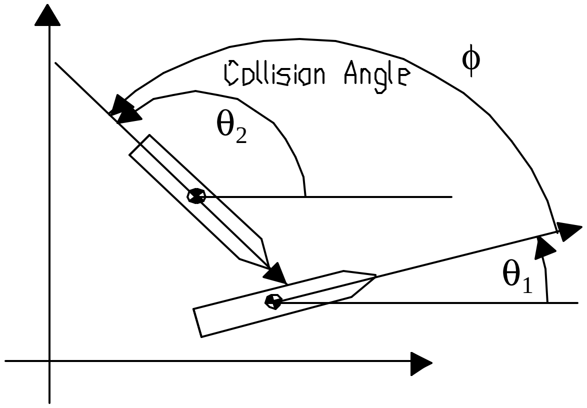


Figure 4. Collision Scenario Geometry

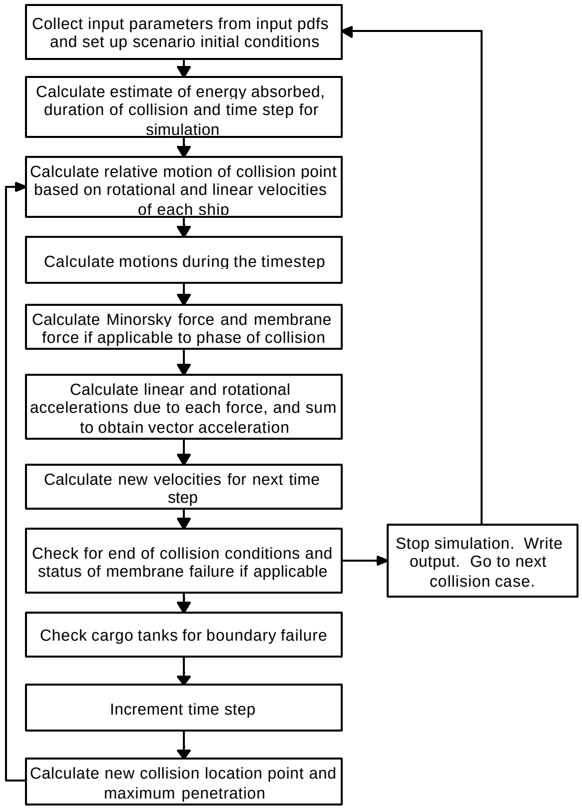


Figure 5. Collision Time Domain Model Process

During the collision, forces are developed through two separate mechanisms. In high energy collisions, the most significant of these is the force associated with plastic deformation of the decks, bottom and inner bottom. This is the force described by Minorsky [12], and further developed by Hutchison [13] and Reardon and Sprung [14]. By assuming that the impinging structure is rigid and of triangular shape, the depth of penetration in each time step can be related to both a decrement of kinetic energy, and a resultant force. This force is considered to act in a direction opposite that of the relative motion between the ships during the time step. In addition to scenario pdf's, a particular value of the Minorsky resistance coefficient is selected for each damage case from a pdf based on reference [14].

The second force is from the resistance of the shell of the struck ship to puncture and tearing. Jones developed an approach to estimate this resistance, which was later extended by Van Mater [11]. This approach treats the shell plate as a broad thin column, pinned at both ends, and provides a closed form solution to calculate the energy stored in the membrane for a given deflection, as well as a method to estimate the deflection at which fracture occurs. In this analysis, this membrane force is calculated for each time step until rupture occurs, and is considered to be zero thereafter. Whether or not membrane deflection reaches the point of expected fracture also indicates whether hull rupture occurs during a particular collision event. For double-hull ships, the same membrane force analysis is carried out for both the inner and outer hulls.

As with grounding, each collision scenario is defined by a set of scenario inputs which are determined by randomly selecting discrete parameter values using a pdf that describes the range and variability of that parameter. The scenario inputs for collision are:

- speed (independently chosen for each ship)
- collision angle
- bow entrance angle (for the striking ship)
- Minorsky energy coefficient
- initial collision contact point
- striking ship mass

The pdfs describing the range and variation for these scenario inputs are presented in Section 3.3.

3.3 Standard Accident Scenario Probability Density Functions (pdfs)

Scenario pdfs are estimated based on limited data, rational argument, expert opinion and sensitivity analysis. Once initial scenario pdfs are established, they are calibrated and refined.

Ship velocity is modeled using a bi-modal normal distribution, centered around a five knot maneuvering speed and a 10 knot cruising speed. Maximum speed is 14 knots and minimum speed is two knots. The standard deviation for both curves is one knot. The area under each bell curve is assumed to be equal, which implies that grounding is equally likely to occur in a maneuvering scenario or a transit scenario. This pdf is used for ship velocity in grounding and both struck and striking ship velocities in collision. Figure 6 shows the specified velocity pdf and a histogram representing bins of velocity values chosen in the simulation. A total of 6000 damage cases are represented in this histogram.

Ship trim is modeled using a uniform distribution with a range of -1 degree to +1 degree. Any discrete value of trim within this range is equally likely. An attempt was made to estimate trim over a typical route, but informal feedback from tanker operators indicates that a uniform distribution is more reasonable. Figure 7 shows the trim pdf and simulation histogram.

