Evaluation of Tug Escort Schemes

Using Simulation of Drifting Tankers

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ABSTRACT

The ability of tug escort vessels to save oil-laden tankers that become disabled in Prince William Sound, Alaska, is tested using a simulation of the drift path of the tankers. Tug escort schemes are intended to save tankers that have lost steering or propulsion by attaching a line and either holding the tanker from running aground until a repair can be made or towing the tanker to port. The ability of an escort tug to save disabled tankers depends on its position at the time of the accident, the location, speed and direction of the tanker at the time of the failure and the wind and current conditions that changed dynamically during a save attempt. To accurately test the save capability of a proposed escort scheme, a simulation of the Prince William Sound is created that models dynamic changes in environmental conditions and thus the movement of the tanker. The simulation is used to test a new escort scheme that had been proposed for Prince William Sound.

Keywords: Marine applications, drift path simulation, escort vessel requirements.

1. Introduction

After a propulsion or steering failure, an oil tanker is at the mercy of the wind, the current and its own momentum. If the failure cannot be repaired in time, the tanker may run aground leading to a hull breach and an oil spill. This accident scenario is a major concern in Prince William Sound, Alaska, the site of the Exxon Valdez grounding (Figure 1). To prevent such events, tug escort schemes have been implemented in a number of ports in the US, with the aim of saving disabled tankers from drifting aground. In this paper, the development of a simulation of drifting tankers is discussed. The model was used to assess the effectiveness of a proposed tug escort scheme in the Prince William Sound (PWS).

Figure 1. The stricken Exxon Valdez spilling oil.

The Oil Pollution Act (1990) and the State of Alaska's oil pollution prevention and response statutes stated that two escorts should be used to escort oil-laden tankers through PWS. The Ship Escort Response Vessels System (SERVS) (see [1]) was created to ensure that each tanker was escorted by two suitable escort tugs, from the port through PWS to the Gulf of Alaska. In some cases, due to inclement weather or the size of the tanker, three escort tugs were used.

Questions concerning the effectiveness and benefits of existing prevention regulations surfaced in early 1995 when the PWS shipping companies,

- ARCO Marine Inc.,
- BP Oil Shipping Company, USA,
- Chevron Shipping Company,
- SeaRiver Maritime Inc., and
- Tesoro Alaska Petroleum Company,

attempted to develop a request for proposals to build a new escort vessel for PWS in response to specific State of Alaska requirements attached to their oil discharge prevention and contingency plans.

The process was put on hold because answers to questions about the effectiveness of the mission, performance and operation of the escort vessels needed to be clarified in order to move forward with the proposal. Even with information learned from the joint industry/government/citizen Disabled Tanker Towing Study, completed in July 1994, the role of escorts and their purpose in the system were not well defined nor accepted by all stakeholders. It was decided that a comprehensive risk assessment should be performed to evaluate all proposals.

The PWS Risk Assessment was a joint project of Det Norske Veritas (DNV), Rensselaer Polytechnic Institute (RPI) and The George Washington University (GWU). The aim of the project was to assess the baseline risk of the system and then to test the effect of proposed risk interventions on the system risk. DNV used a fault tree approach to assess the accident risk, while GWU used a combination of a discrete-event simulation and expert judgment techniques.

As discussed in [2], one result of the GWU model was that although the escort scheme was capable of saving disabled tankers, there was a trade-off due to increased risk of collisions with tugs returning from an escort assignment. Thus it was proposed that instead of escorting tankers with two close escorts through Central PWS, one close escort should be used, with a standby escort ready to assist in case of emergency. There are two areas of primary concern on the outbound route taken by oil-laden tankers in the Prince William Sound; these are the Valdez

Narrows and Hinchinbrook Entrance, indicated in Figure 2. Oil-laden tankers must have close escorts through both areas, as the time available to perform a save is severely limited. However, in the Central PWS, indicated by Zone 2 in Figure 2, it is possible that a disabled tanker could drift for a significant period of time without running aground.

