Tanker Escort-Requirements, Assessments and Validation
Tanker Escort—Requirements, Assessments and Validation

Sridhar Jagannathan (M), David Gray (M), Thomas Mathai (V), The Glosten Associates, Inc., and Johann de Jong (V), Maritime Simulation Center Netherlands

ABSTRACT

Tanker escort practice varies throughout the world and is usually based on a local perception of need and adequacy that is rarely backed up with a rigorous analytical assessment or field trials. In the United States, the Oil Pollution Act of 1990 (OPA '90) has empowered the US Coast Guard (USCG) to set up new regulations for tanker escort, specifically in the waters of Prince William Sound and Puget Sound. State rules also exist such as for Puget Sound and San Francisco Bay to regulate tug escort of tankers. In this paper, the escort requirements of specific waterways are presented with special emphasis on escorting in Prince William Sound, San Francisco Bay and Puget Sound. A summary of escort practice in Europe is also provided.

Two methods for examining and specifying tanker escort requirements are detailed in this paper. The first method is an operations analysis strategy, that examines a specific escort practice such as a tanker-tug combination and determines the boundaries of its applicability. The procedures of this method are applied to the analysis of tanker escort on Prince William Sound. The second method is a systems analysis approach that is oriented towards a rule-making process. In this case the “demand” of a disabled tanker for tug assistance is quantified as a function of displacement, speed, weather and waterway constraints. The application of this methodology to San Francisco Bay is detailed. Both methods make extensive use of computer simulations for tanker maneuvering with tug assistance in a given climatology. A statistical procedure to define the geographical constraints of the waterway is introduced.

USCG rules for tanker escort on Prince William Sound and Puget Sound are reviewed and their interpretation and application discussed in relation to Puget Sound.

OIL TRANSPORT AND ESCORT PRACTICE

Over 600 million tons of crude oil and products are transported every year through US waters, corresponding to about one-third of worldwide annual shipments. Figure 1 shows transport of petroleum (for 1988) categorized by major ports in the US. It can be seen that the ports of New York and Valdez account for almost 40% of the total. These correspond to about 14,000 tanker calls with an average size of 80,000 DWT [1]. As shown in Figure 2, the largest number of tanker calls are in Houston and New York, averaging almost five each day. Figure 3 shows a breakdown of tanker sizes. With declining oil production in the US, it is likely that transport volumes of oil cargo will increase.

Oil spillage into the marine environment comes from a variety of sources including tanker accidents, tanker operations, and municipal and industrial wastes. Table 1 from a 1990 US Coast Guard (USCG) study [2] shows that the contribution from tanker accidents accounts for about 20% of the total. In general, most tanker casualties do not lead to pollution events. A Lloyds's Register of Shipping study [3] in 1990 shows that about 6% of tanker casualties led to spillage. It is also of interest to focus on the type of casualty which leads to oil spills. Figure 4 shows the relative worldwide frequency of incidents and oil spill volume categorized by type of incident. Groundings and collisions are about equally likely and account for about 60% of the volume of oil spilled. Figure 5 shows the corresponding categorization for US waters. In the US, grounding accounts for about 30% of the incidents but results in over 60% of the total volume of spilled oil. The National Research Council study [1] notes that this is due to the shallow waters of the Gulf of Mexico and East Coast ports.
Fig. 1 Petroleum Volume by Major Port Complexes: Crude & Product Import/Export, 1988
Source: US Army Corps Engineers

Fig. 2 US and Foreign-flag Tanker Calls to Major US Ports, 1989.
Source: Lloyd's Information Service, Ltd and Committee Estimates from US Army Corps of Engineers Data

Fig. 3 Deadweight Tonnage: Tanker Size & Port, Selected Ports, 1989
Source: Lloyd's Information Service Ltd.
Table 1

<table>
<thead>
<tr>
<th>Source/Year</th>
<th>1990</th>
<th>1981/85</th>
<th>1973/75</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilge and Fuel Oil</td>
<td>0.25</td>
<td>0.31</td>
<td>*</td>
</tr>
<tr>
<td>Tanker Operational Losses</td>
<td>0.16</td>
<td>0.71</td>
<td>1.08</td>
</tr>
<tr>
<td>Accidental Spillage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tanker Accidents</td>
<td>0.11</td>
<td>0.41</td>
<td>0.20</td>
</tr>
<tr>
<td>Non-Tanker Accidents</td>
<td>0.01</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>Marine Terminal Operations</td>
<td>0.03</td>
<td>0.04</td>
<td>0.50</td>
</tr>
<tr>
<td>Dry-docking</td>
<td>-</td>
<td>0.03</td>
<td>0.25</td>
</tr>
<tr>
<td>Scrapping of Ships</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.57</td>
<td>1.50</td>
<td>2.13</td>
</tr>
</tbody>
</table>

The focus of this paper is on tanker escort, which addresses a significant part of the larger problem of oil transportation risk. Tanker escort refers to the practice of employing tugs to be in the immediate vicinity of the tanker, ready to render assistance in an emergency while the tanker is in transit through constrained and/or regulated waters. The primary intent is to prevent a disabled tanker from grounding or allision. (Allision is accidental contact between a moving vessel and a stationary object, for example a pier or bridge structure, as distinct from collision with another moving vessel.)

It is important to note that tanker escort is not a panacea to oil spillage. Many factors may contribute to collisions and groundings. A DNV study by Karlsen and Kristiansen [4] provides a statistical survey of causal factors for Norwegian shipwrecks for the years 1970-78. Five main groups were identified: technical failure, watch arrangement, vessel control, external conditions and other ship errors. Table 2 taken from this study shows the sub-categories under these main causal groups. Rudder and propulsion failure come under sub-category 'D' of the Technical Failure group. Table 3 taken from the same study shows the distribution of causal factors for the above categories. For the purposes of our paper, groundings and strandings shown in the table are both considered as grounding events.

Figure 6 shows the percentage of causal factors for the important subcategories. Clearly for groundings and strandings, watchkeeping, visibility, navigation and human factors dominate as the primary causal factors followed by machinery failure and maneuvering factors. Tanker escort may not be an effective solution to some of the major causes of groundings. A study focusing on the role of marine navigation and piloting in minimizing the number of accidents is available in [5].
Table 2
Grouping of Causal Factors under Main Areas.
Source: DNV Report No. 80-0079, 1980

<table>
<thead>
<tr>
<th>I. Technical Failure, Ergonomics</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Fault with equipment</td>
</tr>
<tr>
<td>B. Design of ship and bridge plus arrangement</td>
</tr>
<tr>
<td>C. Condition of navigational aids</td>
</tr>
<tr>
<td>D. Remote control of steering engine/propulsion machinery</td>
</tr>
<tr>
<td>E. Fault/inadequacy of communication arrangement</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II. Manning, Watch Arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. Manning of bridge and organization</td>
</tr>
<tr>
<td>N. Watch conditions</td>
</tr>
<tr>
<td>O. Communication</td>
</tr>
<tr>
<td>V. Special human factors</td>
</tr>
<tr>
<td>X. Knowledge, experience</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>III. Vessel Control Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>F. Erroneous/incomplete chart nautical publications</td>
</tr>
<tr>
<td>R. Sailing and maneuverability in relation to manning</td>
</tr>
<tr>
<td>S. Operation of equipment</td>
</tr>
<tr>
<td>T. Information from fixed objects, lighthouses, shore, etc.</td>
</tr>
<tr>
<td>U. Misinterpretation of traffic information</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IV. External Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>G. External conditions that reduce performance capabilities</td>
</tr>
<tr>
<td>I. Fault/inadequacy of lighthouses and marking systems</td>
</tr>
<tr>
<td>P. Reduced visibility</td>
</tr>
<tr>
<td>V. Other Ships</td>
</tr>
<tr>
<td>H. Fault/errors of other ships</td>
</tr>
<tr>
<td>Y. Error of the manning on the other ship</td>
</tr>
</tbody>
</table>

Tanker Escort Practice
Spillage of oil from tanker accidents has focused attention on accident prevention and oil spill response. International, national, state and local authorities have implemented numerous measures to decrease the chances of an accident and to mitigate the consequences in the event of an oil spill. One aspect of these regulations is the use of tugs to escort laden tankers, along with speed and size limits on tankers. A brief review of the regulations in force in US waters shows that past regulations have not been based upon proven efficacy of escort.

For the waters of Puget Sound, the State of Washington escort rules require the escort tugs to have an installed horsepower equal to 5% of the deadweight of the escorted tanker. As an example, a 100,000 DWT tanker would require a 5,000 HP tug as an escort.

In San Francisco Bay, the rules require one pound of forward bollard pull per ton of deadweight of the escorted tanker. For example a 100,000 DWT tanker would require a tug with forward bollard of 100,000 pounds. Using 30 pounds of bollard pull per installed horsepower, the rule would require a tug of around 3,500 HP.

In the waters of Prince William Sound, the escort requirement is set by the USCG. Prior to 1994 the operating procedures were established by Alyeska Pipeline Service Company through its Ship Escort/Response Vessel System (SERVS) to ensure compliance with the Prince William Sound Tanker Oil Discharge Prevention and Contingency Plan as approved by the Alaska Department of Environmental Conservation. The escort procedures established the number of tugs required in escort as a function of tanker size and wind conditions. The port is closed to tanker traffic if the wind speed is greater than a certain level. The escort tugs are chosen from a charter fleet ranging in size from 5,250 HP open propeller tugs to 7,200 HP tugs with propellers in nozzles.

The first safety-based regulations came from the USCG in August of 1994 and are contained in 33 CFR 168 [6]. The rules require escort tugs for oil tankers transiting Prince William Sound, Alaska, and Puget Sound, Washington. This rule-making is mandated by the Oil Pollution Act of 1990 (OPA '90) and took effect on 17 November 1994.

Table 3
Percentage Distribution of Causal Factors in the Main Categories for Each Type of Casualty.
Source: DNV Report No. 80-0079, 1980

<table>
<thead>
<tr>
<th>I. Technical failure, ergonomics</th>
<th>Collision</th>
<th>Contact damage</th>
<th>Grounding</th>
<th>Stranding</th>
<th>All cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>II. Manning, watch arrangement</td>
<td>13.2</td>
<td>18.1</td>
<td>31.2</td>
<td>55.6</td>
<td>29.2</td>
</tr>
<tr>
<td>III. Vessel control tasks</td>
<td>28.8</td>
<td>39.4</td>
<td>37.0</td>
<td>15.8</td>
<td>29.5</td>
</tr>
<tr>
<td>IV. External factors</td>
<td>16.1</td>
<td>15.4</td>
<td>24.8</td>
<td>16.3</td>
<td>20.2</td>
</tr>
<tr>
<td>V. Other ships</td>
<td>34.7</td>
<td>1.1</td>
<td>0.6</td>
<td>1.2</td>
<td>12.8</td>
</tr>
</tbody>
</table>
The rule-making authority was delegated to the USCG. The Coast Guard was to implement these rules in two separate regulatory projects, one addressing escort requirements for the Prince William Sound and Puget Sound, and the other addressing escort requirements for other waters. The recent regulations represent the outcome of the first of these regulatory projects. The second regulatory project is currently in progress.

An acceptable escort system is defined in the rules as one that consists of at least two escort vessels (Section 168.40) and which meets certain performance and operational criteria.

Under the operational requirements (Section 168.50a), the escort vessels are to be positioned relative to the tanker such that timely response to a propulsion or steering failure can be effected. In addition, the transit speed is to be selected such that the escort vessels can safely bring the tanker under control within the navigational limits of the waterway, taking into consideration ambient sea and weather conditions, surrounding vessel traffic, hazards and other factors that may reduce the available sea room.

Under the performance requirements (Section 168.50b), the escort is to have sufficient power to perform a rescue tow of a tanker in calm conditions and to substantially reduce its drift rate in severe winds. The escort should also provide steering and stopping forces that are equivalent to what the tanker itself is capable of when it is fully functional at 6 knots. Minimum escort requirements in four different assist modes have been mandated.