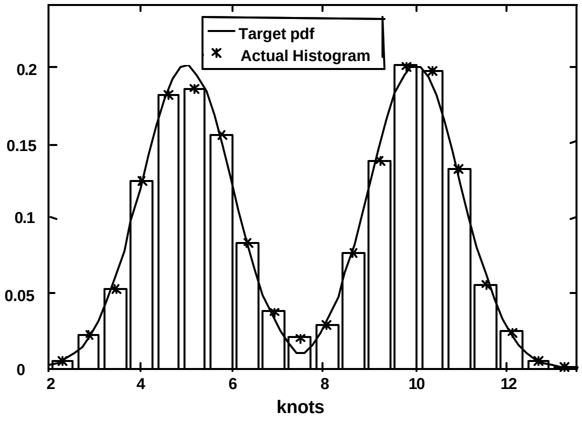


Figure 6. Input Scenario - Ship Velocity pdf

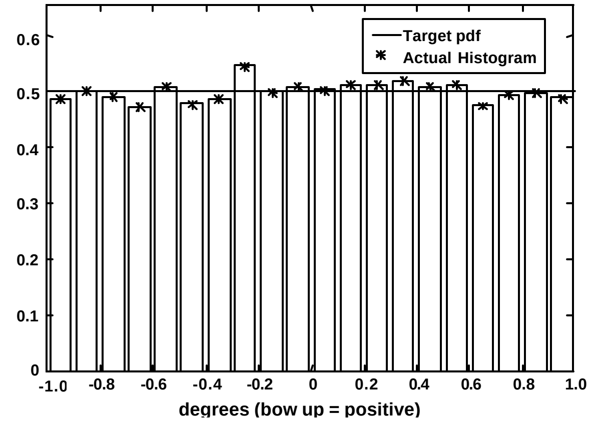


Figure 7. Input Scenario – Ship Trim pdf

The location of the obstruction or rock is defined using two parameters, eccentricity and elevation. Eccentricity or the non-dimensional distance from the ship centerline (2d/Beam) is modeled using a uniform distribution with a range of zero (centerline) to one (half beam). This is consistent with the IMO pdf for transverse location of bottom damage. Figure 8 shows the rock eccentricity pdf and simulation histogram. Rock elevation or non-dimensional height above baseline (h/Depth) is modeled using a linearly decreasing pdf from the baseline up to some maximum height below the waterline. Elevations below the baseline do not cause grounding. Elevations above the waterline are visible obstructions. The final value chosen for maximum non-dimensional height was 0.2. This value was determined by calibration to the IMO pdfs. Figure 9 shows the rock elevation pdf and simulation histogram.

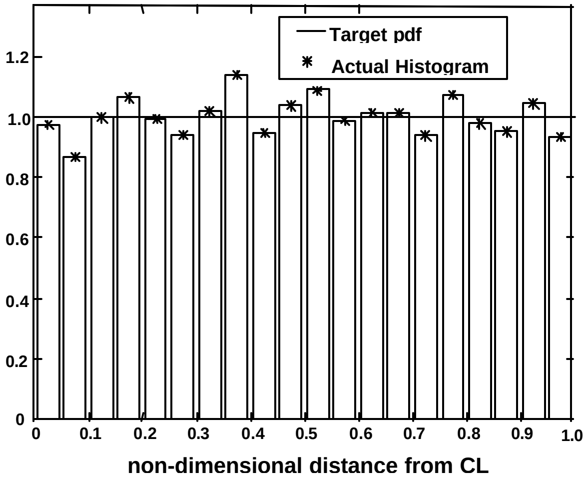


Figure 8. Input Scenario – Rock Eccentricity pdf

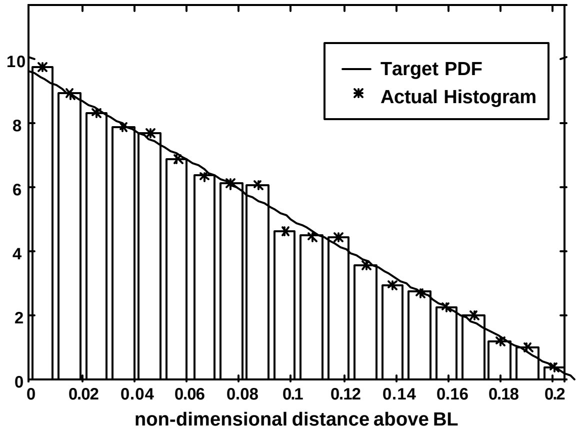


Figure 9. Input Scenario – Rock Elevation

The shape of the rock is described using two variables discussed previously, rock cone side angle and rock tip radius. Pdfs for both of these parameters are modeled using a normal distribution. Rock cone side angle has an upper bound of approximately 55 degrees determined by the limits of the model. The mean value for cone side angle is taken to be half this upper bound or 27.5 degrees with a standard deviation of 3 degrees. Figure 10 shows the side angle pdf and simulation histogram. The mean value chosen for cone tip radius is 5 meters with a standard deviation of 3 meters. This value is determined by calibration to the IMO pdfs. Figure 11 shows the tip radius pdf and simulation histogram.