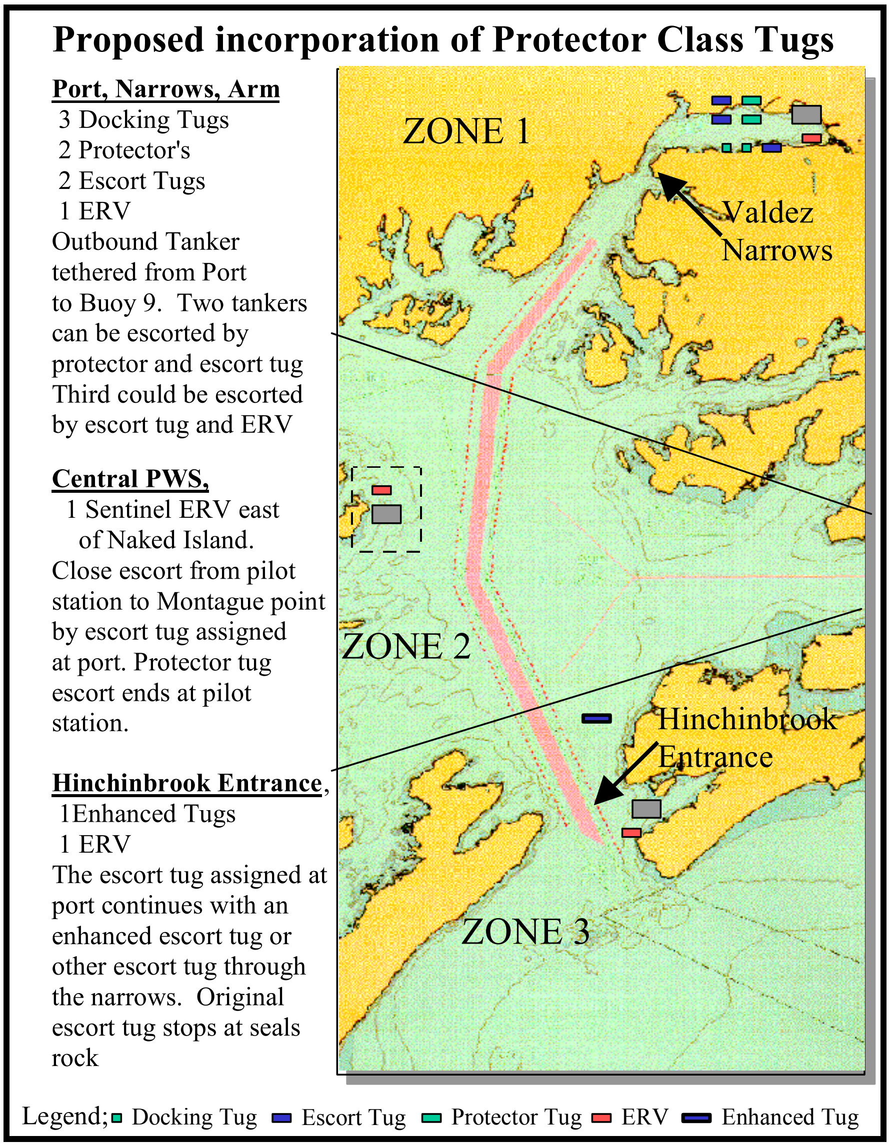

Figure 2. A schematic of the proposed escort scheme

Under the proposed escort scheme, an outbound tanker in dock would be escorted by two escort tugs from the port and through the Valdez Narrows. This part of the outbound transit is marked as Zone 1 in Figure 2. One escort would then maintain position, while the other continued close escort through the Central PWS. Throughout the transit through the Central PWS, another escort tug would be underway at the position indicated by the box to the left of Figure 2. When the tanker reached mid-way in the Central PWS, another escort tug would maintain position at the start of Hinchinbrook Entrance and the stationary escort tug in Zone 1 would return to port. The tug at Hinchinbrook Entrance would then join the close escort through Hinchinbrook Entrance. Thus, in summary, an oil-laden tanker would have two close escorts through Zone 1, a single close escort and standby escorts through Zone 2 and two close escorts through Zone 3. This is a change from the old escort scheme only in Zone 2, where the tankers used to be escorted by two close escorts. However, before the proposed escort scheme could be implemented, the stakeholders required a full analysis to verify that the save capability for disabled tankers is at least as good as the old escort scheme and that the propensity for collisions is reduced.

A summary of the paper is as follows. In Section 2, previously published models for drifting tankers are briefly described. Section 3 discusses the results from the PWS Risk Assessment that led to this simulation and modeling effort. The modeling required to simulate the drift paths of tankers in the PWS is outlined in Section 4. The results of analysis are discussed in Section 5, with a discussion of validity in Section 6. Lastly, Section 7 concludes with the actions taken subsequent to this analysis.

2. Literature Review

The National Research Council has identified the assessment and management of risk in maritime transportation as an important problem domain [3; 4; 5; 6]. Earlier work concentrated on assessing the safety of individual vessels or marine structures, such as nuclear powered vessels [7], vessels transporting liquefied natural gas [8] and offshore oil and gas platforms [9]. More recently, Probabilistic Risk Assessment (PRA) [10] has been introduced in the assessment of risk in the maritime domain [11; 12; 13; 14; 15; 16; 17; 18]. This latter work has examined risk in the context of Maritime Transportation Systems [6].

