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A Probabilistic Analysis Of Tanker Groundings

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Abstract

The culture, design, and operation of the maritime industry all contribute to create an error-inducing system. While risk acceptance and risky behavior are often attributed to the "traditions of the sea," the risks associated with sea transportation are no longer restricted to the domain of the seafarer. Accidents such as the Exxon Valdez, Braer, and the more recent Sea Empress groundings have increased public awareness of these risks. As oil tankers have gotten larger, the tolerance for error has decreased, and the consequences have increased. However, society's concerns are not as much about the proportionate increase in tanker size, as the disproportionate increase in the potential environmental impact. While the tanker industry has been identified by the USCG has a high-risk industry, the USCG has also stated that the industry has a high potential for improvement. A systematic approach must be undertaken to effectively identify tanker accident risks and consequences so that they can be minimized by appropriate safety measures. This paper outlines three levels of assessment that lead to the ultimate probability of oil pollution producing an impact. It concentrates on one aspect of a Level 1 Probabilistic Risk Analysis (PRA) for tanker groundings. The approach utilizes fault trees and event trees and incorporates The Human Error Rate Prediction (THERP) data to quantify individual errors.

The Motivation

Maritime oil spills are a significant international environmental problem. The culture, design, and operation of the maritime industry all contribute to create an error-inducing system [1]. Often, the consequence of these errors is the release of oil into the world's waterways. Since oil spills are low probability-high consequence events, and difficult to predict [2], prevention is the best response. It is the risk of an oil spill that motivates further investigation.

Tankers are the largest contributor by vessel type to worldwide oil spill volume. From 1986 to 1994, tanker spills accounted for 60 percent of the oil spilled from maritime sources [3]. Groundings are a significant cause of tanker oil pollution incidents [4]. Globally, 20 percent of all tanker losses between 1987 and 1991 were due to groundings [5]. From 1981 to 1990, 45 percent of the major oil spill volume in U.S. waters was from groundings [6]. Since groundings present a significant spill classification, this paper is concerned with understanding the causes and probabilities of grounding accidents involving seagoing oil tankers.

The maritime industry has been identified as a high risk operation, requiring an active risk management program [7]. The U.S. Coast Guard (USCG) has expressed a commitment to reduce the risks of the maritime industry. Several major tanker owners have expressed the same commitment of cooperation with the USCG [3]. Rear Admiral Card (Chief, Office of Marine Safety, Security, and Environmental Protection, USCG), has entrusted both industry and the USCG to make "prevention a strategic concept [8]." Yet, in order to effect the appropriate risk management program, this risk must be understood.

While the possibility of an oil spill provides the impetus to investigate groundings, it must be remembered that the magnitude of oil outflow is a function of many unpredictable circumstances. There can be groundings that

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are preceded by marked and profound blunders, yet, the degree of oil spilled may be negligible. So while limiting oil outflow motivates the investigation of groundings, the scope is much broader and concerns itself with the nature of the events leading to the vessel's grounding. Hence, our goal is to understand the nature of the errors that lead to a grounding. This understanding can be an impetus for cultural change throughout the maritime industry--yielding a balanced approach to managing safety performance. The ultimate goal is to have safe and profitable operations balanced by the interaction of management, the work environment, human behavior, and technology, all supported on a firm foundation of sound rules, regulations, and standards [3].

The Means

Probabilistic Risk Assessment (PRA) is a technique for evaluating the hazards of a system, and for identifying areas offering the greatest risk-reducing potential. The approach has matured in the nuclear power industry's study of high consequence accidents. Many of the issues examined in the nuclear industry are germane to the oil tanker industry [9]. Given these similarities, we apply the risk assessment methodologies of the nuclear power industry to the maritime industry.

Figure 1 shows three levels of assessment for developing an overall tanker risk assessment [10]. We focus on a Level 1 assessment for tanker groundings utilizing an event tree/fault tree approach.