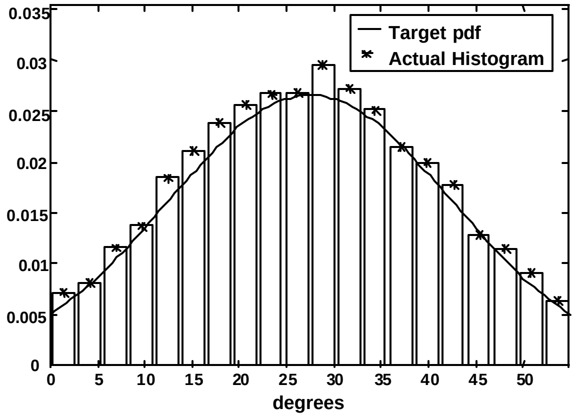


Figure 10. Input Scenario-Rock Cone Side Angle

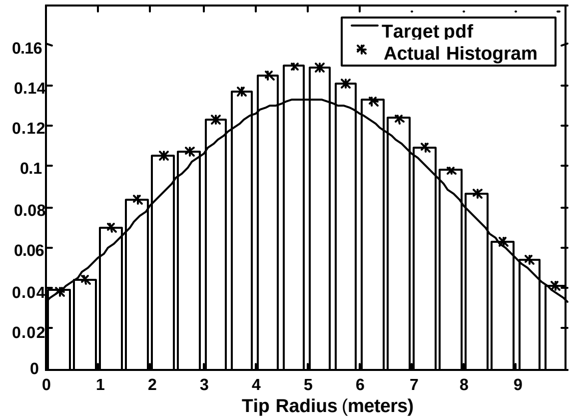


Figure 11. Input scenario - Rock Tip Radius

Collision angle is the angle of incidence between the colliding ships at the moment of impact. Refer to Figure 4. Collision angle is modeled using a uniform distribution with a range of zero to 180 degrees. This distribution is very dependent on the waterway transit geometry. The uniform distribution represents a compromise for a generic tanker in worldwide trade. Collisions occurring at a relative angle of zero degrees are constrained to have an initial impact point at the bow of the struck ship. Collisions occurring at a relative angle of 180 degrees are constrained to have an impact point at the stern, and are only allowed if the striking ship's speed exceeds the struck vessel's speed. Figure 12 shows the collision angle pdf and simulation histogram.

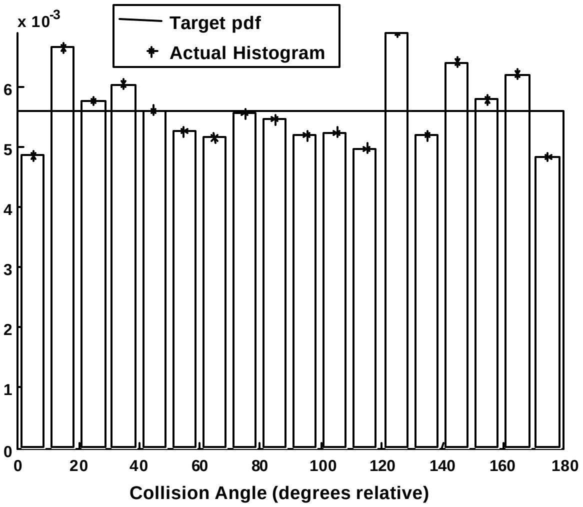


Figure 12. Input scenario – Collision Angle

The point on the struck ship where the striking ship's bow initially makes contact is the impact point. Impact point location is modeled using a uniform distribution with a range from bow to stern. This location is also waterway dependent, and the uniform distribution represents a compromise for worldwide trade. Figure 13 shows the impact point pdf and simulation histogram.

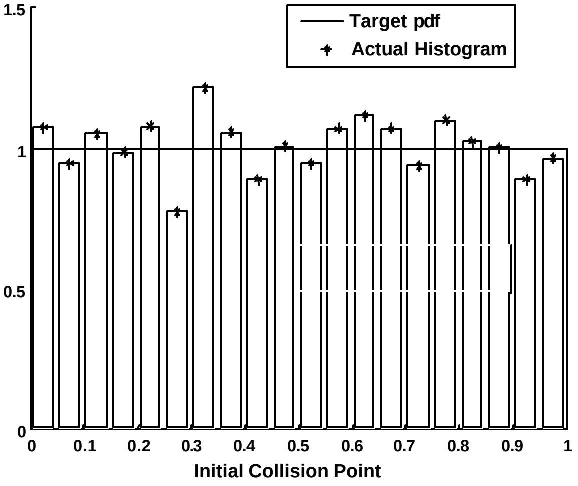


Figure 13. Input scenario – Collision Impact Point

The bow shape of the striking ship is important because it determines the volume of structure damaged during the collision. In this analysis, the shape of the striking ship's bow is idealized as a triangle, with no rake. The bow half-entrance angle is modeled using a normal distribution with a mean value of 38 degrees and standard deviation of 5 degrees. This distribution is based on data presented in [14] and [15] and adjustments made during pdf calibration. Figure 14 shows the bow half-entrance angle pdf and simulation histogram.

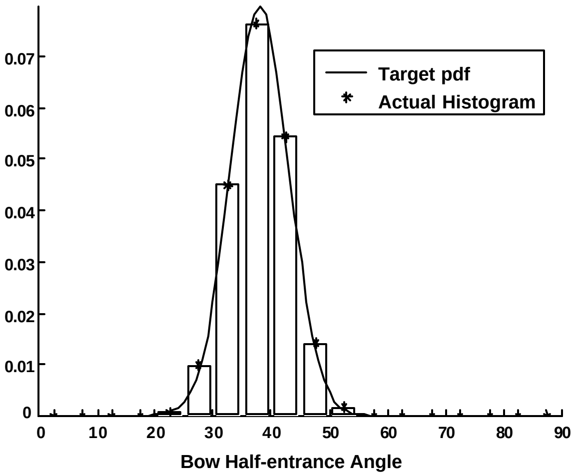


Figure 14. Scenario–Bow Half-Entrance Angle

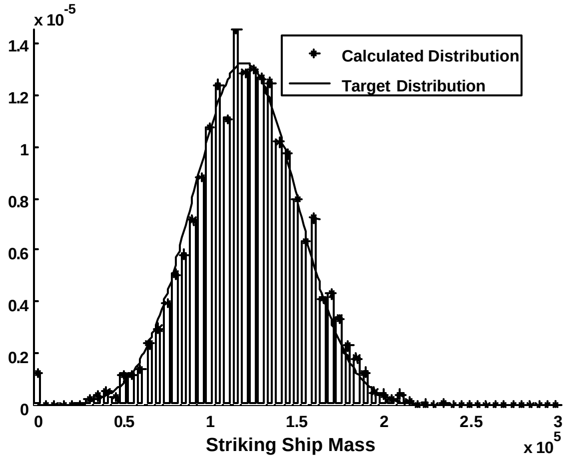


Figure 15. Scenario–Striking Ship Displacement

The striking ship displacement is modeled using a normal distribution with a mean value of 120,000 metric tons, and a standard deviation of 50,000 metric tons. The choice for this distribution is based on data from [16], and adjusted in the calibration process. A common approach to this problem is to assume that the striking ship and the struck ship are identical in all respects. This is based on the assumption that "like ships" travel the same waterways (being engaged in the same trade), and are therefore more likely to have collisions. This approach is not used in this analysis based on the recommendation of tanker operators in the MIT Tanker Safety Project. Figure 15 shows the striking ship displacement pdf and simulation histogram.