In a Maritime Transportation System (MTS), traffic patterns change over time in a complex manner. System simulation has been proposed and used as a modeling tool to assess MTS service levels [19], to perform logistical analysis [20] and to facilitate the design of ports [21]. System simulation was used to assess accident risk in a MTS in the PWS Risk Assessment [22], the Washington State Ferries Risk Assessment [23] and in the analysis described in this paper.

Several models have been proposed for determining the drift path of disabled vessels. In the Marine Accident Risk Calculation System (MARCS), the drift path of disabled tankers is estimated assuming that the wind and current are constant over time [15]. Although the authors admit that this assumption becomes "less valid over long drift times", they claim that this will give conservative estimates of the drift times. The ability of escort tugs to save the disabled vessel is estimated considering the time to reach the vessel (almost zero if a close escort), the time taken to attach a towline, the sea state and the performance of the tug.

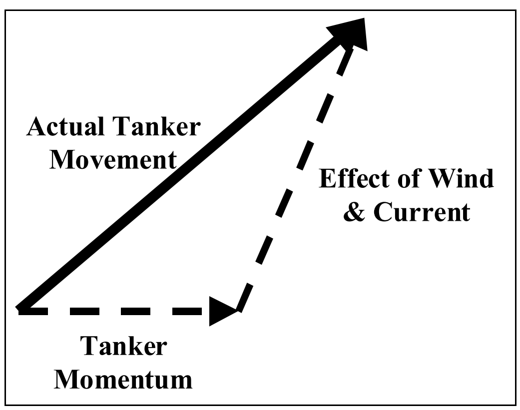

Figure 3. NOAA's trajectory model for drifting tankers.

The National Oceanographic and Atmospheric Administration (NOAA) performed a full scale of analysis of the drift paths of disabled tankers in the Straits of Juan de Fuca [24]. The general form of the model is shown in Figure 3. In this model, the drift speed of the tanker is a vector addition of the wind speed effect on the tanker, the current and the momentum of the tanker. Unlike the MARCS model, NOAA's model can be used with a dynamic model of wind speed and direction, as well as current.

As discussed in [24], complex theoretical models [25;26] give predictions with a large scatter depending on the parameters of the models. Rather than use theoretical models that have not been empirically validated, NOAA's study used a model using parameters estimated from 196 actual test drifts of 47 different vessels. The effect of wind speed on a drifting tanker was shown to be variable. Ship drift behavior was also shown to be highly dependent on wave height and period. The wave conditions in turn depend on the wind direction and duration, the presence of swell generated elsewhere and the fetch geometry of the body of water.

The empirical data used in this study was taken from an Oil Companies International Marine Forum study [27] using questionnaires returned by members of the International Chamber of Shipping. The direction and rate of ship drift was recorded along with wind and current speed and direction. Each of the vessels was fully loaded. Linear relationships were observed between ship drift speed and wind speed, with the drift speed averaging 3% of the wind speed, ranging between 2% and 10%.

We should note that in the NOAA study, "waves are assumed fully developed and in the direction of the wind" [24; 27]. While this assumption may be reasonable out at sea, it is questionable for an area such as PWS. However, as the traffic lanes used by outbound tankers are a considerable distance from land, there is a significant fetch that allows waves to form, making the assumption not completely invalid for Central PWS.

3. *Results from the PWS System Risk Simulation*

The dynamic nature of traffic patterns and other situational variables, such as wind, visibility and ice conditions, mean that risk levels change over time. The PWS Risk Assessment differed from previous maritime risk assessments in that the dynamic nature of risk is captured by integrating system simulation [28] with available techniques in the field of PRA [29] and expert judgment elicitation [30]. A simulation of the maritime system was used to estimate the frequency of the occurrence of system states defined by organizational and situational factors. Available data was next extended using expert judgment techniques to estimate the conditional probability of an accident in each of the defined system states. Finally, both methodologies were integrated in an overall framework to analyze system wide maritime risk in terms of annual accident frequencies called the System Risk Simulation. For a general discussion of the modeling approach used in the PWS Risk Assessment see [22; 31]. For a discussion of the use of simulation in modeling risk in a MTS see [32].