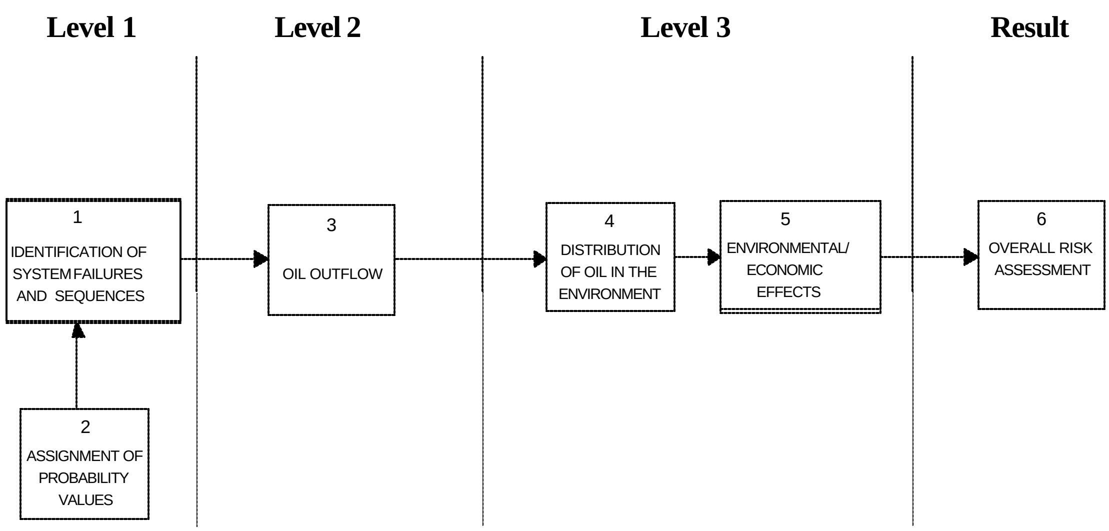

Figure 1: Sequence of Risk Model Evaluations

Level 1: Determine the probability of ship damage and the damage extent.

Level 2: Given that an extent of damage has occurred, determine the probability of oil outflow.

Level 3: Given that oil has been released to the environment, determine the probability of consequences to the environment.

Result: The probability of oil pollution producing adverse economic and environmental consequences.

The event tree/fault tree approach employs discrete logic diagrams to show explicitly the causal relationships within the system model, and determine the probability of accident scenarios. The methodology is widely used in technological systems applications [11], but it is also routinely performed to determine human reliability [12]. Since over 80 percent of maritime casualties have been directly attributed to human error [13], it seems important to utilize a method that is consistent with both the technical and the human aspects of the system.

Human risk assessment is a relatively new discipline [14], and several technical problems arise in trying to assess human reliability in a risk setting. Consequently, the maritime industry has focused on technological and structural fixes of the ship, and punitive models aimed at the operators, as a means to promote accident prevention, rather than addressing human failure causality.

By conducting a PRA and integrating a Human Reliability Analysis (HRA), insight can be gained into the problems presented to and by people aboard ships. The HRA allows the analyst to look at human failure and individual error as events whose causes can be investigated, rather than invoking stop rules at the events themselves and placing blame on the person or persons performing the events. Human failure factors are typically the largest source of uncertainty in a PRA, but they do identify specific areas for potential risk reduction and offer insight into possible risk reduction schemes.

The most popular methods of analyzing individual reliability use decomposition. The basic technique is to break the system down into its constituent elements, or events, to assign reliability estimates to those elements, and compute the aggregated result [15]. The Technique for Human Error Rate Prediction (THERP) is the HRA device used in our analysis. THERP is a method to predict individual error rates and is the most widely used approach in HRA [12]. The approach is similar to a traditional system reliability analysis modified to account for possible individual error, but rather than generate equipment system states, it produces possible human task activities and the corresponding error possibilities [16]. It allows the analyst to evaluate the degradation of the human-machine system likely to be caused by: either individual errors alone or with equipment functioning; operation procedures and practices; or other system and human characteristics that can influence system behavior [17]. It combines a modeling method with a series of empirical data tables containing basic human error probability (HEP) rates that are modified by a series of performance shaping factors (PSFs). The original data used to support the model was obtained from a series of observations and trials conducted at the Sandia National Laboratories. The required steps for a THERP analysis are illustrated in Figure 2.