1) Towing the tanker at 4 knots in calm conditions and holding it in steady position against a 45 knot headwind.
2) Stopping the tanker within the same distance that it could crash-stop itself from a speed of 6 knots using its own propulsion system (suspended as of November 1994).
3) Holding the tanker on a steady course against a 3.5 degree locked rudder at a speed of 6 knots.
4) Turning the tanker 90 degrees, assuming a free-swinging rudder and a speed of 6 knots, within the same distance that it could turn itself with a hard-over rudder.

**Tanker Escort in Europe**

Escort of tankers and other ships carrying dangerous cargoes is still being fiercely debated in Europe. During the two RINA conferences in London at the beginning and end of 1993, serious questions were raised about the meaning and usefulness of escorting, particularly with regard to safety and economy. The commonly agreed upon definition of “escorting” is having tugs available almost immediately that can be called upon to control a
disabled vessel. The tugs would provide service over relatively large areas and be able to travel at considerable speed. However, existing tugs as required for harbor service in many European ports do not actually meet these requirements.

It is generally accepted that only very good reasons would justify the implementation of an escort over long sailing distances. This raises the most serious aspect of an escort system, that is its cost effectiveness. The Lord Donaldson Report 'Safer Ships, Cleaner Seas' [7], the recently written results of the inquiry that followed the grounding of the Braer, concludes "...that there is no justification for large vessels with potentially polluting cargoes to be accompanied by tugs whenever they are within a set distance from land".

Rather, the report extensively addresses the need for stationing salvage tugs at important locations around the coast of Britain. The emphasis on stationing of salvage tugs has a number of reasons including the fact that escorting anywhere outside sheltered waters would require large salvage type tugs. However the report states that it is '...self-evidently ridiculous: it would also be massively expensive and extremely poor value for the money', to have continuous escort with such large tugs. Thus only stationing remains an option. The fact that traffic density in the English Channel and the North Sea is quite high and that there is a large amount of foreign and passing traffic also supports the proposal for stationing salvage type tugs for emergency situations, rather than imposing an escort requirement.

Table 4 summarizes escort practices at various other European ports. The adaptation of equipment and practice to local conditions is clearly evident.

ESCORT ANALYSIS & ANALYSIS STRATEGIES

Escort Analysis

The tanker escort problem may be posed simply as: What is the size of tug(s) required to prevent a disabled tanker from going aground?

Tanker disabilities fall into three categories: loss of propulsion, loss of steering, and loss of both steering and propulsion.

Loss of Propulsion. A tanker with loss of propulsion will slow down and in most cases deviate from its original course due to inherent lack of directional stability. The extent of its deviation will depend on its
inherent characteristics, the transit speed, wind, currents and helm commands.

Loss of Steering. In this case, it is assumed that a steering failure occurs with no bridge control of steering but with propulsion control. Three cases may be recognized: 1) Rudder moves to a new position without a bridge command (such as due to electrical or hydraulic failure), 2) Rudder does not return from a deflected position upon a new bridge command (such as due to electrical, hydraulic or mechanical failure) and 3) Steering indicator fails leading to erroneous bridge action.

Loss of Propulsion and Steering. In this scenario, it is assumed that the ship has a failure of steering compounded by a loss of propulsion. This is clearly the most critical of the three failure scenarios. A closely related scenario is rudder failure with voluntary shutdown of propulsion; in this case the tanker master stops the engine once the rudder failure is recognized. The simulation studies carried out for Prince William Sound [8], San Francisco Bay [9] and Puget Sound all use the assumption of hard-over steering failure coupled with voluntary shutdown of propulsion.

In the effort to define the capability of the escort tugs, two propositions have been advanced, namely the principle of equivalency and the principle of sufficiency. Both endeavor to improve safety of oil transport in the waterway but with dramatically different consequences.

Principle of Equivalency
This proposition states that the escort tug(s) should be as capable as the able tanker itself. Thus, when a tanker is disabled, the escort is a redundant system that takes over and enhances safety. Under this logic, the escort system should have the ability to stop the tanker in the same distance that it can stop itself and should have the same ability to turn the tanker as its own rudder. Appealing though it may be, this proposition suffers from serious flaws:

- The more capable the tanker is in backing down or steering, the greater the tug requirement. Thus capable tankers are penalized in escort costs in comparison to less capable tankers.
- All tankers are not equally capable. Thus the escort system predicated on equivalency will produce inconsistent safety in the waterway.
- There is no basis to believe that equivalency will produce the required standard of safety, since there is no maneuvering standard that tankers have to meet to transit in a given waterway.
- This proposition does not account for the time delay in requesting tug assistance. In the case of steering failure, for instance, substantive off-track travel may have occurred before the "equally capable" escort tug can act.

Part B of the USCG rules used equivalency to set minimum tug requirements.

Principle of Sufficiency
Under this principle, the escort system should have sufficient capability to achieve the required standard of safety. It has the following advantages:

- It achieves a constant standard of safety for all tankers, taking into consideration of size, speed and characteristics.
- It specifically includes the effect of time delays and can account for tethered or untethered escort.
- It allows for systematic speed regulation and tug specification.
- It can take into account environmental effects (i.e., weather, currents).

The studies carried out for Prince William Sound and San Francisco Bay use the principle of sufficiency. Part A of the USCG rules is based on this principle.

Analysis Strategies
This paper presents two approaches to developing an analysis based escort system for the prevention of grounding. The first is an operations analysis approach and the second is a systems analysis approach. Each provides a rational means of defining the escort requirements for a particular ship in a particular waterway.

Operations Analysis Strategy
The operations analysis approach to identifying escort requirements develops from an analysis of individual or representative tankers matched with specific tugboats. The emphasis is on evaluating an existing escort system and probing enhancements that could be made to improve the escort combinations. The principal goals that this strategy should achieve are:

- Include all tankers that pass through the waterway.
- Include all tugs currently available for escort service.
- Examine specific tanker-tug combinations and escort modes of interest.
- Account for the specific hazards in distinct parts of the waterway.
- Account for variability in weather.
- Define a minimum escort procedure for each tanker.

In general, the operations analysis strategy is geared to answer the following question: Given a specific tanker and tug combination, operating mode, and weather condition, what is the maximum acceptable transit speed?
Such an analysis is port-specific, with the simulation variables reflecting practices and conditions of a particular port and the results being compared with navigational limits in that waterway.

The analysis procedure is based on computer simulations of a matrix of combinations of tankers, tugs, maneuvers and environmental conditions.

**Systems Analysis Strategy**

This strategy aims for a consistent set of rules to govern the escort of tankers for a port. The principal goals would be:

- Encompass the range of tanker sizes, displacements and drafts that would apply to the waterway
- Be applicable to a range of transit speeds.
- Allow for the use of different kinds of tug(s) and their combinations.
- Account for the specific hazards in distinct parts of the waterway.
- Be sufficiently simple that regulators, pilots, tanker operators and tug owners can verify their compliance.

In general, the systems analysis strategy is geared to answer the following question: Given a tanker size and desired speed of transit, what is the type and size of tug(s) required for safe transit?

This paper details a unique demand and capability methodology developed for the San Francisco Bay Tanker Escort study [9]. Once a disabling casualty has occurred, such as loss of propulsion or steering, escort vessel(s) assistance may be required to prevent an allision or grounding. The type and extent of required assistance will depend on the type of casualty, the tanker’s maneuvering characteristics, its speed, ambient conditions (current and weather) and the proximity of hazards. The tanker demand is obtained as a function of the regulatory “variables” of ship mass and speed, with fixed parameters of weather and water depth, while satisfying the navigational constraints of the waterway. These parameters together establish the “tanker demand” that has to be met by the escort vessel.

The tanker’s need or demand for assistance is separate from the capability of the tugs that are required to provide it. They must be matched for an optimum escort combination.

The emphasis in the systems analysis approach is in the development of escort rules for a specific port. The concept greatly simplifies the development of an engineered solution for a complicated port with numerous tankers and tugs.

Examples of the use of this approach are the existing state rules in Puget Sound and San Francisco Bay. In both cases, the tanker demand is postulated based on the deadweight of the tanker. But the crucial linkage between tanker demand and speed is missing.

### ANALYSIS COMPONENTS

An analysis of tanker escort using either methodology requires the following elements:

- **Definition of the navigation constraints**
- **Definition of environmental conditions**
- **Tanker modeling for maneuvering behavior**
- **Tug modeling for assistance capability**
- **Failure scenarios**
- **Assistance scenarios**

In this section, the importance and use of each element is developed and alternatives are discussed. Special emphasis is placed on the new and unique tools that have been developed for use in this analysis. The statistical model of the waterway as well as tanker and tug models are explained.

### Definition of the Navigational Constraints

For any analysis, it is necessary to study the tanker routes and the geography of the escort area in order to define the navigational constraints of a disabled vessel. It is within these constraints that a stricken tanker must be stopped if a grounding is to be averted. Consideration must be given to point constraints such as bridges, rocks and islands as well as to bottom contours. A distinction may be drawn between grounding on hard bottom and on mud. In the study of routes covering different geographic regions, it is beneficial to divide the escort area into separate zones based on the environment and the severity of the constraints. This will separate a zone with severe constraints and severe environment from one that is significantly less restrictive. This constitutes a logical approach to ensuring an equitable allocation of escort resources.

A quantitative definition of the navigational constraints for each zone in terms of an allowable reach and an allowable transfer is required. The reach is defined as the distance forward of the tanker and parallel to the tanker’s track where there is adequate water depth so that a grounding or allision would not occur. Transfer is the distance perpendicular to the tanker’s track, either to port or starboard, to the depth contour where grounding would occur or to a point constraint where an allision would occur.

There are several methods of determining the numerical values of the constraint reach and transfer distances. The simplest is to choose the absolute minimums. Using this definition, the reach constraint would be the shortest straight-ahead distance from a turn in the tanker lane to the constraint directly ahead. The minimum transfer distance would be the shortest perpendicular distance to constraints on either side. However, if this approach is adopted, the escort...
requirement would be based on a single-point exposure to the worst case hazard, which may be too restrictive in relation to the entire transit distance.

An alternative approach is to define the reach and transfer constraints as a statistical measure of the exposure of the vessel to potential grounding/allision situations. The statistical measure could be the average distance ahead and abeam measured throughout the entire transit in the escort zone of interest. Percentile measures of reach and transfer distances can also be determined. For example, the 95th or 98th percentile levels are often used in risk analysis and can be used here to define the navigational constraint. The procedure for the calculation of statistically defined constraints begins by measuring the reach and transfer distances from the normal ship track to a constraint. To do this the transit is divided into evenly spaced segments and the ahead and abeam distances are measured. A histogram of the measurements shows the frequency distribution of reach and transfer. Cumulative frequency distributions are then developed and used to determine the percentile reach and transfer for a particular transit of interest. The percentile figure represents the proportion of the total transit distance for which the distance to the constraint is at least as far as the distance stated. For example, if the 95th percentile off-track distance is given, then if 100 locations are randomly selected along the tanker's trackline, the constraint distance would be greater than or equal to the stated distance for 95 of those locations.

**Definition of Environmental Conditions**

The behavior of a stricken tanker and the capability of an escort system are influenced by a number of environmental conditions. These include:

- Wind speed, direction and duration
- Significant wave height, modal period and direction
- Current velocity

The effects of these environmental conditions must be accounted for in tanker maneuvering simulations.

**Tanker Modeling for Maneuvering Behavior**

The mathematical models for ship maneuvering simulations are described by Webster [10]. The basis of computer simulations is a set of three coupled, non-linear differential equations for the horizontal plane motions of a ship. These equations include polynomial representations of the forces acting on the ship as a function of the instantaneous state of the vessel. The polynomials can be viewed as truncated, multivariate Taylor expansions about the ship self-propulsion point which corresponds to a straight line travel at a constant forward speed. In the "square-absolute" method, the polynomials are carried only to the second order whereas in the third order method, cubic terms are retained. The second-order method is considered to have a better theoretical basis to represent the nonlinearities associated with cross-flow phenomena [11]. In either case, a large set of coefficients is necessary to model the forces associated with these coupled degrees of freedom. These coefficients are determined experimentally either by captive model tests [11] or an alternative scheme called system identification [12].