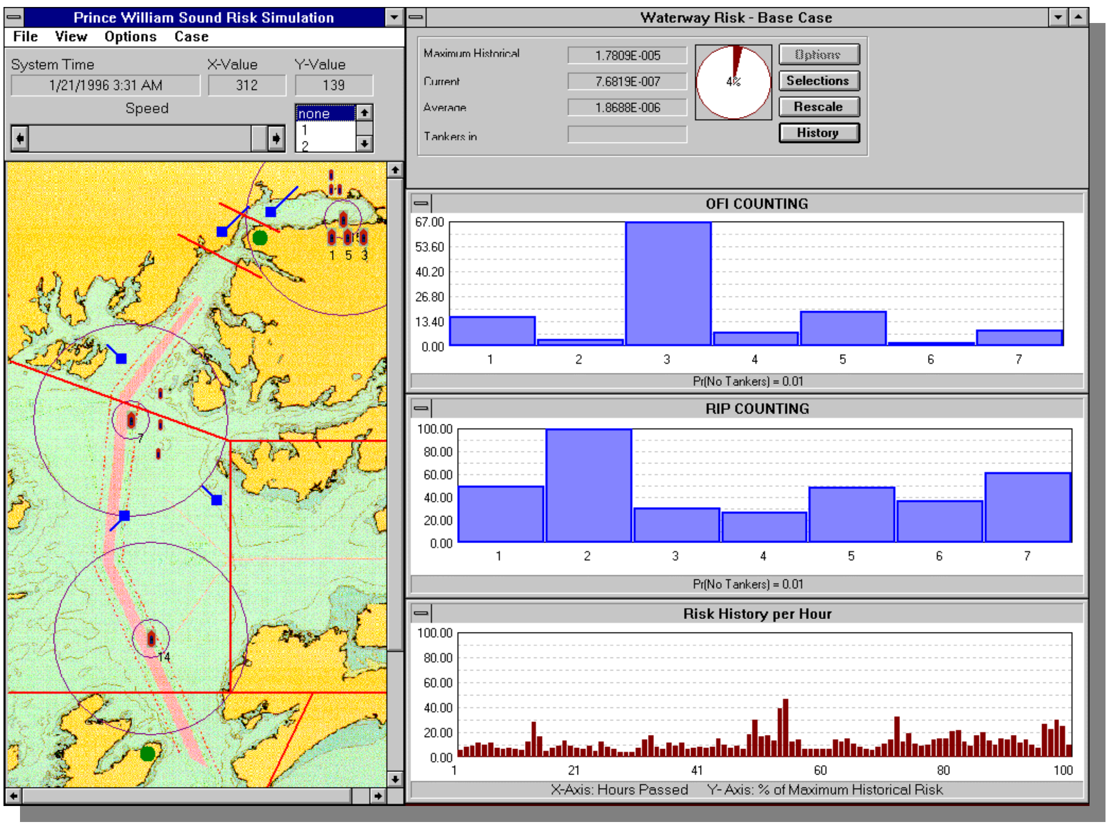

Figure 4. The System Risk Simulation program was created to perform the analysis and demonstrate the results to the Steering Committee.

The System Risk Simulation modeled tanker movements as well as other traffic patterns, wind, visibility and ice (Figure 4). The accident probability model included factors including the wind, visibility, location, proximity to other vessels and the number of close escort tugs accompanying the tanker. The model could thus estimate the annual accident frequencies for collisions, including collisions with returning escort vessels, and drift groundings. Changing the simulation itself to show the number of close escorts and also changing the number of close escorts in the accident probability model give estimates of the effect of various close escort schemes. However, the model could not directly estimate the effect of the proposed standby escorts.

The proposed escort scheme was programmed in to the simulation with one close escort accompanying outbound tankers in Central PWS. Two analyses were then performed by varying the parameter in the accident probability model that represents the effective number of close escorts in Central PWS. The first analysis assumed that outbound tankers in the Central PWS had only one effective close escort, implying that the standby escorts have no effect and cannot assist the single close escort in saving the tanker. The second assumed that they had two effective close escorts, implying that the standby escorts are just as effective as a close escort. Obviously, the truth lies somewhere between these two extremes as the standby escorts must be able to reach the disabled tanker well before it runs aground to be effective.

From the analyses performed, it was estimated that the expected frequency of drift groundings of outbound tankers in the Central PWS is between 1 every 376 years (0.00266 per year) for the one effective escort analysis and 1 every 633 years (0.00158 per year) for the two effective escorts analysis. The expected frequency of drift groundings of outbound tankers in the Central PWS for the old escort scheme was 1 every 617 years (0.00162 per year). If the sentinel escort can reach the disabled tanker with time to assist in a save 96% of the time then the frequency of drift grounding accidents will be the same as achieved by the old escort scheme. The analysis also showed that the new scheme would reduce the collision risk substantially due to decreased interactions between tankers and escort tugs returning from an escort assignment. However, the System Risk Simulation model could not assess how often the standby escorts could reach the disabled tanker with time to assist in a save. Thus, more exact estimates of the drift times were required.