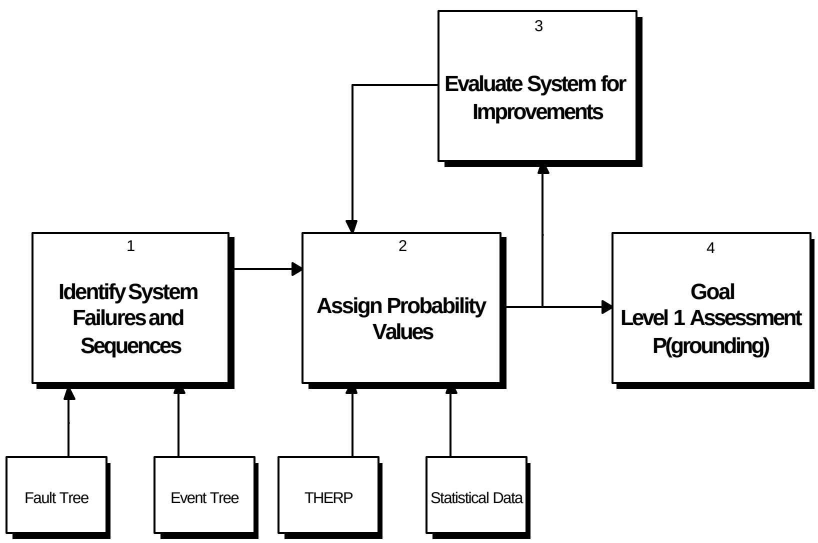

Figure 2: Probability Determination Process Diagram

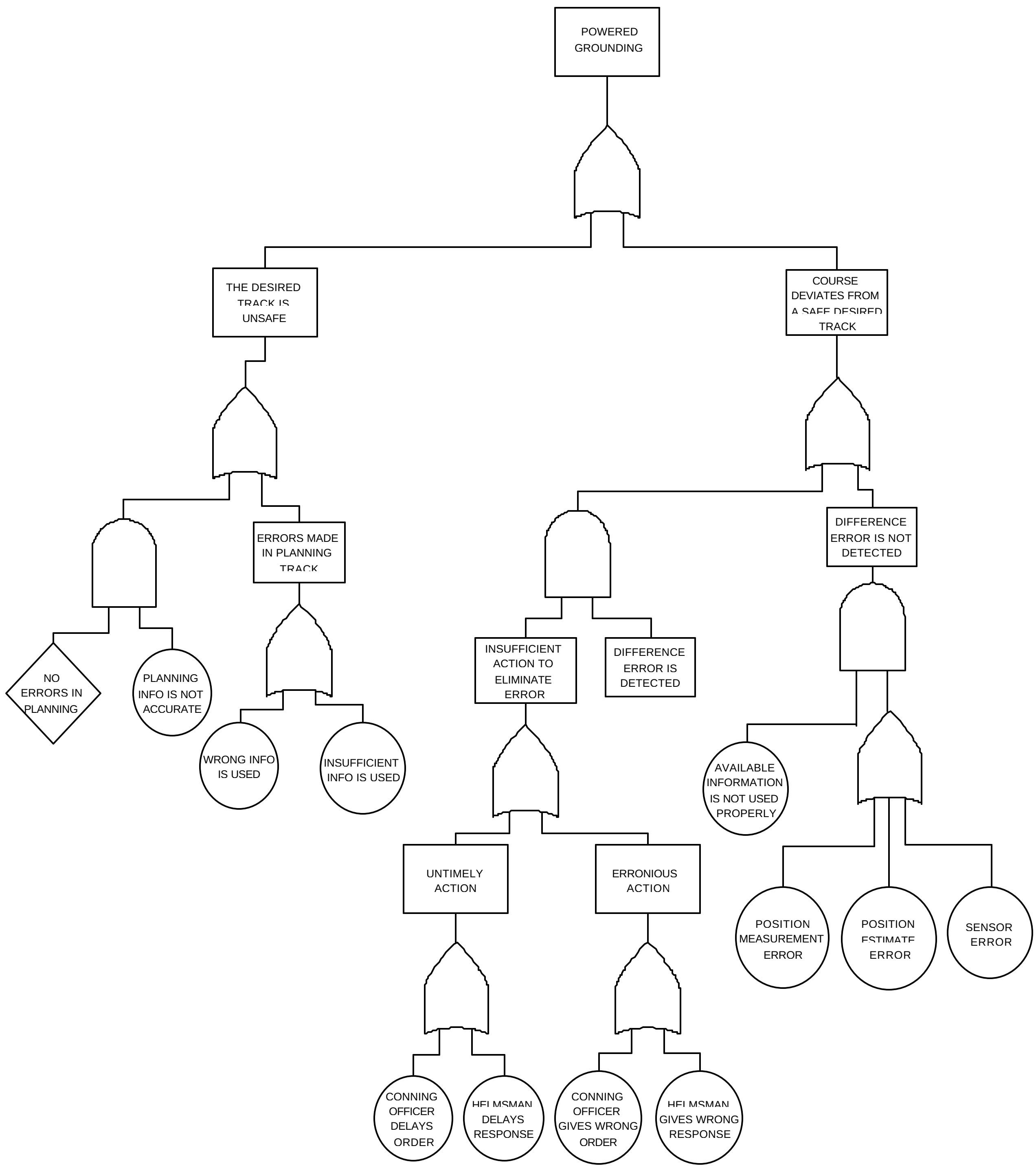

Figure 3 - Powered Grounding Fault Tree

The Grounding Fault Tree

Significant branches of the grounding fault tree are shown in Figures 3 and 9 [10]. In the fault tree, accident faults are broken into two broad categories:

1. *Planning and piloting*: the vessel is able to follow a safe track, however, it proceeds down an unsafe track due to a planning or piloting failure.
2. *Equipment, assistance and environment*: the vessel is unable to follow a safe track because of mechanical failure, assistance failure and/or adverse environmental conditions.

The above breakdown is consistent with a study done by Det Norske Veritas (DNV) [18]. DNV defines the two categories as follows:

1. *Powered grounding*: An event type that occurs when a tanker collides with the shoreline while underway due to navigational error and lack of crew vigilance.
2. *Drift grounding*: An event type that occurs when a tanker loses its ability navigate, through loss of steering or propulsion, and is blown onto the shoreline before it is either taken in tow or is repaired.