For each collision scenario, a particular value is selected for the Minorsky constant which defines the relationship between energy absorption and volume of damaged structure. A pdf is also used to describe this parameter. The Minorsky constant pdf is modeled using a normal distribution with a mean of 47.1 MJ/m3 and standard deviation of 8.8 MJ/m3. This distribution is based on a validation of Minorsky's original work by Reardon and Sprung [14], including the addition of new data points from collisions that have occurred since Minorsky's work in 1959.

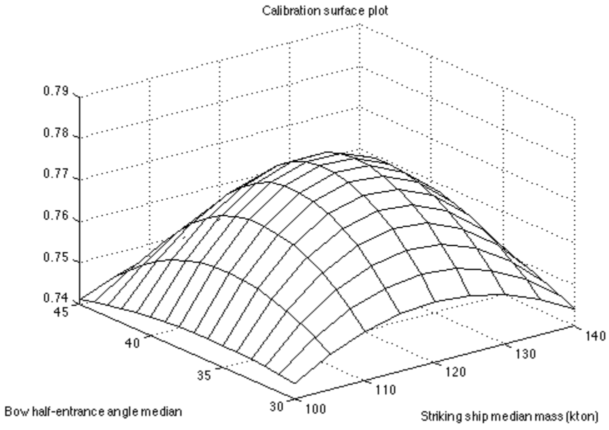


Figure 16. Scenario pdf Calibration Surface

Once initial scenario pdfs are established, they are calibrated and refined by using them to predict damage extents for a representative single hull MARPOL tanker, and modifying them to best match the predicted damage extents to the damage pdfs specified in the IMO Guidelines. Since the IMO pdfs include only cases where the outer hull is ruptured, all non-rupture cases are removed from the predicted pdfs before comparison. A simple fit function is maximized for a matrix of grounding and collision scenario pdf alternatives. Figure 16 shows a two-parameter calibration surface for striking ship mass and bow half-entrance angle. A mean striking ship mass of 125000 mton and mean bow half-entrance angle of 38 degrees are chosen using this surface. The results of this calibration can also be seen by direct comparison of predicted damage pdfs and the IMO damage pdfs. A comparison for grounding length of damage is shown in Figure 17.

Generally, the damage extent pdf's for bottom damage predicted using the scenario pdf's matched well with the IMO damage pdfs. A notable exception is in the prediction for transverse extent of bottom damage. This comparison is shown in Figure 18. In this case, the simulation cannot account for damage extents as large as that seen in the class data since the width of damage is directly related to the width of the object impacted upon the vessel. A wide reef cannot currently be modeled with the *DAMAGE* obstruction geometry.

The collision pdf results are similar to the pdf's established by the IMO guidelines, except for a cluster of damage cases as the penetration approaches the inner longitudinal bulkhead. This can be seen in Figure 26 and is discussed in Section 6.1.

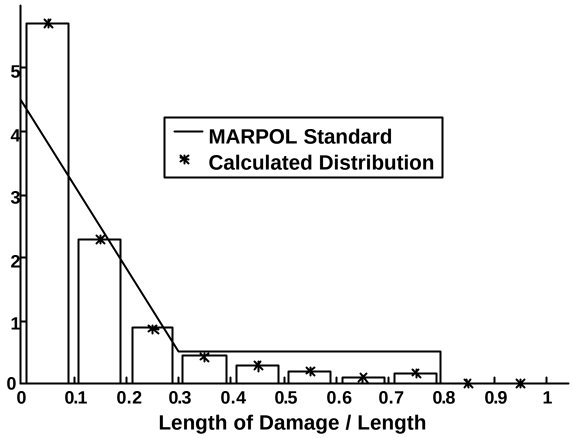


Figure 17. Grounding Length of Damage

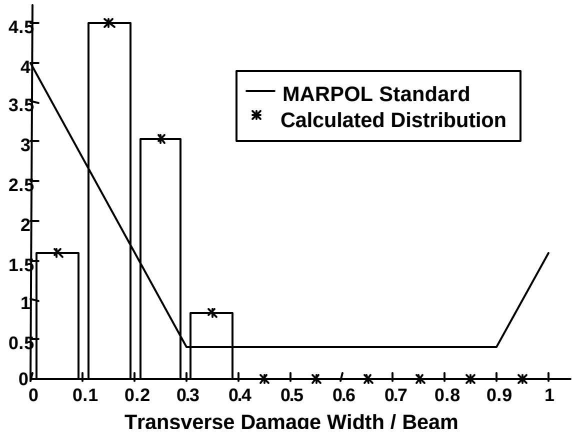


Figure 18. Grounding Transverse Damage

4 TANKER DESIGNS

A family of notional tankers is used to calibrate the input scenario pdfs and estimate the effect of structural enhancements on crashworthiness. The tankers include a MARPOL single hull tanker, a baseline double hull tanker, five double hull tanker variants, and an intermediate oil-tight deck (IOTD or mid-deck) tanker, all of Suezmax (150,000 dwt) dimensions. The single hull tanker (5x3 tank arrangement) is designed consistent in material and configuration with vessels in service between 1980 and 1990, the period included in the data compiled by the classification societies to generate the current IMO damage pdf's. This design is used to calibrate the scenario probability density functions by matching the calculated damage extent density functions to the density functions provided in the Guidelines. The double hull (6x3 tank arrangement) and IOTD (6x2 over 6x1 tank arrangement) tankers are designed using current shipbuilding practices and used to compare structural design alternatives.