4. Simulating Drifting Tankers in the Prince William Sound

The technique that was initially proposed for this analysis was a static vector analysis similar to that used in MARCS [15]. However, it was believed that this approach would not accurately model the dynamic nature of a drifting tanker and may lead to inaccurate answers. Thus a drifting tanker simulation was used to estimate drift times. First, propulsion and steering failure events were sampled from the System Risk Simulation as starting points for the drift simulations. Second, wind speed and current were modeled. Last, a model of the trajectory of a drifting tanker was used that depended on tanker momentum, wind speed and direction and current speed and direction.

The first step in modeling drifting tankers is to determine the starting conditions for each simulated drift. The System Risk Simulation included vessel specific propulsion and steering failure probabilities based on historical incident data supplied by the tanker operators. This simulation was used to sample propulsion and steering failures and to record the positions of the tankers and escort tugs and the environmental conditions at the time of the each such event. These events served as starting positions for the disable tanker drift simulations. 1000 such samples were taken in a 25-year simulation period.

It should be noted, however, that the expected number of propulsion and steering failure incidents in a 25-year period is approximately 50, about 2 per year on average. Thus to sample 1000 starting points without having to run an overly lengthy simulation, importance sampling was used. The probability of a propulsion or steering failure for each tanker was multiplied by 20. As only the percentage of simulated drift paths that ended in grounding was used, not the absolute number, this increase in probability did not affect the results. For each of the 1000 starting events sample, the simulated time and date was recorded, along with the position, speed and direction of the tanker and the positions of each non-escorting tug. This was the starting information for the drift simulation.

The next step in simulating drift paths was to model the dynamic patterns of wind in the PWS. Environmental data was obtained from two main sources, SERVs transit data logs from 1990-1995 and NOAA buoys from May 1995 to March 1996. Figure 5 shows the numbered locations for each data source. The SERVs logs contain weather information taken at three locations during each escort transit; (1) The Narrows, (3) Naked Island, and (5) Seal Rocks. The buoys contain weather information on a half hourly basis at (2) Potato Point, (4) Central Prince William Sound (Buoy 46060) and (6) Seal Rocks (Buoy 46061).

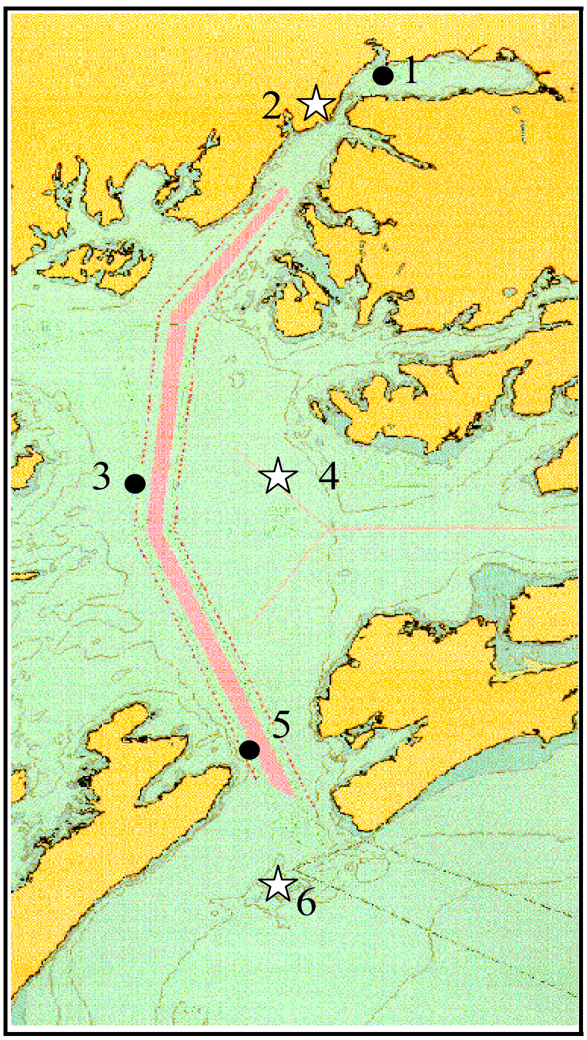

Figure 5. Weather measurement locations in PWS.

Wind data was grouped into four seasons where the steady state characteristics of the wind as described in SERVs six-year summary data were similar. The seasonal breakdown was as follows winter (Nov, Dec, Jan, and Feb), spring (Mar, Apr, and May), summer (Jun, Jul, and Aug), and fall (Sep, and Oct). The simulation required the wind attributes to change as it would typically change over time. The changing wind pattern was modeled as a Markov Chain with a two-dimensional state space (wind speed and wind direction).