Most experiments to determine the maneuvering derivatives have been carried out in deep water. The maneuvering of ships in unrestricted shallow water has been investigated much less. Roseman [11] has given a complete set of shallow water hydrodynamic coefficients for full form ships obtained from planar motion mechanism tests.

Once the set of derivatives is available, the maneuvering equations can be solved directly in the time domain for any maneuver of interest using initial conditions of ship position and velocity. This time-domain approach allows the proper modeling of transitory variables and delayed forcing functions in a highly nonlinear problem. The procedure allows for rudder failure at a specific time and at a given rate, propeller failure and the transient behavior of the propeller, tug assistance in any mode after specified time delays, and environment specification in both magnitude and direction.

Since the maneuvering derivatives in the simulation equations are ship specific, they have to be separately evaluated for each vessel. Some of these derivatives can be computed from first principles. Most of them, however, are based on complex potential and viscous flow phenomena and cannot be theoretically calculated. Typically, the effort to obtain these derivatives for one vessel is substantial, requiring extensive model tests. Hence the common approach to model a specific ship is to first obtain a set of maneuvering derivatives available for a "standard vessel" of the same type and shape. These derivatives would typically be non-dimensionalized by a suitable length scale of the "standard vessel." These are then re-dimensionalized using the length scale of the vessel being studied. The accuracy and validity of these derivatives for the new vessel depend on the extent of departure of the new vessel from the standard vessel. Simulations are then carried out with the new vessel for some standard maneuvers such as spirals, zigzag maneuvers, turning maneuvers and stopping maneuvers. Results of these simulated maneuvers are then compared with available maneuvering data for the newly modeled vessel. If appropriate, the maneuvering derivatives are modified to obtain the observed performance.
Barr [13] compared a number of simulation models of the 278,000 DWT tanker *Esso Osaka*. The maneuvering coefficients used and the hydrodynamic forces predicted were compared among different models. Significant differences were observed, which emphasizes the need for careful validation of any simulation model.

The simulation program SHIPMAN developed by The Glosten Associates predicts the behavior of able as well as disabled ships in a variety of conditions, and has been extensively verified and validated over the past five years. The mathematical model incorporates the square-absolute form of the maneuvering equations. Several maneuvering coefficient data sets suitable for deep as well as shallow water are available to the program. Additional forcing functions are incorporated to model external forces such as those due to tug assistance and the environment. The equations of motion are solved directly in the time-domain using a fourth order Runge-Kutta method. An example comparison of the turning circles predicted by SHIPMAN with the actual tracks in trials is given in Figure 7 for a 40,000 DWT tanker in shallow water.

A numerical simulation program has also been developed by MSCN and was used as the primary analysis tool in the Prince William Sound study. Comparisons of the predictions between the Glosten and MSCN simulations and with full scale trials were used to verify the codes.

**Tug Modeling for Assistance Capability**

The performance of a tug in an emergency maneuver depends on its ability to apply corrective forces to the disabled vessel either through a line or through direct contact with the tanker’s hull. The forces must be applied while the disabled vessel is still moving at speeds close to its transit speed. Any tug can be modeled as a collection of force producing devices: hull, skeg, rudders, propellers and nozzles. The net forces and moments resulting from these components act on a tanker through single or multiple towlines or direct tug-tanker contact.

Two distinct assist modes are considered, one in which the tug is required to brake the tanker and the other in which a tug is called to steer. There are fundamental differences in the exercise of these assist modes between a conventional tug and a tractor tug. Conventional tugs apply braking force by backing down on a head line while being dragged by the tanker through the water. The braking force is developed by the reverse thrust generated by the propeller rotating at the maximum achievable reverse RPM and is augmented by the hull resistance. The propeller torque demand and thrust output with forward speed and reverse RPM, the reverse gear ratio, and the engine torque capability as a function of engine RPM are critical. In particular, if the engine torque at idle is less than the demand torque of the reversed propeller at the equivalent RPM, then the engine will stall when the clutch is engaged. The advance speed at which clutch engagement can be accomplished without exceeding the engine manufacturer’s continuous torque rating is therefore referred to as the *clutch-in speed* and constitutes an important factor in assessing the braking capability of conventional tugs.

Conventional tugs steer by pushing at the stern or the side of the tanker. The force is largely determined by the lift generated by the hull and the thrust produced by the propeller, which also has to overcome the hydrodynamic resistance of the hull. The steering capability is limited by heel, established as geometrical submergence of the main deck edge. It is known that it is
possible to safely submerge a portion of the main deck and produce somewhat larger steering forces; however, the stability and safety of the tug decreases rapidly with continued submergence and a tug skipper will typically begin to reduce power in this circumstance. This is especially true in restricted visibility and stormy conditions. Poor visibility and wave action would make it more difficult for the tug operator to judge the safety margins with respect to heel angle. The deck edge submergence limit on tug capability is thus reasonable and generally accepted [14].

One of the consequences of using conventional tugs in an emergency control maneuver is that there can be a pushing force associated with the steering force. The force is transmitted to the tanker primarily through friction between the two vessels when working alongside, and also to some degree, through the lines if rigged. The force works to maintain the tanker's forward speed.

Unlike conventional tugs, tractor tugs have steerable thrusters and can exert both braking and steering forces by working on a line from the stern of the ship. At speeds below about 6 knots, they operate in the direct mode maintaining an orientation parallel to the towline. The towline pull is primarily due to the propeller thrust and is somewhat augmented by the drag of the hull. At higher speeds, superior performance is obtained in the indirect mode. In the indirect mode, the tug is almost perpendicular to the towline and assumes an angle of attack with respect to the direction of flow. The resulting large hydrodynamic lift forces generated at the hull translate into line pulls considerably in excess of the bollard pull [15]. In either mode, the tug can be suitably positioned behind the tanker to maximize either braking or steering. Figure 8 exemplifies the action of conventional and tractor tugs in assisting a tanker that has lost steering.

In braking or steering assist, the tug master can choose the optimum combination of steering and longitudinal forces. However, in an emergency braking assist, it is assumed that the tugs will be ordered to maximize braking forces irrespective of the associated steering effects (which occur for tractor only). Likewise, in an emergency steering assist, it is assumed that the tugs will be ordered to maximize steering forces regardless of the associated pushing (conventional) or braking (tractor) effects. Thus, tug capability can be quantified by a pair of speed dependent vector force functions: the maximum braking force together with the associated steering force in case of braking assist; and the maximum steering force together with the associated braking (pushing) force in case of steering assist.

The effort involved in evaluating these vector force functions is substantial. A free-body diagram of the various force and moment components to be modeled is given in Figure 9 for the example case of a conventional tug. The tug type, hydrodynamics of the underwater hull with skeg, rudder, etc., propeller characteristics, stability issues like freeboard and metacentric height, and a number of other factors will have to be carefully considered (for a description, see Glosten report on the Prince William Sound Disabled Tanker Towing Study [8] or the San Francisco Bay Tanker Escort Study [9]). The Glosten Associates uses two separate tug simulation programs (TUGSIM for conventional tugs and TRACSIM for tractor tugs) incorporating a quasi-steady analysis of these functions for evaluating the capability of any type of tug. An example comparison of the predicted and measured towline pulls is given in Figure 10.

**Failure Scenarios**

The failure scenarios to be considered in an escort study should be clearly specified. Possible failure modes include propeller failure, rudder failure and combinations thereof. Two worst case scenarios correspond to propeller failure with no steering and hard-over rudder failure with no propulsion. Alternatively, a propeller failure with full rudder capability or a rudder failure with full propulsion may be considered. The resulting escort requirements are significantly different depending on the failure scenarios used in the study. Hence a careful selection of a reasonable set of failure scenarios is extremely important.
Fig. 9 Free-body Diagram of Forces and Moments for a Conventional Tug Model.

Fig. 10 Predicted and Measured Towrope Pulls for Z-Drive Tractor Tugboat.

Assistance Scenarios

The time delay following a disabling failure on a tanker before the escort tug can be of assistance and the nature of that assistance must be carefully postulated. Time delays vary significantly, due to the variability in human performance, environmental conditions, nature of casualty, tanker speed, tug type, escort position, escort mode, emergency towing practices and equipment. This is evident from any escort drill or training simulation of an emergency. The time delay chain of events includes:

- Time delay for failure recognition aboard the tanker and stopping the engine
- Time delay to consider options, cures and notify tugs
- Time required to maneuver tug from its escort position to tanker
• Time required to maneuver and pass messenger line if required
• Time required to connect towline in rescue towing scenarios
• Time delay resulting from tug equipment failures

When deployment of the rescue towing tugs is evaluated, it is also necessary to consider the time it takes a tug to reach the disabled tanker from its stationed position. The possibility that a rescue maneuver is required during a storm at night adds further delays due to the time it takes to arouse the crew, poor visibility, ice on the decks and difficult communications due to winds and darkness. There does not exist a database of the time delays from which statistical estimates can be made. Estimates have to be based on experience, full-scale trials and commentary from experienced towing masters. The time delays used in the studies carried out for Prince William Sound, San Francisco Bay and Puget Sound are illustrated in Figure 11. This figure also shows the failure of the rudder and the subsequent voluntary shutdown of the engine.

An escort tugboat is typically capable of providing assistance in towing, braking and steering. The type of assistance depends on the nature of the tanker casualty, its speed, navigational constraints, tug type, escort position, and escort mode (whether tethered or untethered). In case of tanker failure in open water where there is no continuous tug escort, the tanker is subject to steady drifting under the prevailing environment. In constrained waterways where there is continuous escort, tugs are required to render more immediate assistance. In case of propeller failure, the tug may be required to limit the headreach of the tanker. The tug can accomplish this either by applying maximum retarding force to brake the tanker or, if appropriate, by applying maximum steering force to turn the tanker. In case of rudder failure, the tug is required to limit the transfer. The tug can accomplish this by engaging in one of the following maneuvers:

• Assist the turn of the failed rudder
• Oppose the turn of the failed rudder
• Retard and stop the vessel

In the assist maneuver, the objective is to apply maximum steering force to make the turn of the tanker as tight as possible so that the tanker turns around within the allowable off-track transfer distance. In the oppose maneuver, the objective is to return the tanker to its original heading and course by opposing the rudder forces and turning the tanker against its rudder. In the retard maneuver, the objective is to stop the tanker as quickly as possible by exerting maximum retarding force. The control of the tanker’s turn is not a primary objective in this maneuver. Conventional tugboats will exert retarding force by backing down on their engines and pulling with their bow line. In general, the conventional tugboat can, at higher speeds, exert only an in-line force opposing tanker motion, i.e., there is negligible controlled steering force that can be exerted. Tractor tugboats, on the other hand, are in the indirect mode at higher speeds and their retarding force has a steering force component.

In the following sections, these analysis components are utilized to derive solutions for specific waterways.

![Normalized Response](image1)

(a) Prince William Sound

![Normalized Response](image2)

(b) San Francisco Bay

![Normalized Response](image3)

(c) Puget Sound

Fig. 11 Postulated Sequence of Events following a Rudder Failure.
APPLICATION OF OPERATIONS ANALYSIS IN PRINCE WILLIAM SOUND

The procedures and a summary of the results of a matrix-based analysis are presented in this section. The methodology comes from a comprehensive study of tanker escort in Prince William Sound, Alaska, conducted by the Glosten Associates in collaboration with Maritime Simulation Centre the Netherlands. The study was prepared for the Disabled Tanker Towing Study Group (DTTSG), of Alaska. The objective of the study was to evaluate, using computer simulations, the capability of existing escort vessels and operating practices, and some alternatives, that could enhance escort and rescue towing preparedness in the Sound.