Table 1 - Tanker Principal Characteristics

LBP	264 m
Beam	48 m
Depth (at Deck Edge)	24 m
Draft (Full Load)	16.8 m
Deadweight	150,000 mton
Cargo Volume	167,000 m^3
Displacement	178,000 mton

Table 2 - Tanker Structural Parameters

Hull ID	Plate Thickness	Stiffener Size	Stiffener Spacing	Frame Spacing
DH01	NGT 120% minimum req'd	NGT twice required stiffener SM	0.8 m	4.7 m
DH02	150 % of DH01 thickness	NGT twice required stiffener SM	0.8 m	4.7 m
DH03	NGT 120% minimum req'd	150% DH01 Stiffener SM	0.8 m	4.7 m
DH04	NGT 120% minimum req'd	NGT twice required stiffener SM	0.6 m	4.7 m
DH05	Same as DH01	Same as DH01	0.8 m	3.7 m
IOTD	NGT 120% minimum req'd	NGT twice required stiffener SM	0.8 m	4.7 m

All the tanker designs have the same principal characteristics as listed in Table 1, with bulkheads located to maintain equal cargo capacities and compliance with MARPOL Regulations for protective location of segregated ballast tanks, maximum tank volume and double hull dimensions. Scantlings are determined using the American Bureau of Shipping *SafeHull* system to ensure compliance with class rules for longitudinal and transverse member strength. Midship sections for the double hull and IOTD tankers are shown in Figures 19 and 20.

The effect of structural enhancements on crashworthiness is studied using five separate double hull variants. Each variant is a derivative of the original, modified as shown in Table 2. For each new variant design, the remaining structural parameters are resized using *SafeHull* to ensure minimum compliance with class scantling requirements.

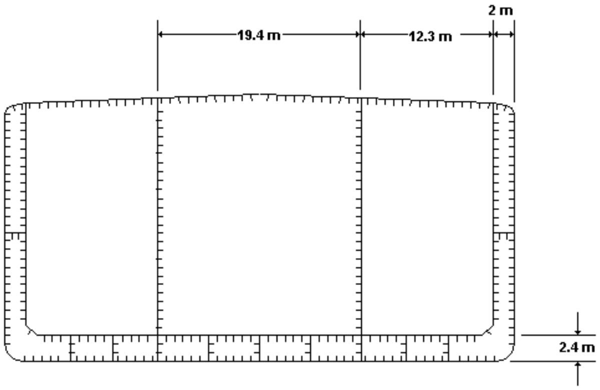


Figure 19. Double Hull Tanker Midship Section

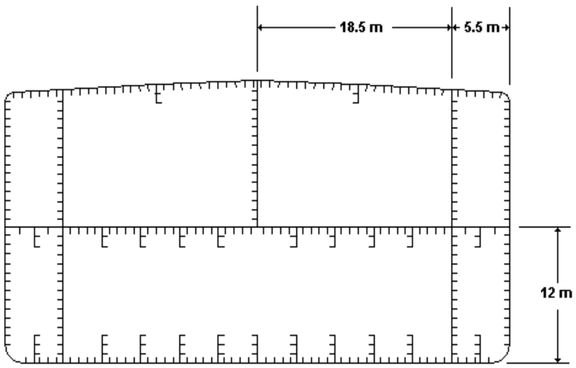


Figure 20. IOTD Tanker Midship Section

5 ENVIRONMENTAL RISK INDEX

The SNAME T&R Ad Hoc Panel on the Environmental Performance of Tankers [5] proposed using mean accident cost as the spill risk metric as shown in Equation 2:

$$\text{Mean Accident Cost} = \int_0^{Cap} p(Q)\,Cost(Q)\,dQ \qquad (2)$$

where: Cap = total ship oil capacity (m3)
Q = oil outflow (m3)
p(Q) = outflow pdf for specific ship
Cost(Q) = outflow cost ($M)

It was also demonstrated by the Ad Hoc Panel that a standard Rayleigh distribution provides an excellent fit to outflow pdfs. Using the probability of zero outflow, P_0, and the non-dimensional mean outflow given outflow, μ_x, the non-dimensional outflow given outflow pdf is:

$$p_x(x, P0, \mu_x) = (1 - P0)\,\frac{x}{A\,\mu_x^2}\cdot e^{\frac{-x^2}{2A\mu_x^2}} \qquad (3)$$

where: $A = 2/\pi$
x = non-dimensional outflow = Q/Cap
μ_x = non-dimensional mean outflow given that outflow has occurred = $O_M/(1-P_0)$

Applying this pdf to Equation 2, the mean accident cost can be expressed as a function of cargo capacity, mean outflow, P_0 and the outflow cost function:

$$\text{Mean Accident Cost} = \int_0^1 p_x(x, P_0, \mu_x)\,Cost(x{*}Cap)\,dx \qquad (4)$$

The lack of adequate cost information presents a fundamental problem in any effort to assemble an outflow cost function. This was a major conclusion in the Ad Hoc Panel's study. Three hypothetical outflow cost functions were used by the Ad Hoc Panel to illustrate the proposed framework. Comments on the Ad Hoc Panel paper and discussion at a subsequent workshop suggested a number of other cost function shapes and relative magnitudes. In order to evaluate the sensitivity of mean accident cost to the probability of zero outflow and mean outflow, isorisk (constant mean accident cost, Equation 4) curves are plotted as a function of P_0 and O_M for a range of cost functions and for the *SIMPLIFIED* pollution prevention index (E50) used by the Adhoc Panel. Figure 21 shows the unit or average cost curves representative of a sample of the cost functions considered. A number of these curves are discussed in the Adhoc Panel paper [5]. Figure 22 shows the corresponding cost isorisk curves and the E50 isorisk curve. Each of these isorisk curves is derived from a different cost function, and represents combinations of P_0 and O_M which give the same mean accident cost or environmental index value as the 145K dwt IMO reference tanker. All curves pass through the reference tanker values of P_{0R} and O_{MR}.