It was decided that the wind attributes in the drift simulation would be reevaluated once every hour as the NOAA buoy data was collected on this basis. A Markov transition matrix was utilized to replicate the typical characteristics of wind in the PWS. A four-direction weather vane (0-90°, 90-180°, 180-270°, 270-360°) and four discrete wind speeds (0-20mph, 20-30mph, 30-45mph, 45mph and up) were defined. The combination of the four wind speeds and directions combine to make sixteen different possible conditions that wind could be in at any location at any particular time in the PWS, see Table 1. It is possible in one hour to transition from any one of these states to any other state. However, this transition probability is different for different states and is estimated from the data.

Table 1. Possible wind states at each location.

Wind Speed	Wind Direction
45 mph & Up	270-360, 0-90, 180-270, 90-180
30-45 mph	270-360, 0-90, 180-270, 90-180
20-30 mph	270-360, 0-90, 180-270, 90-180
0-20 mph	270-360, 0-90, 180-270, 90-180

The most complete data on wind was obtained from the Seal Rocks buoy. Thus a Markov Chain transition matrix with the 16 possible states was estimated from data from this buoy. The wind speed and direction for the other locations were assumed to be dependent upon the state at the Seals Rock buoy. After the completion of the analysis for the wind model, wind states at each location could be sampled once an hour in the simulation.

The wind model was programmed into the tanker drift path simulation. However, observations of the simulated drift paths obtained were not satisfactory. As there were only 6 simulated wind locations assumed in the model, the tanker movement appeared erratic at the borders of each location. Thus a more detailed wind field was assumed with 400 square cells across the study area. The cells covering a data source location took the values sampled from the original wind model. Other cells were assumed to be a weighted vector addition of the closest simulated locations. The weights used were obtained using expert judgment. This gave a more realistic movement of the tanker without such sudden changes in wind effect at the boundaries.

Modeling current in the Prince William Sound was more complex. Current and sea state data is collected, but is sparse. Moreover, it is uncertain that the currents collected by the measurement equipment in place are valid for use in a tanker drift model. To overcome this problem, a worst case current was assumed of 1 knot to the west. This is the strongest current possible and would drift a tanker towards the closest land point in the Central PWS.

With the starting points for the tanker drifts and the wind and current model, the drift trajectories could be simulated using the drift model from [24]. The simulation created was called the Disabled Tanker Drift Simulation. The position of the tanker and the escort vessels was calculated every five minutes of simulated time. These calculations took in to account the previous position of the tanker, its previous speed and direction, the wind speed and direction and the speed and direction of the current. The three vectors (tanker momentum, wind and current) were added. The effect of the wind was assumed to be 3% of the wind speed, the average value found in [27]. However, as the empirical study found variations between 2% and 10% of wind speed, to assert the validity of any results a full sensitivity analysis was performed and is described in Section 6.

It should be noted that the drifting tanker actually has one close escort that can perform a save. Rather than attempt to estimate the effect of this escort in the Disabled Tanker Drift Simulation, the close escort was assumed to have no effect. Each of the escorts has the ability to hold any tanker in the PWS calling fleet in any conditions seen in the Central PWS once a line was attached. We also assume that the tanker itself does not take measures to slow its drift. These are worst-case assumptions meaning that the estimate of the effect of the standby escort is extremely conservative.

Two counts were kept in the simulation:

1. The time until the standby escort reaches the drifting tanker.
2. The time until the drifting tanker runs aground assuming no assistance from the escorts.

The difference between these counts gives the time available for the standby escort to perform a save before the tanker runs aground.

5. Results of the Disabled Tanker Drift Simulation

With the momentum of the tanker, the dynamically changing wind and the worst case current, the drift path of the tanker could be accurately estimated. Figures 6 and 7 show two sampled drift paths. Figure 6 shows the shortest simulated drift time, specifically at Hinchinbrook Entrance. It should be noted, however, that at this point the tanker has a single, close escort and is heading to join up with an enhanced capability tug at Hinchinbrook Entrance. Thus the probability of a save is very high. Figure 7 shows a possible long drift time, with the wind direction changing and the tanker drifting in circles in the Central PWS.