The causality derived by the fault tree is consistent with the grounding definitions developed by DNV. For consistency and clarity the DNV terms are used to describe the two broad causal categories. The OR gate immediately preceding the grounding event in the fault tree has an input from the powered grounding portion of the fault tree (Figure 3) and an input from the drift grounding portion of the fault tree (Figure 9). The probability of grounding is calculated using Boolean algebra working from bottom to top.

Powered Grounding

The fundamental failures resulting in a powered grounding (Figure 3) are in the processes of planning and piloting. Voyage planning and piloting are essential skills required of any mariner. Those elements of the fault tree extending from “The Desired Track is Unsafe” constitute faults in the planning process. Likewise, those elements extending from “Course Deviates from a Safe Desired Track” are characteristic faults of the piloting process.

Event trees are used to quantify the probabilities of the faults identified in the fault tree. Event trees are developed by sequencing the fundamental events of each of the processes contributing to a failure event [19]. From the event trees, the probabilities of either success, or failure of each of the processes, or elements of the processes are calculated. When events are human actions, HEP’s are determined from Reference [17]. In Table 1 the nuclear power tasks analogous to those of interest, and for which the data are formulated, are noted.

Passage Planning

The process of passage planning is analyzed using the event tree shown in Figure 4. The mariner has several sources of information available to ensure a safe and efficient passage. The process of verifying that charts reflect the most accurate navigational information involves checking various notices that are published to reflect changes in navigational information. Periodicals are issued to correct or update navigational publications.

Prior to departure and arrival, publications must be corrected as necessary to reflect the most recent changes. The process can be tedious and time consuming. To determine the HEP value to apply to this task, the Table for “Estimated Probabilities of Error When Using Written Procedures Correctly” from Reference [17] is used. It is assumed that the process for checking the navigation periodicals and messages is analogous to the HEP for following procedures with no check-off provision.