Geography
Prince William Sound (PWS) is a small inland sea with an area of nearly 2,500 square miles. It is located on the south central coast of the State of Alaska. The Sound extends approximately 35 N.M. north to south and is about 50 N.M. east to west. The maximum water depths are greater than 2,300 feet. The coastline is rugged and rocky with many fjords and tide-water glaciers. It is surrounded by mountains, some as high as 13,000 feet. Fig. 12 is a chart of Prince William Sound.

Five geographic subregions were defined for this analysis. In each subregion the escort and emergency response is different, primarily driven by the differences in wind and wave conditions and differences in available sea room. Two of the subregions, Valdez Narrows and Hinchinbrook Entrance, are shown in Figs. 13 and 14. A 1,100 foot tanker is shown drawn to scale to give an indication of the dimensions of these waterways.

Climatology
The wind and wave environments in the study area vary from the protected waters of Port Valdez to the extremes of winter in the Gulf of Alaska. In each of the geographic subregions the weather is highly variable, ranging from extended periods of calm to severe winter gales. There are also significant variations with the seasons.

The wind and wave conditions were defined to be consistent with one of the objectives of the study which was to evaluate escort operations in a worst case scenario. Table 5 presents a summary of the worst case wind and wave conditions used in the computer simulations. The study also evaluated escort operations in other than worst case conditions.

Tankers
In addition to the geography and climatology, the analysis of escort operations requires that the
investigators identify the sizes and principal characteristics of the tankers that call at the port. The fleet of vessels operating in Prince William Sound is fairly easy to catalog due to restrictions on oil export and the fact that almost all are American flagged.

Three tanker sizes were chosen as representative. Individual vessels in the three sizes were identified. Maneuvering data for each ship and access to the vessels for full scale trials was provided by the operating companies in order to develop and verify the computer-based maneuvering simulator. The principal dimensions of the chosen vessels are presented in Table 6.

The preparation of the hydrodynamic maneuvering models was started by selecting tankers from the MSCN database that were similar to the those under investigation. Once selected, the maneuvering coefficients were scaled as appropriate, using Froude techniques. Any differences due to the propulsion system and hull appendages were calculated and incorporated. In some cases the availability of empirical data enabled the coefficients to be refined to achieve improved results.

The numerical model used in this study is a variation on the Abkowitz procedure consisting of a Taylor series expansion. A selection is made from the Taylor series based on the physical relevance of the terms with emphasis on eliminating unnecessary high order terms.

A single numerical model for each tanker was adopted for use in both low speed / high drift maneuvering and standard propelled maneuvers. The range of applicability of the source data and the choice of coefficients supports this choice.

**Table 5**

<table>
<thead>
<tr>
<th>Region</th>
<th>Criteria</th>
<th>Wind Speed</th>
<th>Wave Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valdez Narrows</td>
<td>Just above Closure</td>
<td>45 kts</td>
<td>5.8 ft</td>
</tr>
<tr>
<td>Valdez Arm</td>
<td>Closure of Narrows</td>
<td>45 kts</td>
<td>8.9 ft</td>
</tr>
<tr>
<td>Prince William Sound</td>
<td>25 year storm</td>
<td>60 kts</td>
<td>14.4 ft</td>
</tr>
<tr>
<td>Hinchinbrook Entrance</td>
<td>Just above Closure</td>
<td>65 kts</td>
<td>20 ft</td>
</tr>
<tr>
<td>Gulf of Alaska</td>
<td>Closure of Entrance</td>
<td>70 kts</td>
<td>25 ft</td>
</tr>
</tbody>
</table>

A significant part of an escort operation analysis is to quantify the performance of the tugs that provide tanker escort. Potential additions to the escort fleet require modeling. At the time of this study, there were eleven tugs that provided escort and spill response capabilities in Prince William Sound. The tugs are provided by charter to Alyeska by Crowley Marine Services, Inc., and Tidewater Marine. Five of
the vessels are designated as ERVs (Escort Response Vessels). The ERVs are fitted to provide emergency pushing and towing assistance and are equipped with first response oil containment and recovery equipment. Some of the other six vessels provide docking services at the terminal and are assigned to escort through the Narrows and Prince William Sound.

A summary of the capabilities of the tugs modeled for the Prince William Sound study is presented in Table 7.

**Full Scale Trials**

The numerical models of tanker maneuvering and tug capabilities were extensively tested and verified in a complete set of full scale trials conducted in Port Valdez. The full scale trails included all three of the selected tankers and representatives of each tug class chartered for escort. A total of sixteen assist maneuvers were conducted using the three ships at different times. The tested scenarios were conducted assuming a 35° rudder failure from an initial speed of 6 knots, with untethered tugs and 60 second time delays for failure recognition and tug notification. As many as four tugs were called upon to assist simultaneously. The tracks of the simulated emergency assist were recorded from DGPS signals and compared with computer predictions. The trials were conducted by MARIN and an extensive documentation of the results is presented as an appendix to the Prince William Sound Disabled Tanker Towing Study [8].

**Failure Scenario**

The failure scenario is the combination of events and conditions that precede emergency assist from the escorting tugs. For the Prince William Sound study it was decided to evaluate a so-called worst case incident where worst case implies placing the highest demand on the capabilities of the tug or tugs to prevent a grounding incident. It was accepted by the DTTSG that the worst case failure scenario would be a 35° locked rudder failure and simultaneous shutdown or loss of the propulsion system upon rudder failure recognition. Thus, once rudder failure is identified and the propulsion is stopped, the tanker master has no further control of the vessel. The probability of this event occurring was not evaluated.

**Table 7**

**Escort Tugs in Prince William Sound**

<table>
<thead>
<tr>
<th>Tug</th>
<th>Power</th>
<th>Predicted Ahead Bollard</th>
<th>Maximum Steering Force at 6 kts</th>
</tr>
</thead>
<tbody>
<tr>
<td>135 ft. twin screw, open wheel, three rudders</td>
<td>5,750 BHP</td>
<td>105,000 lbs.</td>
<td>85,000 lbs.</td>
</tr>
<tr>
<td>135 ft. twin screw, open wheel, three rudders</td>
<td>7,200 BHP</td>
<td>148,000</td>
<td>115,000</td>
</tr>
<tr>
<td>150 ft. twin screw, nozzles, two rudders</td>
<td>7,200 BHP</td>
<td>217,000</td>
<td>120,000</td>
</tr>
<tr>
<td>195 ft. twin screw, nozzles, two rudders</td>
<td>5,750 BHP</td>
<td>175,000</td>
<td>75,000</td>
</tr>
<tr>
<td>145 ft., twin screw, open wheel, two rudders</td>
<td>7,280 BHP</td>
<td>132,000</td>
<td>120,000</td>
</tr>
<tr>
<td>100 ft. midsize VSP tractor</td>
<td>4,000 BHP</td>
<td>98,000</td>
<td>75,000</td>
</tr>
<tr>
<td>155 ft. enhanced VSP tractor</td>
<td>7,600 BHP</td>
<td>170,000</td>
<td>150,000</td>
</tr>
<tr>
<td>100 ft. Z-propeller pusher type tug</td>
<td>7,110 BHP</td>
<td>110,000</td>
<td>44,000</td>
</tr>
<tr>
<td>245 ft. deep sea salvage tug</td>
<td>22,000 iHP</td>
<td>370,000</td>
<td>na</td>
</tr>
</tbody>
</table>
A tanker master with access to either steering or power can use a number of possible actions to vary the heading and drift rates of a disabled vessel. Reversing the engine can sometimes be an effective strategy in maneuvering to avoid grounding. Except for investigating the consequences of engine reversal, other interventions by the tanker master were not evaluated.

Variations on the worst case failure scenario with reduced rudder angles, reduced wind speeds and reduced failure recognition and response times were also evaluated. In addition, to account for variability in the time required for failure recognition, calling for assistance, and for tug maneuvering and make-up, a Monte Carlo type inquiry was implemented. Using this technique, the variability in human response to the demands of the emergency are in part evaluated. Monte Carlo evaluations were carried out using a small subset of scenarios for which the proposed most probable time delays produced a successful response maneuver. With the Monte Carlo technique, it is possible to define the conditional probability of escort success.

**Time Delay for Failure Recognition**

Recognition of a rudder failure, especially at night, depends on the pilot's and helmsman's awareness of the compass, rudder angle indicator, turn rate indicator and radar. Attentiveness is required and is to be expected when transiting restricted waterways; however, it is reasonable to assume that interpreting the information, some of which may be contradictory, will result in a time delay before a rudder failure is diagnosed.

During the time period after rudder failure, but before recognition of the failure, it is assumed that the engine will be maintained at speed. Three different failure recognition time delays were evaluated in the Prince William Sound study. They were 30 seconds and 60 seconds for scenarios in Valdez Narrows and 2 minutes for scenarios in the other subregions. The Monte Carlo simulations used 60 ± 30 seconds in Valdez Narrows and 120 ± 60 seconds elsewhere.

**Time Delay for Calling Assistance**

The second component of the overall time delay is the period after the engine is stopped, but before the decision is made as to what type of assistance is required. It is during this time that the pilot, master, mate, engineer, helmsman and possibly others must determine what has happened and how serious it is, consider a strategy, and plan a course of action. Some uncertainty and confusion are possible. The helmsman may be directed to try corrective actions. Training and pre-departure escort conferences will minimize the decision time delay, but it cannot be eliminated.

The Prince William Sound study assumed that in the Narrows, an additional 60 seconds would be required between failure recognition and the time that the tugs are ordered to intervention positions. In the other subregions, where time is not a critical factor, a time delay of 4 minutes is used. The Monte Carlo simulations used 60 ± 30 seconds in Valdez Narrows and 4 ± 2 minutes in central Prince William Sound.

**Time Delays for Maneuvering to Position**

The time delay for the tug to maneuver into position is quantified separately from the two time delays described above. The time for the tugs to become effective will vary with tug type, maneuverability, assigned push locations, the number of tugs involved and escorting positions. Tugs sent to the forward quarter will take longer to become effective than those sent to aft positions. In cases requiring two tugs to work side-by-side, it will be necessary for the first tug to position itself and begin working before the second tug can move into place. The times used in the study vary from 1 to 10 minutes for the escort scenarios in the Narrows and from 20 minutes to over 3 hours for maneuvering and making up a towing connection, if required, in the other regions. The longest time delay for maneuvering and rigging a towing connection is that assumed for the Gulf of Alaska in 70 knots of wind and 25 foot significant wave heights.

**Matrix of Cases**

A matrix of simulation cases was defined so that a basis of comparison of potential safety enhancements could be made. The matrix of cases includes as many combinations as possible of geographic regions, tug types, escort deployments, time delays and tanker sizes and speeds. The matrix analysis methodology can result in a significant number of scenarios.

For example, in the Prince William Sound Study there were:

- **Eight locations**
  - Valdez Narrows
  - Valdez Arm
  - The north part of PWS (west of Bligh Reef)
  - The central section of PWS (east of Naked Island)
  - The south section of PWS (n.e. of Smith Island)
  - Hinchinbrook Entrance
  - Gulf of Alaska at Seal Rocks
  - Gulf of Alaska in the safety fairway
  - (12 n.m ESE of Seal Rocks)

- **Three wind speeds and associated wave conditions**
  - 45, 30 and 15 knots in Valdez Narrows and Valdez Arm
  - 60, 40 and 20 knots in central PWS and Hinchinbrook Entrance
  - 70, 50 and 30 knots in the Gulf of Alaska
- Three tanker sizes
  - 90,000, 170,000 and 265,000 dwt
- Nine tugs: 5 existing and 4 alternate mgs
  - 5,750 & 7,200 HP nozzle tugs
  - 5,750 & 7,200 HP open wheel tugs
  - 7,280 HP open wheel tug
  - 4,000 & 7,600 HP VSP tractors
  - 7,110 HP stem mounted Z-drive tug
  - 22,000 iHP salvage tug
- Three transit speeds in Valdez Narrows.
  Two speeds in the other areas
  - 4, 5 and 6 knots in Valdez Narrows
  - 10 and 15 knots elsewhere
- Four tanker failure scenarios
  - Rudder failure at 35° with engine shutdown
  - Rudder failure at 20° with engine shutdown
  - Rudder failure at 10° with engine shutdown
  - Rudder failure at 35° with engine backing
- Multiple combinations of failure recognition and tug notification time delays
  - Four combinations for Valdez Narrows
    - 30 or 60 seconds for recognition
    - 30 or 60 seconds for tug notification
  - Monte Carlo simulation of time delays in Valdez Narrows and central PWS
  - One time delay combination for Valdez Arm, Hinchinbrook Entrance and the Gulf
- Multiple tug deployment scenarios
  - Untethered and tethered tugs in Valdez Narrows and Valdez Arm
  - Untethered close escort, lagging escort, standby but underway deployments or anchored deployments at strategic locations in central PWS and Hinchinbrook Entrance
- Multiple tug positioning for emergency assist
  - Alongside aft quarter
  - Alongside forward quarter
  - On transom as rudder tug (conventional tugs) or for assist on a line (tractor tugs)
  - Rigged forward for towing
  - Tandem towing with two tugs
  - Cross wind towing with one tug
  - Upwind towing

A study formulated by producing scenarios that are combinations of the above described variables can quickly become enormous. The Disabled Tanker Towing Study contains the results of 1,179 simulation cases, not including the results of the Monte Carlo investigation.