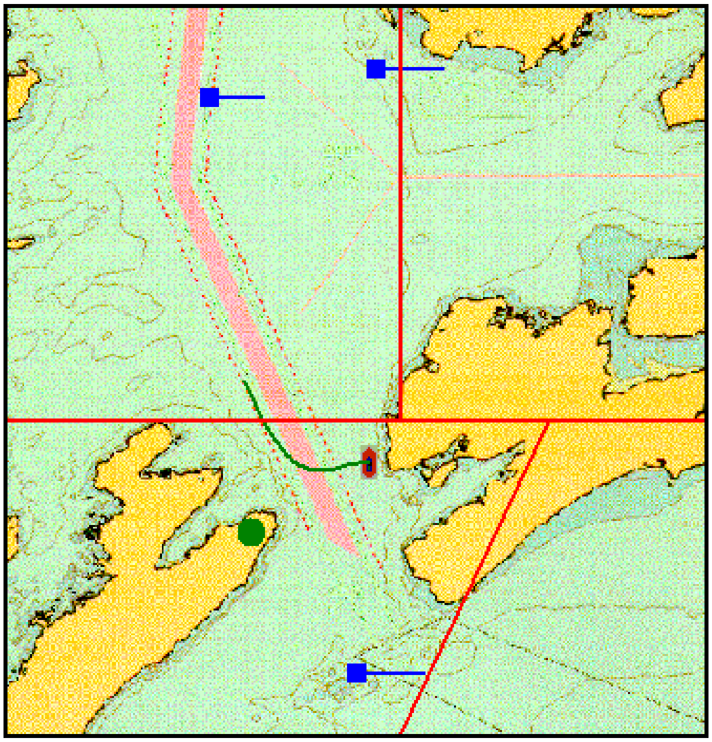

Figure 6. A short drift time scenario.

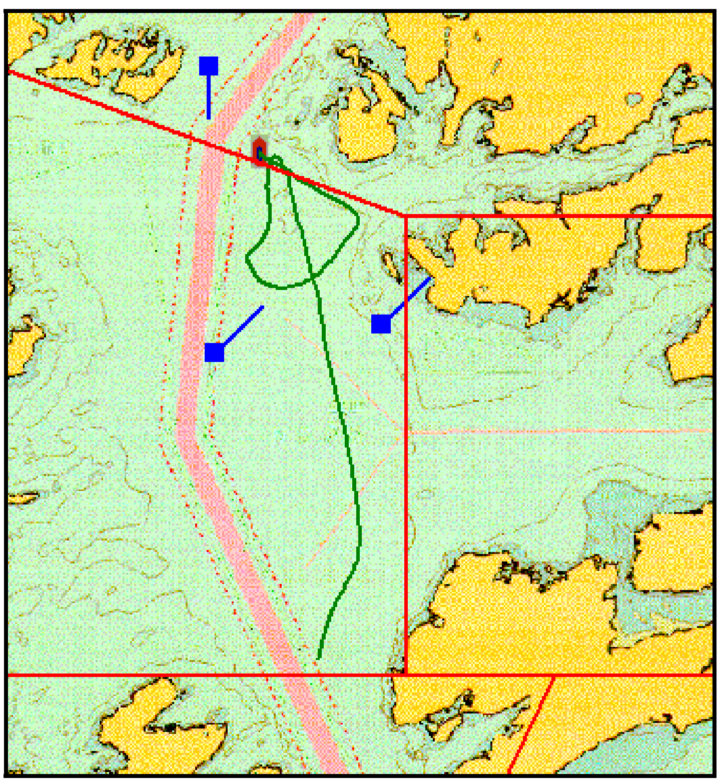

Figure 7. A long drift time scenario.

In 99% of simulated drift paths, the response times were less than 1½ hours. 15% of the drift times are above 12 hours. Figure 8 shows the distribution of the time that the standby escort has after reaching the disabled tanker before it runs aground. This is the time available for the standby escort to make a save if the close escort cannot. The shortest 3 drift paths were 45, 55 and 60 minutes. In the 1000 simulated scenarios, the second escort was able to reach the drifting tanker with more than one hour to make a save 99.7% of the time. In training drills, SERVS personnel attach a line in less than 1 hour irrespective of current conditions. In 96% of the scenarios, the save time was more than 2 hours. Recall that the simulation risk models determined that the threshold value for an equivalent save capability was 96%. Thus, the proposed escort scheme is shown to have a save capability at least equivalent to the old escort scheme and as mentioned previously reduces the collision risk substantially.