Referring to Figures 21 and 22. For constant and moderately increasing or decreasing unit spill cost with increasing spill size, the isorisk curves approximate a constant mean outflow curve equal to O_{MR} and independent of P_0. Isorisk curves corresponding with unit cost functions that increase steeply over the range of possible spill sizes have a negative slope as a function of P_0 which is opposite to the current IMO pollution index. For a given value of O_M, larger values of P_0 result in larger values of mean outflow given outflow, $\mu_x = O_M/(1-P_0)$ which pushes the outflow distribution to the right aligning with higher cost values. None of the cost functions considered result in an isorisk curve with a significant positive slope similar to that obtained using the current IMO pollution prevention index.

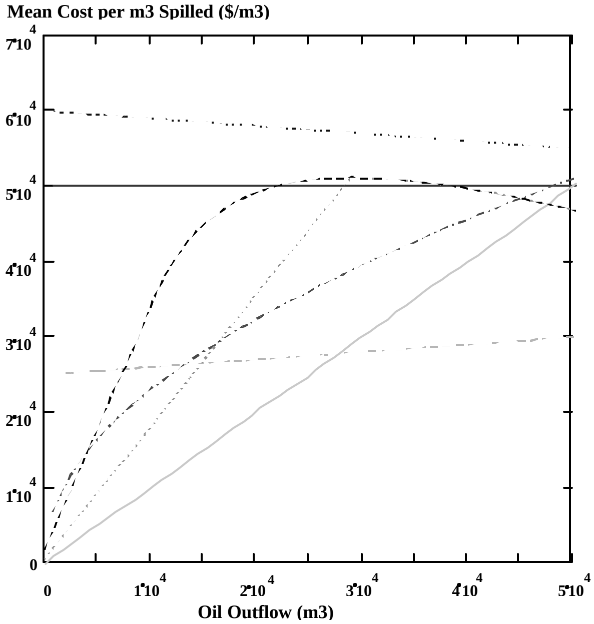


Figure 21. Hypothetical Unit Spill Cost Curves

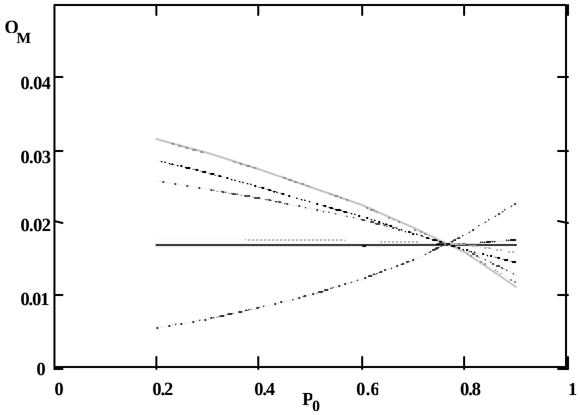


Figure 22. IsoRisk (Constant Mean Cost) Curves

There is insufficient data to define or select a particular cost function at this time, however, for a wide range of reasonable cost functions, mean outflow dominates the resulting risk. Based on this result, until data becomes available to define a single cost curve, the mean outflow parameter, O_M, is a more rational single metric for tanker risk than the current "pollution prevention index".

6 RESULTS

As an initial demonstration of the proposed methodology, it is applied to the single hull tanker, the series of double hull tankers and the intermediate oil-tight deck tanker described in Section 4.

6.1 Damage Extents

Figures 23, 24 and 25 compare the predicted bottom damage pdfs for the single hull, IOTD and baseline double hull designs. These pdfs include "no-rupture" cases, and should not be compared to the IMO pdfs.