The matrix of simulation cases investigated may include combinations which for operational reasons cannot be successfully implemented. However, the practical issues associated with any proposed escort operation and emergency response maneuver can and must be carefully studied by the appropriate experts.

The study was formulated as an analysis of the existing system, proposed alternatives and trends in disabled tanker control as a function of the independent variables. It was not set up to be the sole basis for designing an escort vessel or escort system.

**Evaluation of Results**

To judge the success or failure of an emergency response maneuver, the DTTS T defined a series of red zones. Entry into a red zone is defined as an escort system failure. The boundaries of the red zones were chosen based on the available maneuvering room and the proposed emergency response action. This methodology was chosen in part because the 10 fathom contour in Prince William Sound (or other potential grounding depth) is generally coincident with the shoreline, thus leaving no safety margin for uncertainties. Table 8 summarizes the chosen red zone definitions.

<table>
<thead>
<tr>
<th>Location</th>
<th>Red Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valdez Narrows</td>
<td>Between shore and 300 yards from tanker trackline.</td>
</tr>
<tr>
<td>Valdez Arm</td>
<td>Between shore and 1/2 n.m. offshore from the 10 fathom contour, except at Buoy 9 and Rocky Point between shore and 300 yards from outside edge of tanker lanes</td>
</tr>
<tr>
<td>Prince William Sound</td>
<td>Between shore and 1 hour offshore at the drift rate of the three sizes of tankers in 60 knot 1 minute average winds with associated wave drift forces</td>
</tr>
<tr>
<td>Hinchinbrook Entrance</td>
<td>Between shore and 1 n.m. offshore from the 10 fathom contour, except at Zaikof Point &amp; Cape Hinchinbrook between shore and 1/2 n.m. offshore from the 10 fathom contour</td>
</tr>
</tbody>
</table>

**Results**

Several methods are available to present the results of an operations analysis. The first is to show disabled tanker tracklines plotted over an outline chart of the area being considered. Several examples are shown in Figs. 15 through 22. The boundaries of the red zones are shown as straight lines approximately parallel to the shore.

The first three figures show variants for escort in Valdez Narrows. Fig. 15 shows the simulated trackline
of a disabled 265,000 dwt tanker in a worst case scenario, assuming four tugs in untethered escort. This scenario models the escort plan that was in place prior to the completion of the towing study. Although there is adequate power available from the tugs to restore the tanker to its original heading, there is inadequate time and space available to successfully complete the maneuver if a worst case incident were to occur. Fig. 16 shows a similar maneuver with a 7,200 HP nozzle tug tethered as a rudder tug and a 5,750 HP nozzle tug in close escort. Comparing this figure with that plotted in Fig. 17 demonstrates the consequences of reduced transit speed, reduced wind speed and reduced failure recognition time. The tug deployment and operating conditions modeled for Fig. 17 are representative of the escort plan implemented following the completion of the towing study.

Figs. 18 and 19 are two examples of rescue towing maneuvers in Valdez Arm. The scenarios differ only in the tanker transit speed. Both show a 265,000 dwt tanker with a 7,200 HP nozzle mg in untethered escort. Winds are initially on the port beam blowing 45 knots with significant wave heights of 12.3 feet from the SE. The time required to move from the escort position and maneuver to the bow of the tanker and rig a towing connection is modeled as 40 minutes. In the first scenario the tanker is traveling at 10 knots, in the second it is traveling at 6 knots. The difference in the vessels’ behavior with a 35° starboard rudder is clearly demonstrated. When traveling at 10 knots the turning moment generated by the rudder is greater than that produced by the wind force on the superstructure, resulting in an initial turn to starboard. At 6 knots the reverse is true and the vessel turns to port. Other scenarios developed for the evaluation of escort maneuvers in Valdez Arm are contained in Ref. [8].

Fig. 20 is one example of several hundred tracklines produced for the investigation of rescue towing scenarios in the open waters of central Prince William Sound. The track shows the initial turn of the tanker to starboard, its downwind drift without tug assistance, the effects of a 5,750 HP open wheel tug that is unable to tow the tanker to windward, and finally the rigging of a second tug and the success of the tandem tow. The scenario shows that the maneuver would be successful if the disabling failure occurred in the location shown; however, if it were to occur abeam of Glacier Island (to the northwest), a grounding would not have been prevented.

The final two figures (Figs. 21 and 22) show tracklines for two examples of a rescue tow maneuver in the Gulf of Alaska. The scenarios for these cases are identical, however the first shows a tow with a 7,200 HP nozzle tug and the second, shows the tow with a 22,000 HP deep sea salvage tug. Clearly in the first example the tug does not have adequate power to prevent the disabled vessel from continuing its downwind drift toward Montague Island. The second figure shows that the salvage tug is able to maneuver the disabled ship. There are numerous rescue tow
that a study of this complexity contains nearly 1,200 such figures, it is easy to imagine the difficulties of presentation and interpretation of the results.

However, the results of an operations analysis can also be presented in a graphical form as plots of off-track deviation as a function of some of the underlying scenario parameters. In this way an escort vessel's ability to control a disabled vessel with decreasing tanker speed or decreasing wind speed is demonstrated. Figs. 23 and 24 show examples of deviation from initial track as a function of wind speed and transit speed. The examples show the dependency of transfer distance when operating wind speed is reduced from 45 to 30 knots or when transit speed is reduced from 6 to 5 knots. A comparison of Figs. 23 and 24 demonstrates the significance of prompt intervention (reduced time delays), especially when wind speeds and transit speeds are reduced to a level where the tugs have adequate power to intervene effectively.

Other dependencies can also be shown graphically. An example of off-track distances as a function of failure rudder angle is shown in Fig. 25. Other combinations of the scenario parameters are presented in Ref. [8].

Fig. 17 Computer Simulation of Emergency Assist in Valdez Narrows

Fig. 18 Computer Simulation of Rescue Towing in Valdez Arm

Fig. 19 Computer Simulation of Rescue Towing in Valdez Arm
The results of the Monte Carlo simulations for time delay variability are presented in Table 9 for Valdez Narrows and Table 10 for central Prince William Sound.

An appropriate probability distributions was selected to describe the random nature of these delays. The distribution function incorporates the essential characteristics of real-world time delays. The time delays are positive and not less than a prescribed minimum value. A practical upper limit is required. The probability distribution should not only account for the normal deviations in the time required to do a job but also incorporate the possibility of a significant delay due to an external event such as equipment failure or change in weather. The distribution function is required to be asymmetric and have upper and lower bounds. A beta distribution was chosen. The distribution function is fully described and the parameters used are summarized in Ref. [8]. The mode and the variance of time delays are estimates based on a careful evaluation of the actions required between failure event initiation and application of tug force. The minimum, maximum and mean are the parameters used to define the distribution and are adjusted to yield the postulated mode and variance.
Parametric Study of Emergency Assist – Valdez Narrows
7200 HP Nozzle Tug vs Rudder Tug, 5750 HP Tug arrives from Escort Position
Failure Recognition Time Delay: 50 sec
Tug Notification Time Delay: 50 sec
Failure Rudder Angle: 35 deg
Scenario: Valdez Narrows,
7,200 HP Nozzle Tug Tethered, 5,750 HP Nozzle Tug Untethered

Each mean and standard deviation of transfer distance presented in Table 9 is the result of 600 Monte Carlo trials. Every trial independently sampled the beta distributions for time delays for failure recognition and tug notification, time for first tug to become effective and time for second tug to become effective. The results show a wide variability in transfer distances even though the variability in the time delay parameters is fairly narrow banded.

Table 10 presents the results of 1,000 trials for three tanker sizes in central Prince William Sound. The table shows the probabilities that the disabled vessel will drift between 4 and 6 N.M. before the tandem tow becomes effective. A beta distribution is again assumed for failure recognition, tug notification and for the first and second tugs to become effective. The most probable time delay for the first tug to maneuver and become effective is 39 minutes with a standard deviation of 9 minutes. The second tug does not begin its maneuver and transfer of tow wire until after the first is connected and pulling. The model for the second tug uses 49 minutes as the most probable period of additional delay with a standard deviation of 9 minutes. The longer time results from the requirement to maneuver in the presence of the first tug and its tow wire.

Summary of Prince William Sound Study
The simulations of the worst case scenario demonstrated the need to reconsider untethered escort through Valdez Narrows. The demands resulting from the worst case scenario; 6 knot transit speed, 45 knots of wind, 6 foot seas, 35° rudder failure, one minute failure recognition time before engine shutdown and one additional minute before tugs are called, exceed the abilities of all existing and alternative tug types to control the disabled vessel in the required distance. However, the simulations show that a disabled vessel of any of the three sizes studied can be kept out of the red zone of the Narrows if the worst case failure were to occur with 45 knot winds astern, provided that the transit speed is reduced to 4 knots and tethering of one tractor astern and one ERV alongside, or one conventional tug as rudder tug with two additional tugs alongside, was implemented. Another solution found from the simulations has been implemented as the current escort procedure. It incorporates reducing transit speed to 5 knots and
Table 9

Probability of Tanker Transfer Exceeding Selected Distances in central Prince William Sound

<table>
<thead>
<tr>
<th>Run</th>
<th>Distances to red zone</th>
<th>Naked Is.</th>
<th>4 n.m.</th>
<th>4.5 n.m.</th>
<th>5 n.m.</th>
<th>5.5 n.m.</th>
<th>6 n.m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>9a.0</td>
<td>3.7 n.m.</td>
<td>6 n.m.</td>
<td>95%</td>
<td>67%</td>
<td>28%</td>
<td>7%</td>
<td>1%</td>
</tr>
<tr>
<td>9a.2</td>
<td>3.5 n.m.</td>
<td>6 n.m.</td>
<td>99%</td>
<td>84%</td>
<td>48%</td>
<td>17%</td>
<td>4%</td>
</tr>
<tr>
<td>9a.4</td>
<td>3.4 n.m.</td>
<td>6 n.m.</td>
<td>32%</td>
<td>9%</td>
<td>2%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

9a.0 265,000 dwt tanker with 5,750 HP open wheel tug and ERV in continuous escort.
9a.2 170,000 dwt tanker with 5,750 HP open wheel tug and ERV in continuous escort.
9a.4 90,000 dwt tanker with 5,750 HP open wheel tug and ERV in continuous escort.

Redefining the closure condition so that no transits will take place in wind speeds above 30 knots. In addition the 7,200 HP nozzle tug will be tethered as a rudder tug.

In the worst case scenarios for areas of Prince William Sound other than the Narrows, the primary issues are distances to the leeshore and adequate towing ability of the tugs in the worst case environment. Outbound laden tankers in the southbound traffic separation system (TSS) lanes in Valdez Arm, central Prince William Sound and Hinchinbrook Entrance will not have adequate searoom in the worst case scenario for the rescue tow to be rigged and control gained before the disabled vessel enters the corresponding red zone. To succeed in the worst case scenario the outbound vessel would need to be able to move to the east, away from the leeshore in each area.