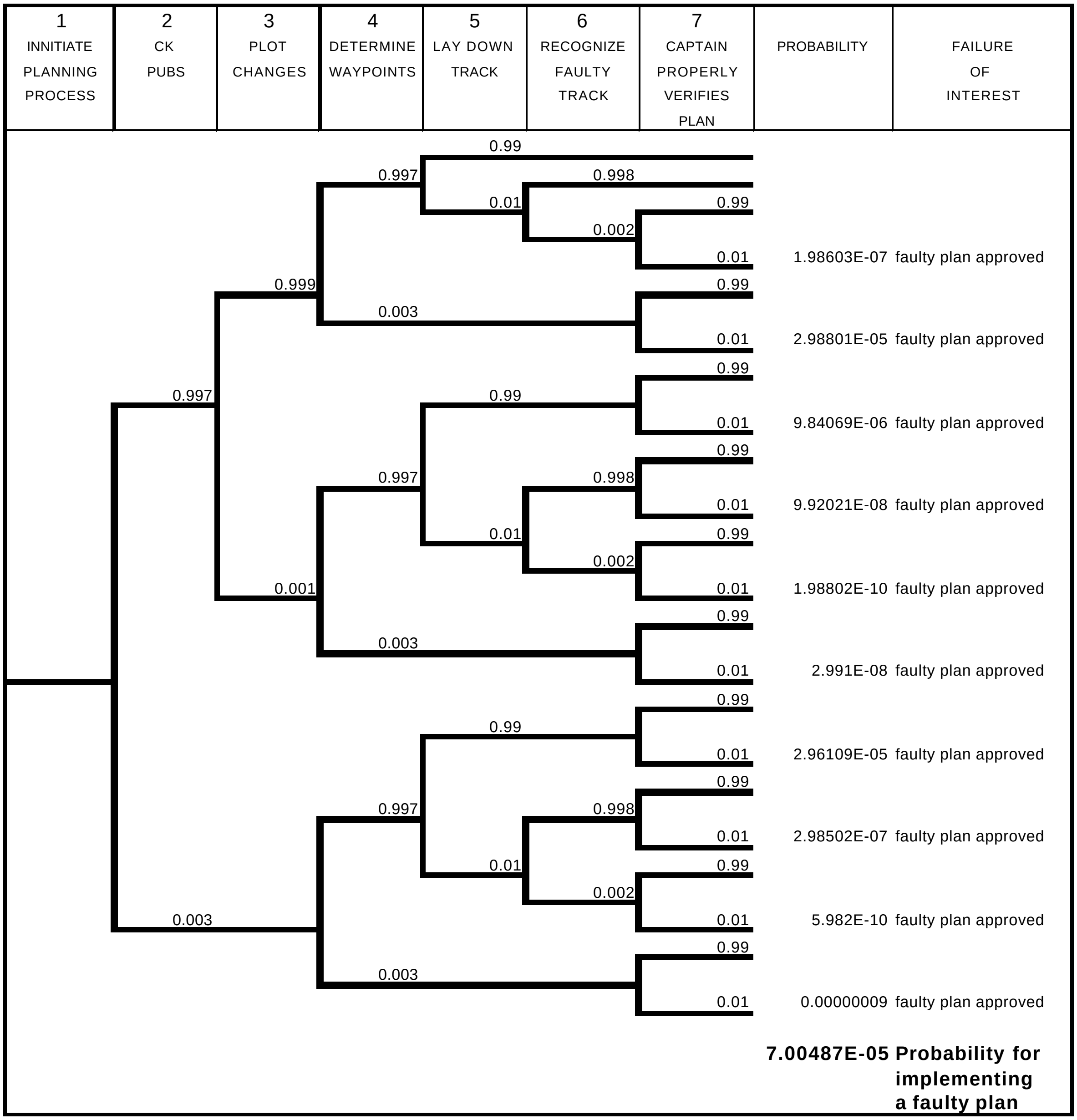

Figure 4 - Passage Planning Event Tree Incorporating Plot-Waypoint Dependency

The HEP for correctly entering the changes in the appropriate charts and publications is taken from the same table. Since the mariner has developed a list of changes to make, the HEP is taken from the line item for procedures with check-off provisions.

The task of determining waypoints for the passage involves studying the charts to determine the track to take the vessel from origin to destination. It is assumed that the HEP is analogous to that of preparing written procedures.

The task of laying down the track involves the plotting of the waypoints and high-lighting any hazards to navigation. The process requires relatively precise use of dividers and simple mathematical calculations, analogous to a reactor technician's use of a micrometer. The Handbook categorizes these tasks under arithmetic computations.

It can be assumed that the first four events are independent of each other, since it is unlikely that the successive event will induce the operator to believe that the previous event was performed incorrectly. In other words, there is no mechanism for recovery. However, the performance of Event 5 does provide for recovery. It can be rationalized that in the process of plotting the track, the plotter has a general idea of the way the track will lay-out before actually plotting it, since the waypoints were determined from studying the charts. If this dependence is assumed, the event tree must model the recovery event.

The recovery event is the recognition of the faulty track after the track is laid-out. This presumes that the individual laying down the track is checking it for the specific purpose of meeting the constraints of a safe passage. This is analogous to the Table in Reference [17] for checking displays for a specific purpose. This recovery event becomes Event 6 in the event tree.

The approval process requires that the Captain verifies the validity of the track. A successful verification implies that the Captain has disapproved an improper plan. The analogous HEP from the handbook corresponds to the table for "Estimated Probabilities of a Checker's Failure to Detect Errors." A summary of the chosen probabilities is given in Table 1. The final probability calculated for implementing a faulty plan is $\mathbf{7.0049 \times 10^{-5}}$.

Table 1: Human Error Probabilities (HEPs) for Passage Planning [17]

Event Number	Maritime Task	Analogous Nuclear Power Task	HEP
2	Check periodicals for changes in charts	Procedures with no check-off provision	0.003
3	Enter changes	Procedures with check-off provision	0.001
4	Determine waypoints	Writing a procedural item incorrectly	0.003
5	Plot track	Procedures requiring simple arithmetic	0.01
6	Recognize faulty track	Check chart recorder with limits	0.002
7	Captain approval	Hands-on type checking	0.01

Planning Information

Inherent in evaluating the probability of the desired track being unsafe, is the determination of the probability that the information used to plan the track is inaccurate. Only a small portion of U.S. waters have been surveyed using the most advanced techniques, and 60 percent of the soundings shown on nautical charts are based on lead-line surveys conducted over 45 years ago [20, 21].

A query of the CASMAIN database [23] was performed for the causes of vessel groundings. Interest lies in the cases where the vessels did not have the navigational information reflecting the actual environmental conditions. It was assumed that the following causes attributed to the casualty in the database were a result of inaccurate information:

1. Channel not maintained.
2. Unmarked channel hazard.
3. Inadequate weather information available.
4. Improper navigational aid location.

The results of the query yielded 1,874 cases between the years 1980 and 1991 where vessels grounded due to false navigational information. Of the 1,874 vessel accidents identified, 298 involved tankers. The location for these accidents is dominated by those that occurred in inland waters. This illustrates the importance of understanding inland water and river dynamics and the increased caution that must be exercised when transiting inland waters and rivers.

Vessel transit data for four of the busiest ports in the U.S.--San Francisco Entrance, New Orleans, Baton Rouge, and Valdez was obtained from the Army Corps of Engineers [22] and is summarized in Table 2. The accident quotient is assumed to approximate the probability of grounding attributable to incorrect planning information. This data provides an estimate for the probability of inaccurate information causing an accident.