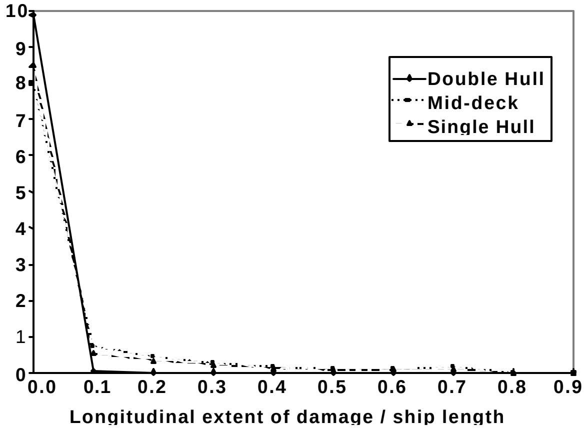


Figure 23. Grounding Length of Damage

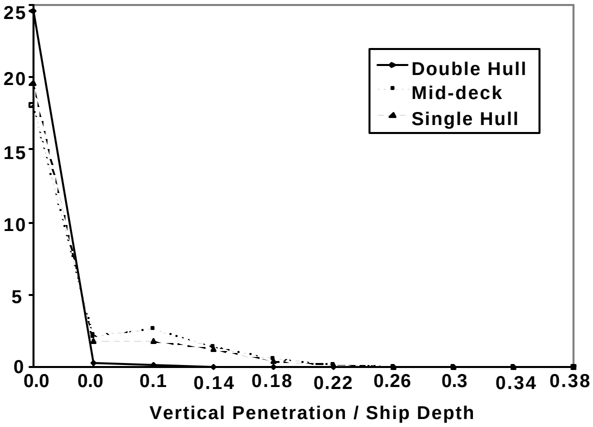


Figure 24. Grounding Vertical Penetration

The damage extents for the single hull and mid-deck designs are similar. The damage extents for the double hull design show a larger probability for small or no damage (no rupture). Damage length rarely exceeds 0.15L, vertical penetration rarely exceeds 0.06D, and transverse extent rarely exceeds 0.15B/2. The double hull is significantly more crash-worthy in bottom damage than the single hull design. This advantage is not considered in the current IMO Guidelines.

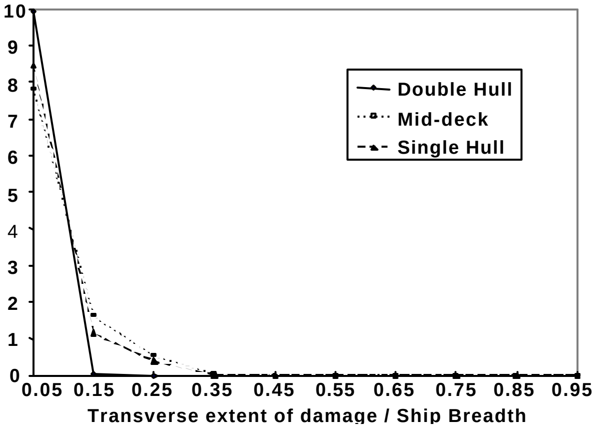


Figure 25. Grounding Transverse Damage Extent

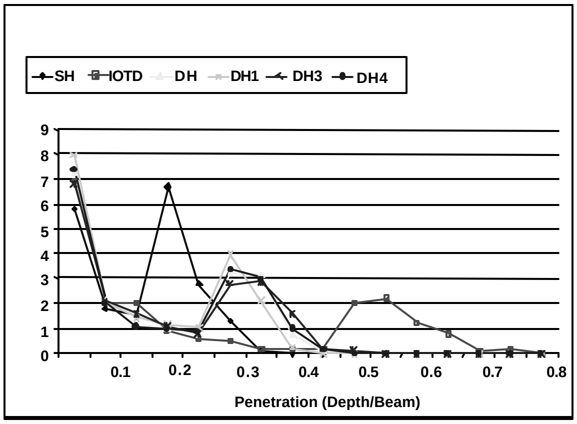


Figure 26. Collision Transverse Penetration

Figure 26 compares the predicted side transverse penetration pdfs for the single hull, IOTD and double hull designs. Figure 26 shows two main concentrations of transverse penetration for each design. There is a cluster of collisions that are halted or nearly halted by the shell of the ship. This is a consistent feature for all designs. There is second cluster of cases that are stopped by the next internal longitudinal bulkhead. The mid-deck ship has a third cluster at 0.5B, which corresponds to its centerline bulkhead.

Application of the IMO Guidelines assumes damage extents can be described using independent random variables. Because the IMO pdf's are developed from a limited set of data, it was impossible for IMO to include any kind of coupling between damage extents and still have enough cases to provide a valid statistical basis. One of the benefits of the method outlined in this paper is that once the models are validated, a sufficient number of cases can be run to provide this statistical basis, and the results can be analyzed to assess coupling.

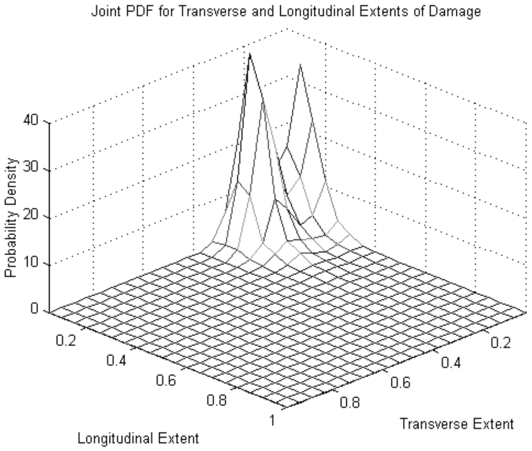


Figure 27. Joint Collision Damage Extent pdf

Figure 27 shows the joint pdf for transverse and longitudinal extent of damage in collision. The other joint damage pdfs are similar. By examining the pdfs for transverse extent at various cut-planes of constant longitudinal extent, it can be seen that the transverse extent pdf does vary as a function of longitudinal extent. The two parameters are coupled. Fortunately this coupling is only a problem in the current IMO method which assumes and uses independent damage extent pdf's. By by-passing the application of damage extent pdf's in the proposed methodology, the problem of damage extent dependency is avoided. Scenario pdf's may have some dependency between variables, but much less than damage extents resulting from a common accident.

Table 3. Grounding Oil Outflow Results

	P_0	O_M
Baseline Double Hull (DHull)	0.978	0.00073
DHull02 increased plating	0.983	0.00048
DHull03 increased stiffener size	0.979	0.00067
DHull04 decreased stiff. spacing	0.977	0.00077
DHull05 decreased frame spacing	0.979	0.00067
Intermediate oil-tight deck	0.722	0.00047
Single Hull	0.774	.01897

6.2 Oil Outflow

Table 3 compares oil outflow in grounding for the single hull, IOTD and double hull designs. These results reflect the damage extents presented in Section 6.1. They also reflect the subdivision and hydrostatic balance of the designs. The significant advantage due to hydrostatic balance in the IOTD design is nearly matched by the crash-worthiness of the double hull design. Using the IMO pdfs, double hull grounding oil outflow is usually closer to single hull results than IOTD results. By properly considering crash-worthiness, the double hull and the IOTD grounding mean outflow values are the same order of magnitude, and both are much smaller than their respective collision mean outflow values. The single hull grounding mean outflow is much larger than the double hull and IOTD designs, and the same order of magnitude as its collision mean outflow. This is an important result.