In addition, adequate towing power is required. In the worst case conditions in Valdez Arm, any of the existing tugs would be capable of towing any of the three sizes of tanker to windward. In central Prince William Sound the smallest class of tug requires additional assist from an ERV tug to succeed in towing any of the three tankers to windward. The largest class tug is capable of towing any of the tankers in these conditions. In the Hinchinbrook Entrance scenarios, a salvage tug of the size modeled or the 7,200 BHP conventional nozzle equipped tug in tandem with an ERV tug is required for a tow to windward. In the modeled worst case conditions in the Gulf of Alaska, a tow to windward is possible only with the salvage tug and 90,000 dwt tanker combination. In some circumstances, depending on the location of the disabling event with respect to the local geography, the currents, and the wind and wave directions, changing the downwind drift heading of the disabled vessel can be adequate to bring the ship into the lee of an island or keeping it from grounding until the weather moderates.

The results of the parametric study provide additional insight into operating conditions and assist maneuvers that can potentially improve the safety of transit from Port Valdez to the Gulf of Alaska. The results clearly show the value with respect to off-track distances of reduced transit speed, lower wind conditions and faster response times for the application of corrective tug forces. Although these trends are not surprising, the results of the study make it possible to evaluate the combination of conditions which will provide for the best achievable level of safety for the transport of oil by ship through Prince William Sound.

Table 10

Probability of Tanker Entering Red Zone in Valdez Narrows

<table>
<thead>
<tr>
<th>Run</th>
<th>Distance to red zone (yd)</th>
<th>Transfer (yd)</th>
<th>w/ modal delays</th>
<th>mean</th>
<th>σ</th>
<th>Probability of transfer (yd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a.11</td>
<td>300</td>
<td>296</td>
<td>245</td>
<td>185</td>
<td>33%</td>
<td>&gt; 300 yds</td>
</tr>
<tr>
<td>5a.6</td>
<td>300</td>
<td>255</td>
<td>229</td>
<td>200</td>
<td>27%</td>
<td>&gt; 300 yds</td>
</tr>
<tr>
<td>5a.7</td>
<td>300</td>
<td>304</td>
<td>266</td>
<td>184</td>
<td>36%</td>
<td>&gt; 300 yds</td>
</tr>
<tr>
<td>5a.8</td>
<td>300</td>
<td>200</td>
<td>178</td>
<td>135</td>
<td>16%</td>
<td>&gt; 300 yds</td>
</tr>
</tbody>
</table>

4a.11 Smallest tanker (90,000 dwt) at 4 knots, most effective tug tethered and working as a rudder tug and with an ERV coming from close escort.
5a.6 Largest tanker (265,000 dwt) at 4 knots, 7600 VSP tug tethered and working aft, with an ERV tug to stem quarter.
5a.7 Midsize tanker (170,000 dwt) at 4 knots, 7600 VSP tug tethered and working aft, with an ERV tug to stem quarter.
5a.8 Smallest tanker (90,000 dwt) at 4 knots, 7600 VSP tug tethered and working aft, with an ERV tug to stem quarter.
APPLICATION OF SYSTEMS APPROACH IN SAN FRANCISCO BAY

The San Francisco Bay study was carried out at the initiative of Chevron Shipping Company and ARCO Marine, Inc. An industry based Technical Advisory Group (TAG), consisting of tanker owners, tugboat operators and harbor pilots provided guidance throughout the course of the study. The primary objective was to define the escort requirements of tank vessels operating in San Francisco Bay, taking into account the waterway geometry, vessel size and transit speed. In view of this, a new systems approach was adopted: the tanker’s need or demand for effective assistance was separated from the capability of the tugs required to provide the assistance. The tanker demand was obtained as a function of the regulatory “variables” of ship mass and speed, with fixed parameters of weather and water depth, while satisfying the constraints of the waterway. Water depth can also be considered a component of the waterway constraint; however, because there is reasonably uniform depth in each escort zone, it was defined as a fixed parameter for this study. The tugboat’s capability was then matched with the tanker demand to obtain a valid escort solution.

The following three tankers or tanker classes were selected based on the recommendations of TAG as generally representative of the tanker fleet transiting San Francisco Bay.

- 153,000 DWT tanker, nominally called Class I
- 80,000 DWT tanker, nominally called Class II
- 40,000 DWT tanker, nominally called Class III

The following tugs were selected for the study from the fleet of tugboats engaged in escort duty in the bay.

**Conventional Tugboats**
- 7,200 HP twin screw conventional tugboat (213 kips bollard), called Class I
- 7,200 HP twin screw conventional tugboat (150 kips bollard), called Class II (high)
- 5,650 HP twin screw conventional tugboat (89 kips bollard), called Class II (low)
- 2,900 HP twin screw conventional tugboat (75 kips bollard), called Class III

**Tractor Tugboats**
- 4,000 HP cycloidal tractor (100 kips bollard)
- 3,200 HP Z-drive tractor (100 kips bollard)

**Concepts of Tanker Demand and Tug Capability**

The systems approach assesses demand and capability as a way of resolving the escort problem. The essential focus is on the demands of the tanker, in the event of disabling failure as it transits the bay. The type and extent of assistance required will depend on the type of casualty, the tanker’s maneuvering characteristics, its speed, ambient conditions and the proximity of hazards. These parameters together establish the tanker demand that has to be met by the escort vessel.

Tankers transiting the San Francisco Bay area range from about 5,000 DWT to about 175,000 DWT and consist of both US flag and foreign flag vessels. This size range and diversity produces a large spectrum of tankers in terms of age, dimensions, equipment type and crew capability. In principle, the “tanker demand” is unique for each vessel since each vessel or vessel class has its own maneuvering behavior. However, it is clear that such a vessel-specific requirement is not feasible in the context of the kind of rule-making that is anticipated. Regulatory definition of tank vessels must be generic, addressing easily quantifiable parameters such as deadweight or displacement. The first important parameter to be considered is the physical mass of the vessel.

The second important variable is transit speed. As speed increases, the kinetic energy of the tanker increases in a quadratic manner. When a disabling casualty occurs, this kinetic energy has to be controlled by the escort vessel. Speed also has an important consequence on the tanker’s maneuvering behavior. For the case of propulsion failure, the stopping distance of the tanker increases with speed. For the case of steering failure, the rate of turn is proportional to speed.

Other important parameters are ambient conditions and the hazards imposed by the waterway. The ambient conditions are defined by wind speed and current. For the purposes of this study they have a fixed value, as determined by TAG. The hazards imposed by the waterway are varied, consisting of bridge piers, islands, rocks, grounding contours and sides of channels. In part, they are accounted for by the defined escort zones. These hazards have been extensively investigated and quantified in this study. In the theoretical investigations, they are introduced as distance constraints that limit the viable solutions for the tanker demand problem.

The escort vessel must have the capability to meet the demand of the tanker that it is escorting. The tugboat’s capability has to be matched in conjunction with the parameters that establish the tanker demand.

Given a failure, the problem has been formulated in terms of the required “tanker demand” to effect a maneuver that will control the tanker within the design constraint. The capability function indicates the ability of a given tug to meet that demand. It follows that when capability meets or exceeds demand, the tug is able to control the tanker as required. In this study, the demand and the capability functions were defined and the above premise was validated.
Tanker Routes and Navigational Constraints

The tanker routes for vessels transiting San Francisco Bay were provided by the Technical Advisory Group. The route chosen is representative of the approximate average path of the vessels from the COLREGS line to either Anchorage 9 or north to the refineries at Richmond or Martinez. The State of California tug escort regulations covering San Francisco Bay divide the region into six escort zones. At the request of the project administrators, the escort zones were reconfigured for this analysis into Escort Areas I and II. The escort areas as they have been defined and used in this analysis are shown in Figure 26.

![Fig. 26 San Francisco Bay Tanker Escort Areas.](image)

The navigational constraints in the two escort areas were quantified based on the statistical approach previously described. Histograms of the available headreach and transfer distances were constructed and the cumulative distributions used to determine the percentiles for the particular transit of interest (see, for example, Figure 27). The 95th percentile distances were eventually chosen by the administrators of the project to define the navigational constraint. These distances are summarized in Table 11.

![Fig. 27 Histogram of Transfer Distances for the Route from COLREGS line to Buoy R12.](image)

Figure 28 shows the 95th percentile constraint plotted as a distance on either side of the normal track from COLREGS to Buoy R12. Areas where the 95th percentile distance crosses the constraining depth contour are circled. Similar charts were prepared for the other transit routes.

### Table 11

<table>
<thead>
<tr>
<th>Area</th>
<th>Route</th>
<th>95th Percentile Distance (ft)</th>
<th>Hdrch.</th>
<th>Tmfr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>COLREGS - Anch. 9</td>
<td>5,500</td>
<td>5,500</td>
<td>1,640</td>
</tr>
<tr>
<td>I</td>
<td>COLREGS - Buoy R12</td>
<td>5,440</td>
<td>5,440</td>
<td>1,830</td>
</tr>
<tr>
<td>I</td>
<td>Anch. 9 - Buoy R12</td>
<td>4,860</td>
<td>4,860</td>
<td>2,000</td>
</tr>
<tr>
<td>II</td>
<td>Buoy R12 - Benicia Bridge</td>
<td>3,190</td>
<td>3,190</td>
<td>280</td>
</tr>
</tbody>
</table>

Failure and Assistance Scenarios

Two worst case tanker failure scenarios were defined, where the worst case implies the assumption of an extreme tanker casualty. In the first case, it was assumed that there was loss of propulsion and the tanker had no means to control its speed or heading, and the rudder was assumed locked on centerline. In the second case, the tanker was assumed to have a 35 degree hard-over rudder failure. Simultaneous shutdown or loss of the propulsion system upon rudder failure recognition was assumed.

The tugs were assumed to be in continuous escort within the bay. Two time delays were investigated, corresponding to the cases of the assist tugboat tethered and untethered. The time delays were provided by TAG and reflect data from the full scale timing trials described in a later subsection. It was assumed that the tug was effective from 30 seconds after failure in tethered escort mode. In the untethered escort mode, additional time was required for the tug to approach the tanker and to make up. Hence in this mode, the tug was assumed to be effective from 2 minutes after failure.
Initially, a set of simulations were carried out using the Glosten program SHIPMAN to study the relative effectiveness of the various alternative maneuvers discussed previously. It was found that over a large range of speeds, tanker sizes and time delays, the retard maneuver was the most effective. Thus, it was determined that retarding the tanker was the maneuver of choice on which the demand and capability functions were to be based for either propeller or rudder failure. Figure 29 shows the average transfer following loss of
steering as a function of displacement and for alternative maneuvers. This does not imply that the retard maneuver is always the most effective or that it should necessarily be the maneuver of choice for all accidents in the bay. Rather, the intent was to use a consistently effective maneuver for the determination of tanker demand. In this regard, consistency was with respect to tanker sizes, speed, time delays and type of tug. The retard maneuver was found to meet this standard of consistency.

The assist maneuver was also found to be generally effective. However, the following subjective considerations had to be noted:

• In an assist maneuver the tanker is turned around and thus presents a broadside to the side of the channel. If the maneuver should fail, extensive damage could be caused from a tear alongside the hull. With a conventional tugboat, the steering force is accompanied by a pushing force which keeps speed on the vessel.

• Conversely, in the retard maneuver the speed of the tanker is reduced while the tanker turns. Even if the maneuver should fail, the tanker is almost perpendicular to the side of the channel. If collision against the channel side or bottom should occur, it will be at low speed and the consequences should be small due to the tanker bow and the presence of the collision bulkhead. The chances of damage to the cargo tanks are reduced.

The oppose maneuver was found to be effective for low speed tethered escort. Such low speed tethered transits are suitable for Escort Area II where the available reach and transfer distances are considerably smaller. In the event of rudder failure, the tug provides immediate steering assistance to oppose the turn of the tanker. In case of propeller failure, the tug serves to reduce the speed of the tanker and keep it on course until the arrival of additional tugs or until the tanker is able to drop anchor.