Table 2 - Incorrect Planning Information Accident Quotients [23]

Port	Number of Transits	Number of Accidents	Accident Quotient	Number of Tanker Transits	Number of Tanker Accidents	Tanker Accident Quotient
Valdez	13036	2	1.398×10^{-4}	9033	0	0
San Francisco Bay Entrance	43995	3	6.819×10^{-5}	10133	0	0
New Orleans/Baton Rouge	943855	83	8.794×10^{-5}	13825	19	1.374×10^{-3}
Total	1000886	88	8.680×10^{-5}	32991	19	1.896×10^{-5}
Mean		**29.3**	**9.86 x 10-5**		**6.33**	**4.58 x 10-4**
Standard Deviation			**3.70 x 10-5**			**7.93 x 10-4**

Accident Quotient = <u>Number of Accidents due to Faulty Navigational Information</u>
Number of Transits

Piloting

In the piloting event tree, the initiating event is the actual course deviating from the planned track. The subsequent sequence of events is as follows:

1. *The actual course deviates from the planned track*. This is the initiating event and the resulting probabilities are conditional upon this initial deviation.
2. *A difference error between the actual course and the planned track is generated*. To enable a detection of a deviation, the on board sensors detect and offer this information to the bridge team.
3. *A fix is taken and plotted*. Once the onboard sensors offer the information to the bridge team, the bridge team plots a fix on the chart.
4. *The difference error is detected*. When the fix is plotted, the bridge team evaluates the fix to detect that a difference exists between the actual position and the desired position.
5. *A correct course change is ordered*. Once the ship's deviation is recognized, a course change is given to negate further deviation.
6. *The helm responds correctly*. The helm responds with the proper rudder order to bring the ship's track back to the planned track.

The generation of a difference error between the actual course and the desired track is a function of the accuracy and reliability of the radar used to fix the ship's position and the Global Positions System (GPS). The IMO has mandated performance standards for required navigational equipment in the *International Convention for the Safety of Life at Sea* [24]. Because there is no standard system installed on tankers, a value for the probability of generating a difference error is chosen based on the value presented in Reference [25].

The process of taking a fix typically involves the taking of at least two radar ranges. This is done by selecting appropriate navigational aids, obtaining the ranges, and then plotting those ranges. The navigator must read the ranges off the radar and plot them correctly on the chart. The result is the estimated ship's position at the time the ranges were determined. The HEP is chosen from the table for "Probabilities of Errors of Commission in Reading Quantitative Information from Displays." The recording of the information obtained involves more than just writing down the information. Since some skill is required in using the dividers to plot the ranges at the correct scale, the HEP for recording is taken from the table for "Probabilities of Error of Commission in Recording Readings" and the higher HEP is used.

Once the fix is plotted, the navigator assesses whether the course is following the desired track. This is analogous to a check-reading task where the navigator checks the plotted fix to ensure it is within tolerable limits of the desired track [26].

Given that the error in the course is detected, the conning officer determines the correct course change to order. This can be as simple as a rudder order. While there is no written procedure to follow, it is assumed that when a course deviation is detected the procedure is to order a course change. The corresponding HEP is taken from "Estimated Probabilities of Error When Using Written Procedures Correctly."

Once the order to change course is given, the helm must properly respond to the order. This involves turning the wheel while watching the rudder angle indicator and the gyro repeater until the ordered course is achieved. The helmsman must immediately respond and the procedure followed involves some skill. The standard order to the helm involves both a rudder angle order and a final course to steady on. The table “Estimated Probabilities of Errors in Recalling Special Instruction Items Given Orally” is used.