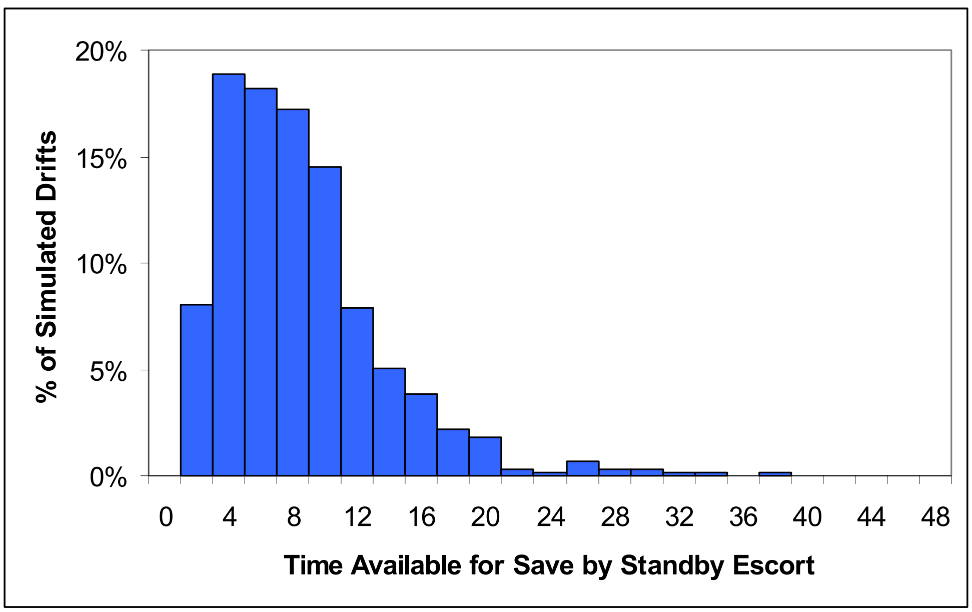

Figure 8. The distribution of times the standby escort took to reach the drifting tanker.

6. Validation of the Results

An important question in any study is the validity of study results. To assess the validity of the results of the System Risk Simulation, graphical comparisons to the actual system and numerical comparison using summary statistics were used. Specifically, United States Coast Guard (USCG) personnel from the Vessel Traffic Service in PWS, who monitor traffic using screens resembling the graphical simulation output, verified the general traffic behavior of the simulation regarding adherence to traffic rules, and vessel arrival and departure patterns. In addition, summary statistics from the simulation, such as the average number of trips to the anchorage area as a result of weather-based closure conditions, the average number of tanker diversions due to ice in tanker lanes and the average number of closed waterways at separate locations due to weather restrictions, were favorably compared to those observed in the VTS system.

However, validation of the Disabled Tanker Drift Simulation is more difficult. The weather model was validated by comparison to source data and graphical demonstration to local mariners and USCG personnel. However, the actual drift paths were more difficult to validate. Test drifts were performed in Central PWS for the Disabled Tanker Towing Study, but actual drift paths were not recorded. The fact that the model used was based on empirical data rather than untested assumptions leads a certain amount of credibility, but the effect of wind speed on drifting tankers is uncertain. In the empirical studies [24], tankers drifted at between 2% and 10% of the wind speed. The value chosen for the analysis was the average value of 3% and the drift simulations showed that the standby escort could reach a disabled tanker with enough time to make a save 99.7% of the time. However, the robustness of this result to the assumed wind effect has not been demonstrated.

The simulations were repeated with wind effect values of 2% and 10%. Table 2 shows the proportion of the simulations in which the escort tugs reached the disabled tanker with enough time to make a save for wind effect values of 2%, 3% and 10%, along with a 95% confidence interval expressing the uncertainty remaining after the 1000 simulation runs. Notice that the proportion of simulations in which saves were possible decreases with a higher wind effect. However, the 95% confidence intervals overlap so this result is not statistically significant at the 5% significance level. Most importantly though, the proportion of simulations remains above the

96% threshold for each value of wind effect tested. Thus, although results of the model may be sensitive to the assumed wind effect, the results of the analysis are robust with respect to this assumption.

Table 2. Results of the Sensitivity Analysis on Wind Effect

WIND EFFECT	PROPORTION	95% CONFIDENCE INTERVAL
2%	99.8%	[98.7%, 100%]
3%	99.7%	[98.9%, 100%]
10%	98.3%	[97.3%, 99.4%]

7. Conclusions

The results of the analysis described in this paper have helped the PWS Tanker Association and the USCG to improve the escort rules and procedures for Prince William Sound. The analysis has been subsequently used to assess the effect of increasing the speed of tankers in Central PWS and changes to the traffic lanes in Central PWS, the latter requiring a change to international maritime law.

Further changes to the escort system have included the introduction of new escort tugs aimed specifically at saving tankers in the Valdez Narrows and Hinchinbrook Entrance areas. An enhanced capability tug called the Gulf Service, shown in Figure 9, is now used to escort oil laden tankers through Hinchinbrook Entrance. Figure 10 shows the tractor tug Nanuq, which along with its sister vessel the Tan'erliq now escorts vessels through the Valdez Narrows.

Figure 9. The enhanced capability tug Gulf Service.

Figure 10. The tractor tug Nanuq.

Biography

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