Tanker Demand for Propeller Failure

For propeller failure, the tanker demand and tug capability functions were developed based on the tug applying maximum retarding force to limit the headreach of the tanker. A suitable candidate for the demand function was found to be the constant astern force to be applied to a disabled tanker. This constant force is applied after the tanker has coasted for a period of time corresponding to the time delay in assistance and the force must be sufficient to stop the vessel within the allowable headreach.

The constant astern force as a function of the stopping distance calculated based on Hewins et al. [16] is shown in Figure 30 for the case of the Class I tanker with an initial speed of 10 knots over ground. A straight path and centered rudder were assumed. Similar plots were initially constructed for a range of tanker displacements, initial speeds, time delays and tidal currents. The effect of such factors as the time delay in tug assistance and deployment of drogues from an assisting tug, were demonstrated. The astern force required increases with time delay and this increase is critical for shorter stopping distances. The effectiveness of auxiliary braking devices such as brake flaps or drogues [17] is proportional to the square of the speed through water and therefore decreases rapidly as the ship speed falls.

![Figure 30](image-url)
allowable straight-line stopping distance. This is based on permitting the tanker to turn, fully utilizing the available transfer as well as the headreach during a stopping maneuver. Thus the stopping distance in Escort Area I was calculated to be 6,500 feet. Since stopping distance represents the distance covered by the center of gravity of the ship, an effective stopping distance was then defined for each vessel by subtracting half a ship-length from the available 6,500 feet. Suitable allowances to offset the loads due to astern winds were then added. Tables of average braking demands were prepared for tanker displacements ranging from 20,000 to 180,000 LT, speeds of 6 to 12 knots through water, prevailing currents up to 4 knots, time delays of 30 and 120 seconds, and astern winds up to 20 knots. These tables were then used, together with similar tables for the steering demand, to determine the governing average braking demand.

Tanker Demand for Rudder Failure

The retarding maneuver was used to determine the demand definition for steering failure also. Although with propeller failure it is possible to develop an analytical procedure based on the assumption of straight-line stopping, with rudder failure the energy dissipation mechanism is much more complex. While the initial kinetic energy is the same in both cases and the ship is brought to a stop, the work done by the retarding force may, in fact, be only a small fraction of the initial kinetic energy in the case of rudder failure.

The approach taken was to carry out numerical simulations over the range of parameters to determine the tanker demand for steering failure. The tanker demand is determined in the form of constant retarding force, which brings the tanker to a stop. This procedure associates a constant retarding force to the transfer during the maneuver. Simulations were carried out with the Glosten program SHIPMAN. The simulation program begins with the tanker at an initial speed and propeller setting and with the rudder centered. At time zero, the rudder is moved to hard-over. Fifteen seconds later, the loss of steering is recognized on the bridge. The simulator then orders the engine shutdown with a propeller wind-down at 4 RPM per second. The delay for tug notification is 15 seconds from the recognition of the casualty. For tethered escort, there is no further reaction time delay. For untethered escort, there is a tug reaction time delay of 90 seconds after notification. The sequence of events is illustrated in Figure 11. For each tanker and speed, a full simulation is carried out with a constant retarding force applied after the notification and the reaction time delay. With this constant retarding force, the tanker is brought to zero forward speed. The maximum transfer is then recorded along with the corresponding retarding force. This procedure was repeated for all three tankers at various displacements, for speeds ranging from 6 to 12 knots through water, wind speeds up to 20 knots and retarding forces to a maximum of 500 kips.

Based on the simulation results, the constant force required to limit tanker transfer to within the available off-track distance (see Table 11) was plotted as a function of displacement. The data for these tanker demands as a function of displacement were quite consistent. But the effect of different tanker characteristics and loading resulted in some scatter of the data. The effect of not tethering the tug was generally significant and the additional demand ranged from about 25% at 6 knots to 75% at 10 knots. Figure 31 is for tethered escort at 10 knots in 20 knot astern wind. From these plots, tables giving the average braking demand were prepared as in the case of propeller failure.

![AVERAGE ASTERN FORCE REQUIRED TO STOP TANKER](image)

Fig. 31 Average Braking Demands for Rudder Failure as a Function of Displacement for a Speed of 10 knots Through Water and for Prescribed Transfer Distances

It was assumed that any prevailing current was aligned with the initial track of the tanker, either assisting or opposing the vessel. This assumption is less reasonable in open waters and more reasonable in constrained waters. Since the constraint on off-track distance will be imposed mostly in constrained waters (under bridges, through channels, etc.), it is reasonable to make the assumption of collinearity of ship track with tidal current. If the ship track is parallel to the current, then there is no navigational correction due to current on the off-track distance since the current is then by definition, orthogonal. Thus the reach distance will need to be corrected for a given current but the off-track distance is not altered. For the steering failure case, this
correction on reach is irrelevant since reach is not the constraining factor. What is important, however, is that the current changes the speed through water for both the tanker and the assisting tug.

**Tug Capability**

The tanker demands defined above, which may be called the *average braking demands*, have to be matched by the tugboat's ability to apply a retarding force. The tugboat's ability is quantified by a pair of speed-dependent vector force functions: the maximum braking force and any associated steering force. However, they do not provide an accurate measure of the overall capability of the tugboat in meeting a specified demand. A suitable *average braking capability* needs to be defined. This was done by averaging the braking force over speeds as follows:

$$C(v_0) = \frac{1}{v_0 + v_c} \int_{v_0 + v_c}^{v_0} f_b(v) \, dv$$

(1)

Here, $f_b(v)$ is the tug's braking force as a function of its speed through the water, $v_0$ is the initial speed through water and $v_c$ is the prevailing current speed. $v_c$ is positive for an assisting current (in the same direction as the tanker velocity) and negative for an opposing current (in a direction opposite to tanker velocity). Note that in an assisting current, the tanker has to make sternway at the speed of current in order to remain stationary with respect to ground, whereas in an opposing current, the tanker is effectively brought to a stop when its speed through water is equal to the current velocity.

For conventional tugs, due to their ineffectiveness at speeds higher than the clutch-in speed, the capability predicted by Equation 1 is multiplied by a penalty function defined by:

$$p(v_0) = \begin{cases} 
1 & \text{for } v_0 < v' \\
\frac{v' + v_c}{v_0 + v_c} & \text{for } v_0 > v'
\end{cases}$$

(2)

where $v'$ is the clutch-in speed. A rough estimate of the capability predicted by Equations 1 and 2 for most conventional tugs in slack water is simply:

$$C_{conv}(v_0) = \begin{cases} 
f_b(0) & \text{for } v_0 < v' \\
f_b(0) \left( \frac{v'}{v_0} \right)^2 & \text{for } v_0 > v'
\end{cases}$$

(3)

where $f_b(0)$ is the astern bollard. The clutch-in speed for each conventional tug is unique and is not necessarily a constant as discussed previously. At the direction of TAG, the complexities of the clutch-in problem were simplified by assuming that all conventional tugs can engage the clutch at 7 knots and begin to back down.

**Validation of Demand and Capability Definitions**

The above definitions of the demand function and the capability function had to be validated. The task was to prove that whenever tug capability meets or exceeds tanker demand, the tug will indeed stop the tanker within the allowable distance. To this end, a number of simulations were carried out using specific tanker-tug combinations. It was necessary to account for the variation of the tug braking force as a function of speed through water and the ineffectiveness of most conventional tugs at speeds higher than about 7 knots due to clutch-in problems. The trackreach in case of propeller failure and transfer in the event of rudder failure were then noted. In each case, the average braking capability of the tug was shown to match the average braking demand of the tanker corresponding to the simulated trackreach (propeller failure) or transfer (rudder failure), thus demonstrating the validity of the demand and capability formulation.

**Full-scale Trials**

Full-scale tanker-tugboat trials were conducted in San Francisco Bay Anchorage 9 in August of 1994. The tanker participating in the tests was the *GTT Chevron Oregon*, a 40,000 DWT vessel owned by Chevron Shipping Company. This vessel has a gas turbine-electric propulsion with a controllable pitch propeller driven at constant revolutions. Three tugboats participated in the trials. They were the *Delta Billie* (3,200 HP Z-drive tractor), *American Eagle* (5,650 HP Class II conventional) and *Orion* (2,900 HP Class III conventional). On the day of the test, relatively calm weather and clear skies prevailed.

The program consisted of three different categories of tests:

- Make up tests
- Turning circles
- Pull tests

The make up tests were intended to provide estimates of the time required for a tugboat in close untethered escort to make up in an emergency. A set of eight make up tests were conducted. The set covered initial tanker speeds of 8 and 10 knots through water, escort positions astern and abeam, and lines from tugboat and tanker. In each test, the time taken by the tugboat to arrive at the stern, time to make up and time to pay out and put tension in the line were measured using stopwatches.
The average time to apply tension in the towline was found to be 2 minutes from the instant of notification.

Two turning circles were carried out in shallow water depths. These tests were designed to examine the effect of shallow water, which exists in many parts of San Francisco Bay, on the maneuvering characteristics of the tanker. The tanker location and heading were measured at 10 second intervals until a 360 degree turn was completed. The information was used to calibrate the numerical tanker model for shallow water maneuvering.

The pull tests simulated the action of a tugboat following loss of tanker power or steering. The participating tugboat remained tethered to the tanker transom for the duration of these tests. The tether arrangement incorporated a load cell rigged between the tugboat's towline and the tanker's bitt. This load cell was used to determine the tension in the towline during the course of the tests. Prior to each test, the tanker steered a steady course at the intended test speed with the tugboat staying close behind so as to maintain slack in the lines. For propeller failure simulations, the tanker reduced the propeller pitch to obtain zero thrust. After a time delay of 15 seconds, the tugboat was notified. For steering failure cases, a hard-over rudder was first applied. After 15 seconds, the propeller pitch was reduced as before, and simultaneously the tugboat was notified. The tugboat then applied maximum braking force to retard the tanker. The location, heading and towline tension were measured at 10 second intervals.

A total of seven pull-tests were conducted and the results were used to verify the tugboat and tanker models used in the study.

A detailed description of the tests can be found in the Glosten report on the San Francisco Bay Tanker Escort Study [9].

**Statement of Escort Requirements**

Based on the results of the study, tug requirements for Escort Area I were stated in terms of a quantity called the *average braking demand*. The average braking demand was obtained as the larger of the propeller demand and the steering demand for each combination of displacement, speed through water, time delay and wind speed. In general for a given speed through water, the steering demand was found to exceed the propeller demand in slack and opposing currents, whereas the propeller demand was found to exceed the steering demand in assisting currents. Wind effects for the chosen wind speed were found to be marginal. The demands were presented in the form of tables. Each table gave the braking demands for tanker displacements ranging from 20,000 to 180,000 LT, speeds of 6 to 12 knots through water, and time delays of 30 seconds and 2 minutes corresponding to tethered and untethered escort. Table 12 is an example of average braking demands for the case of a 2 knot assisting current.

The assisting tugs were then required to have an equivalent *average braking capability* to meet this demand. Table 13 was provided to assist in the selection of tug combinations satisfying this requirement.