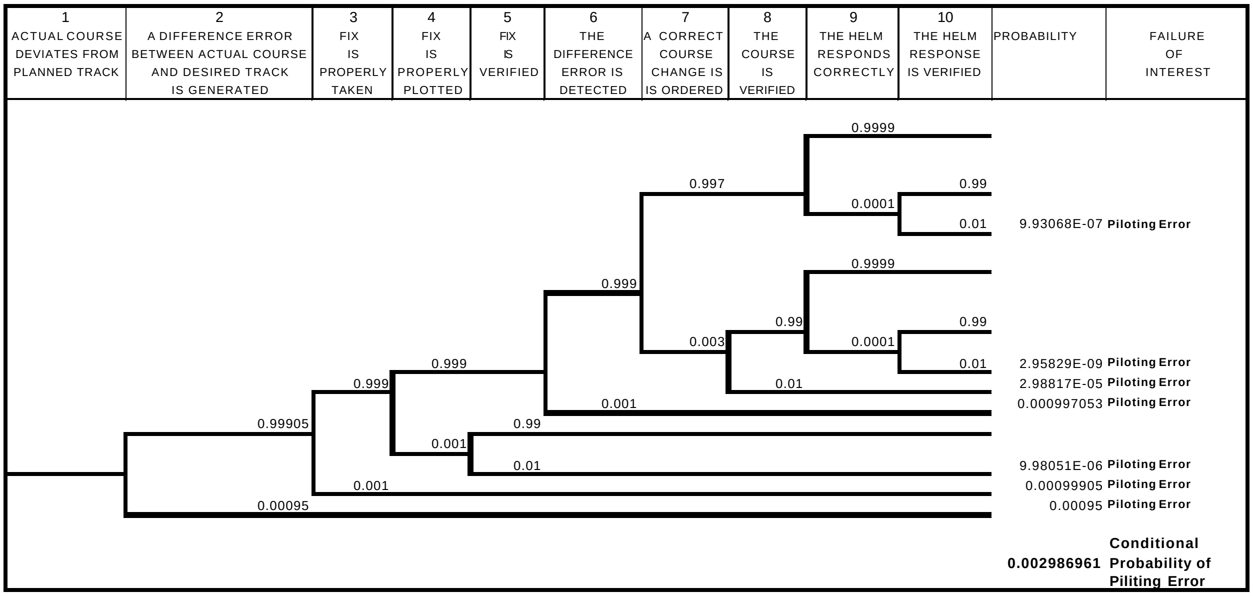

Figure 5 - Piloting Event Tree Incorporating a Verification Event

Once the helm responds to the order, the next event is to detect that the difference error is eliminated, which begins the sequence of events again. Therefore, the resulting probability is based on the number of fixes and assumes that the fix frequency is greater than the rate of departure from track. The resulting failure probability for this process is $\mathbf{9.91 \times 10^{-3}}$ without recovery. A more detailed analysis is done to determine the failure probability when recovery and redundancy are applied. Considering a verification role for the mate and pilot in taking fixes and ordering course changes, the failure probability is lowered. The analogous role in a nuclear power plant is that of either a second checker or an inspector. Figure 5 is the event tree for this process. Table 3 summarizes analogous nuclear power tasks used to determine HEP values. Incorporating a verification role for the mate and the conning officer yields a probability of piloting error of $\mathbf{2.98 \times 10^{-3}}$. Further verification must be included when the role of the Captain is considered. The Captain is responsible for the safe navigation of the vessel at all times. As such, the prudent Captain takes an active role in the piloting process. Incorporating the Captain’s verification yields a more complex event tree with a final probability for piloting error of $\mathbf{1.95 \times 10^{-3}}$

Table 3 - Human Error Probabilities (HEPs) for Piloting Errors [17]

Event Number	Maritime Task	Analogous Nuclear Power Task	HEP
3	Read radar ranges (take a fix)	Reading a digital display	0.001
4	Plot ranges	Recording readings	0.001
5	Verify fix	Hands-on type of checking	0.01
6	Detect the difference error between actual course and desired track	Check-reading with limits	0.001
7	Order a course change	Nonpassive task error of commission	0.003
8	Verify course	Hands-on type of checking	0.01
9	Helm responds to order	Failure to recall two items given orally	0.003
10	Verify helm response	Hands-on type of checking	0.01

The piloting event tree illustrates the importance of the verification role for each of the officers on the bridge. A summary of the results for the piloting event tree analysis is provided in Table 4 with varying levels of verification:

Table 4: Summary of Piloting Failure Probabilities for Varying Levels of Verification

Level of Verification	Failure Probability
None	1.38×10^{-2}
Mate and Conning Officer	2.98×10^{-3}
Mate, Conning Officer and Captain	1.95×10^{-3}

The results show that the additional verification role reduces the failure probability by an order of magnitude. Since the Captain is the individual who is responsible for the vessel, prudence dictates a verification role because it provides an additional recovery event for failure of either the mate or conning officer to perform their respective verification events. The Captain's verification role reduces the failure probability by an additional 30 percent. The Captain plays an integral role in the error detection cycle that is modeled to allow for a recovery event after each of the piloting processes.

Region 1: Region for possible recovery
Region 2: Region for no recovery

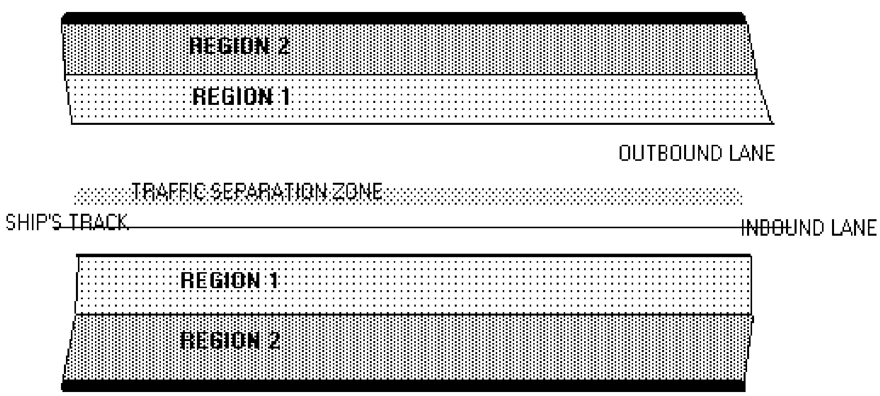

Figure 6 - Hypothetical Waterway

The piloting failure probability is time dependent; as the piloting process is periodic throughout the transit. Additional consideration must be made for recovery events after each of the piloting processes as the vessel transits the waterway. Consider the hypothetical waterway in Figure 6. As the ship proceeds down the intended track, there can be errors in the piloting cycle that are not detected; however, the ship is not necessarily in a failure state. As the ship deviates from its intended track into Region 1, there exists the ability to recover. Once the ship enters Region 2, however, the ability to maneuver the ship to avoid grounding is lost, and avoiding grounding becomes impossible.