The high probability of zero grounding outflow in the double hull design indicates the protective resistance of the inner/outer hull combination. When the outer hull of the IOTD and single hull designs is ruptured, a minimum of one percent of the oil in affected tanks is lost. By including “zero-rupture” cases, P_0 is larger than in the IMO analysis for all designs, but particularly for the double hull design.

Table 4. Collision Oil Outflow Results

	P_0	O_M
Baseline Double Hull (DHull)	0.47	0.06
DHull02 increased plating	0.49	0.05
DHull03 increased stiffener size	0.47	0.06
DHull04 decreased stiff. spacing	0.45	0.06
DHull05 decreased frame spacing	0.45	0.05
Intermediate oil-tight deck	0.62	0.10
Single Hull	0.50	0.08

Collision outflow results are compared in Table 4. In collision, the double sides in the IOTD design and the protectively-located ballast tanks in the single hull design result in large P_0 values compared to the double hull designs. The mid-deck design has the highest probability of zero outflow, but also the highest mean outflow. The high mean outflow is very dependent on subdivision. Once the cargo boundary is breached, 75% of the oil in that cargo section is lost. Refer to Figure 20. This ship would have better performance if an intermediate oil-tight deck were combined with a more typical "three tank across" arrangement or a center line bulkhead in the lower tank. To explore this, the simulation was run again with a lower centerline bulkhead added to the design. P_0 remained constant at 62%, but mean outflow dropped from 10% to 8%. Although an improvement, this change also adds weight and cost to the IOTD design, and the outflow of any design can be improved by adding subdivision. The double hull designs have a lower P_0 in collision, due to the relatively small protective layer of their double-side, but have the lowest mean outflow because of their subdivision

The double hull designs all show similar performance in collision. The Dhull02 design with thicker shell, bottom and deck plating, shows the best performance within the double-hull group. This results from the heavier horizontal element volume (decks and bottom) increasing the Minorsky energy absorption, and the thicker side shell increasing the membrane resistance. The effect of stiffeners and frames is not captured in the collision model.

Table 5. Combined Oil Outflow Results

	P_0	O_M
Baseline Double Hull (DHull)	0.77	0.024
DHull02 increased plating	0.79	0.020
DHull03 increased stiffener size	0.77	0.024
DHull04 decreased stiff. spacing	0.77	0.025
DHull05 decreased frame spacing	0.77	0.020
Intermediate oil-tight deck	0.68	0.040
Single Hull	0.66	0.043

The combined mean outflow results shown in Table 5 are dominated by the relatively large outflow in collision for all designs. In this study, when the effects of structure, subdivision and hydrostatic pressure are all considered, the double hull designs provide superior mean outflow performance compared to IOTD and single hull designs. By considering the structural advantage of the double hull, double hull mean outflow in grounding is reduced to the same order of magnitude as the IOTD, and mean outflow in collision becomes the dominant contributor to combined mean outflow. These particular double hull designs are superior to the particular IOTD design considered in this research because they are nearly equivalent in grounding and have better performance in collision. Using the IMO damage pdfs which do not consider double hull crash-worthiness, the opposite result is obtained.

7 CONCLUSION

A probabilistic methodology for evaluating the environmental risk of tankers using theoretical models to predict damage extent is proposed and demonstrated. The mean outflow parameter is shown to be the best oil outflow risk index until sufficient cost data can be collected to calculate mean outflow cost.

The proposed methodology corrects the following deficiencies in the current IMO Guidelines:

- It considers the ship structural design in calculating extents of damage.
- By calculating damage extents directly, without the intermediate step of damage pdfs, it avoids the problems of random variable independence and scaling.
- It applies a rational definition of oil spill risk.

A very preliminary estimate of accident scenario pdfs is included in the proposed methodology. These pdfs are improved somewhat by calibration to current IMO damage pdfs.

Applying mean outflow to the assessment of alternative tanker designs without correcting the other deficiencies in the current Guidelines immediately upsets the delicate political balance between double hull designs and IOTD designs implicit in the current environmental index. By including the effect of structural design on damage extents and ultimately oil outflow, this research demonstrates that this balance can be rationally restored. Once valid performance-based criteria are in place, the problem becomes designing and selecting the most cost effective designs which provide an acceptable level of environmental risk.

No effort was made to optimize the environmental performance of the designs in this research, therefore no conclusions about the relative merit of the general design concepts should be made. However, it is interesting to note that once the effect of structural design is included in the evaluation of the double hull oil outflow, its grounding mean outflow is reduced to be two orders of magnitude less than the collision mean outflow as in the IOTD design. Collision damage extents and subdivision then become the dominant factors affecting tanker environmental performance. This emphasizes the importance of an accurate collision damage model and collision scenario pdfs.

8 FUTURE WORK

- Further refine and validate input scenario descriptions, especially those for collision.

- Reevaluate the 0.4:0.6 relative probability of collision to grounding.

- Evaluate other damage prediction models.

- Improve damage prediction models, particularly the collision model.

- Collect and organize more accident damage data. Validate the damage models.

- Increase the international effort to collect and synthesize cost data into a reliable cost function.

- Once more analysis has been completed, revisit the possibility of replacing the damage extent models with closed form parametric equations or tables. This would enable a “Simplified” oil outflow calculation.

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