**Table 12**

<table>
<thead>
<tr>
<th>Displacement (1000*LT)</th>
<th>30 seconds</th>
<th>2 minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Speed through water (knots)</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Speed over ground (knots)</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Average Braking Demand (kips)</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>20</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>40</td>
<td>45</td>
<td>65</td>
</tr>
<tr>
<td>60</td>
<td>55</td>
<td>85</td>
</tr>
<tr>
<td>80</td>
<td>60</td>
<td>110</td>
</tr>
<tr>
<td>100</td>
<td>80</td>
<td>155</td>
</tr>
<tr>
<td>120</td>
<td>100</td>
<td>195</td>
</tr>
<tr>
<td>140</td>
<td>125</td>
<td>215</td>
</tr>
<tr>
<td>160</td>
<td>145</td>
<td>250</td>
</tr>
<tr>
<td>180</td>
<td>160</td>
<td>285</td>
</tr>
</tbody>
</table>

14-30
Table 13
Average Braking Capability

<table>
<thead>
<tr>
<th>Speed through water (knots)</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tug</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Class III</td>
<td>45</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>Class II (low)</td>
<td>70</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td>Class II (high)</td>
<td>115</td>
<td>85</td>
<td>55</td>
</tr>
<tr>
<td>Class I</td>
<td>130</td>
<td>100</td>
<td>65</td>
</tr>
<tr>
<td>Z-drive Tractor</td>
<td>90</td>
<td>95</td>
<td>100</td>
</tr>
<tr>
<td>Cycloidal Tractor</td>
<td>110</td>
<td>115</td>
<td>125</td>
</tr>
</tbody>
</table>

In Escort Area II, the tight channel constraints require the tugs to be tethered to enable immediate assistance. Analysis of a representative set of cases showed that the tankers, given propulsion or steering failure, needed to be steered by the escort tugs. Based on a number of simulations of low speed tethered escort, the following rules for Escort Area II were derived which were predicated on the corresponding requirements in Escort Area I.

- A tug with adequate capability to escort a given tanker untethered in Escort Area I, can escort the same tanker at the same speed through Escort Area II provided it is tethered.
- A tug with adequate capability to escort a given tanker tethered in Escort Area I can escort the same tanker through Escort Area II provided that: (1) it remains tethered, (2) and the speed of transit is reduced to 6 knots through water.

Figure 32 shows the results of simulations of some valid escort solutions for Escort Area I superposed on the area map. The figure illustrates the anticipated outcome of a steering failure and subsequent tug assistance for various locations along the tanker route within the bay. In 1995, additional studies of single failure scenarios were carried out which are documented in a separate Glosten report [18]. The Harbor Safety Committee is expected to adopt tanker escort rules for San Francisco Bay based on the Glosten studies [9,18].

COMPLIANCE WITH USCG RULES IN PUGET SOUND

The new USCG rules (33 CFR Part 168), which took effect on 17 November 1994, require a validated escort system for all tankers transiting Prince William Sound and Puget Sound. As indicated in the beginning of this paper, the rules have a two-part requirement. The first part (Section 168.50a) is a “safety in the waterway” requirement and the second part (Section 168.50b) is a “minimum capability” requirement.

The requirements of Section 168.50b can be quantified easily for each tanker. These “tanker demands” can be matched against known capabilities of tug combinations. The tanker operator can then choose one or more of these tug combinations that look feasible from operational and contractual perspectives. These tug combinations then have to be verified as viable escorts meeting the requirements in Section 168.50a.

In this connection, it should be noted that Section 168.50b(2) initially mandated escort performance capability sufficient to stop the tanker within the same distance that it could crash-stop itself from a speed of 6 knots using its own propulsion system. The tanker demands under this clause were representative of the astern thrust capability of the vessel. Thus a diesel ship that typically has 85% of ahead power available astern posed substantially larger demands compared to a steam ship of the same size with only 40% of its power available astern. This was tantamount to penalizing the more capable ships. This clause has been suspended.

In several recent studies for major tanker operators, a set of escort solutions for the Puget Sound area were identified and validated against the regulations. Initial selection of candidate escort solutions was done in
consultation with the tanker owners and tug operators and drew upon their extensive operational experience. For each escort solution, the demands and capabilities under 168.50b were initially quantified and the adequacy of the escort under this section demonstrated in charts like Figure 33. In the figure, the demands corresponding to each of the four clauses are shown as a percentage of the capability of the intended escort system. Thus for a valid escort solution, each should be less than the 100% level (except the stopping requirement which is currently suspended).

Fig. 33 Demonstration of Compliance with USCG Part B Requirements for the case of a 75K DWT Tanker Escorted by a 3,000 HP Tractor Tug and a 5,400 HP Conventional Tug

The adequacy of the escort under Section 168.50a then has to be demonstrated. This entails computer simulations of tanker maneuvering and some key assumptions regarding operations, failure scenarios, environmental conditions and navigational constraints. In Puget Sound, Rosario Straits and Guemes Channel, narrow waterways often restrict a tanker's off-track transfer while offering plenty of room for advance. Loss of steering was clearly the critical failure mode. In consultation with tug and tanker operators, it was decided that a rudder failure should be combined with engine shutdown, either voluntary or otherwise, for a worst case scenario. The USCG rules do not prescribe such a dual failure criteria in validating an escort. In fact, a recent study has clearly indicated the benefits of the tanker applying astern thrust following rudder failure. Nonetheless, the Prince William Sound and the San Francisco Bay studies [8,9] were both based on dual failure and this conservative assumption was carried through in Puget Sound.

Fig. 34 Demonstration of Compliance with USCG Part A Requirements for the case of a 75K DWT Tanker Escorted by a 3,000 HP Tractor Tug and a 5,400 HP Conventional Tug.

Navigational constraints were quantified based on the statistical approach described earlier. In accordance with the regulations, two dedicated tugs were always in escort. In tethered escorts, only the primary or the most capable tug was tethered prior to the casualty. Following tanker failure, both tugs performed the same maneuver after suitable time delays, with the primary tug at the stern and the secondary tug at the aft side of tanker.
The tanker failure and the postulated tug assistance were simulated using the Glosten program SHIPMAN.

The predicted trackline of the tanker was superposed over lines of allowable transfer for each escort area. Figure 34, for example, shows the predicted track of a 75,000 DWT tanker after hard-over rudder failure under the action of a 3,000 HP tractor and a 5,400 HP conventional tug. Figure 34(a) is for a speed of 10 knots and 34(b) is for 8 knots. The figures clearly demonstrate that with the postulated escort system, a speed of 10 knots is in full compliance with the rules in Puget Sound and Rosario Straits. A reduced speed of 8 knots is required in Guemex Channel.

Based on the study, escort selection guides were prepared for a majority of the tankers transiting through Puget Sound, Rosario Straits and the Guemes Channel. These guides provide a quick and convenient reference for selecting suitable combinations of escort tugs and transit speeds in demonstrable compliance with the recent USCG rules.

**SUMMARY AND CONCLUSIONS**

Oil transport involves risks of various kinds, many of which can be assessed, analyzed, planned for and mitigated. One risk scenario is that of a loaded tanker suffering a disablement during transit through a constrained waterway. The provision for tug escort is to reduce the likelihood of such a disabled tanker going aground.

Tanker escort practice has developed differently from one locale to another. The procedures in each port are responses to local precedents, physical conditions and local regulations. Escort practice has often been based on anecdotal accounts, demands from outside the maritime community, competitive pressures or incomplete analyses. In this paper, our efforts are directed at developing a rational basis and an analysis strategy for defining the demands of tanker escort and analyzing procedures currently in place.

A principal assumption is that a tanker disablement has occurred. More specifically, the studies underlying this paper have the presumption that the tanker is completely disabled having lost both steering and propulsion. At present there exists no database to validate or refute this hypothesis. It should be noted that this assumption of complete disablement of the tanker is conservative; indeed, it is appropriate to ask whether it is unnecessarily conservative.

Two methodologies to assess tanker escort have been detailed, namely, an operations analysis which is useful for investigating and modifying existing practice and a systems analysis which is geared towards rule-making. The two methods differ in their perspective and their objectives. The operations analysis is inherently microscopic, focused on examining specific tanker-tug combinations, with great attention to the detail of an escort operation and the likely response and consequence. This allows an existing practice to be modified to ensure that the tug(s) and tanker are properly matched for a desired transit speed in a design climatology. The systems analysis methodology is macroscopic and is geared to establishing a regulatory framework to improve safety in the waterway. A properly carried out systems analysis will ensure that all tankers escorted according to the regulatory framework will have suitable escorts. However, since the detail of each tanker and tug combination is lost, many tanker-tug combinations will be conservative relative to the postulated standard.

It should be noted that no standards currently exist for either the microscopic or the macroscopic perspective. Widely divergent views persist in the industry on several key elements of these analyses. A preliminary effort to set standards has been initiated by the US Coast Guard with the formation of an American Society for the Testing of Metals (ASTM) committee to set procedures for interpreting the US Coast Guard rules for tanker escort.

We believe that a collective effort on the part of the tanker industry, regulatory bodies, environmental agencies and other interested parties is needed to address the following important issues:

1) There is no recognized procedure to understand and quantify the global risk to a waterway as posed by oil transport. Studies such as the ones detailed in this paper address only conditional risk. They do not address causal factors for tanker accidents, other sources of oil spillage, likelihood of oil spillage upon grounding, spill response equipment available in the vicinity and the assets at risk given an oil spill. In the absence of the bigger picture of risk, it is quite possible that scarce resources are committed to tanker escort without a corresponding improvement in system safety.

2) It is essential to understand the frequency and types of tanker failures. A database of tanker disablements should be prepared for a more accurate list of failure scenarios. Specifically, the probabilities associated with individual and joint failures of the steering gear, wheelhouse indicators, propulsion machinery and control systems should be catalogued.

3) Quick recognition of failure on board the tanker is essential. In the studies carried out, recognition time for a rudder failure has ranged from 15 seconds to 60 seconds after initiation of the event. The consequence of late recognition in a narrow waterway can be disastrous. Steering failure alarm
systems such as those specified by USCG under 46 CFR Sub-part 113 are vital.

4) Once the failure is recognized, it is essential that a protocol for response exists. Such a protocol might vary over the transit route and be specific to a tanker-tug escort system. There should be minimal delay in responding (with such response as stopping propulsion or backing down) and in notifying the escorting tugs to assist. In our studies, this notification delay has ranged from 15 seconds to 60 seconds. The key to minimizing this delay is education and training. The tanker crew, the pilot and the tug crew need to be educated on the capability of the escort system and the assumptions that underlie it. They also need to know the alternatives if the failure differs from the design scenario. Education of this kind can be provided through training manuals and interactive PC-based simulators. Training may be carried out on full mission simulators or in the field.

5) There is no clear definition of what constitutes failure in an emergency scenario. For Prince William Sound, the "red zone" originated at the minimum allowable off-track distance. In both the San Francisco Bay and the Puget Sound studies, a certain level of risk of grounding was allowed due to the statistical methods employed. Moreover, grounding in soft mud might not lead to tank rupture. Double hull tankers should possibly be treated differently from single hull tankers.

6) Stopping the tanker using a line tethered to its stern is quite effective and has the added advantage of speed reduction. Thus, even if the maneuver is not fully successful, the associated kinetic energy of the tanker is much reduced. In order to allow for such a maneuver, improved deck fittings are necessary to withstand the forces imposed.

7) The effectiveness of tethered escort should be noted. If the casualty can be recognized early, the demand on a tethered tug is appreciably lower than that on an untethered escort tug. In a steering failure situation, the tethered tug can effectively steer a tanker. Except where it is not feasible due to operational considerations, tethered escort should be considered the deployment of choice.

8) Tanker escort regulations and practice should allow for change. For instance, an improved alarm system or watch practice could reduce failure recognition times. Improvements in tug escort technology may lead to different methods of providing assistance. It should be possible for tanker operators to revise their equipment and procedures and demonstrate through computer simulations or full scale trials that the intent of safety of transit in the waterway is fully met.

REFERENCES


ACKNOWLEDGMENTS

This paper draws upon the experience of several studies carried out over the last five years. ARCO Marine, Inc. and FOSS Maritime supported the pioneering studies, tests and trials that led to the escort plans for ARCO tankers in Puget Sound. Captain Jim Morgan of ARCO and Steve Scalzo of FOSS have provided us continued support and encouragement. We also would like to thank all the members of the Disabled Tanker Towing Study Group and particularly Robert A. Levine of ARCO Marine who served as the project manager. For the San Francisco Bay study we received considerable help from all members of the Technical Advisory Group, and from Captain Morris A. Croce and John Immink of Chevron.

Numerous other individuals from our organization as well as others have played a role and we are grateful for their assistance and support.