After each sequence of events in the piloting process, there is some probability, given that the ship fails to correct its course to the desired track, that the crew will recognize the error and implement correction in the next piloting sequence. The error detection factor is the probability that the bridge team will recognize its failure in the piloting cycle before reaching Region 2.

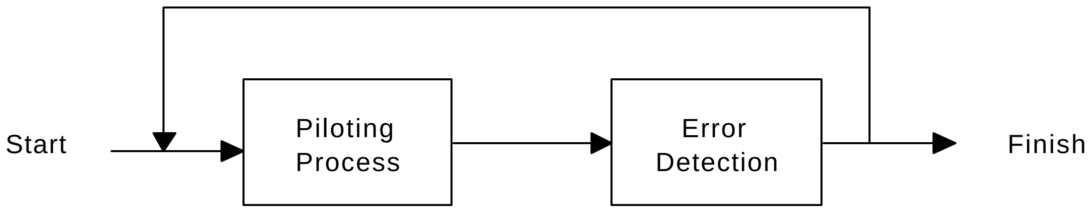

Figure 7 - Piloting, with Recovery, Flow Path

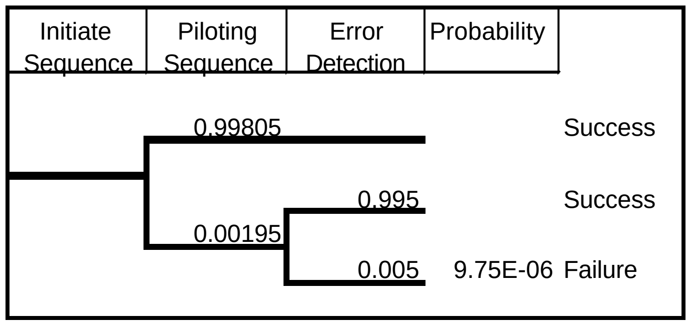

Figure 8 - Piloting and Recovery Event Tree

From Reference [17], the nominal checking probability provides the basis for determining a value for the error detection factor. The lower limit of 0.005 is chosen as the error factor because of the many cues available to the mariner to recover. Given this failure probability, the event tree (Figure 8) is constructed from the flow chart of Figure 7. Implicit in the above model, is the assumption that the probabilities remain constant through each successive cycle. This is only an approximation, because as the bridge team fails on one cycle, it is plausible that the likelihood for failure on the next cycle is higher. The model uses a path dependent error detection factor. For this example, the error detection factor is held constant and a cycle time of three minutes is assumed. The resulting relative rate of failure is the product of the piloting error and recovery factor divided by the cycle time, or $\mathbf{1.95 \times 10^{-4}}$ failures per hour.

For time dependent functions, the probability of failure of the system as a function of time can be defined by the unreliability function **F(t)**. The unreliability function is determined by integrating the probability density function (pdf) **f(t)**, which characterizes the behavior of the system.

The exponential distribution used to describe this pdf is:

$$\mathbf{f(t)} = \lambda \mathbf{e}^{(-\lambda t)} \qquad \textbf{(1)}$$

where λ equals the relative rate of failure. The probability of piloting failure or unreliability function is determined as follows:

$$\mathbf{F(t)} = \int_0^t \mathbf{f(\theta)}\ \mathbf{d(\theta)}$$

$$\mathbf{F(t) = 1 - e}^{(-\lambda t)} \qquad \textbf{(2)}$$

The probability of piloting failure along the track is determined by evaluating **F(t)** over the time of the transit. For small values of λt, **F(t)** is approximately equal to λt.

Drift Grounding

The drift grounding portion of the grounding fault tree is expanded in Figure 9. In order for a drift grounding to occur, all of the following failure conditions must be present:

1. *Unsafe wind/current*: the prevailing winds and currents must be such that the environmental forces exerted on the vessel tend the vessel towards an grounding hazard.
2. *Assistance failure*: there is either a failure to request assistance or the assistance fails to tend the vessel away from a grounding hazard.
3. *Anchor failure*: there is failure to let-go the anchor or a failure of the anchor in preventing the vessel from tending towards a grounding hazard.
4. *Loss of steerage way*: the ship is unable to proceed with directional stability due to either a loss of steering or propulsion.

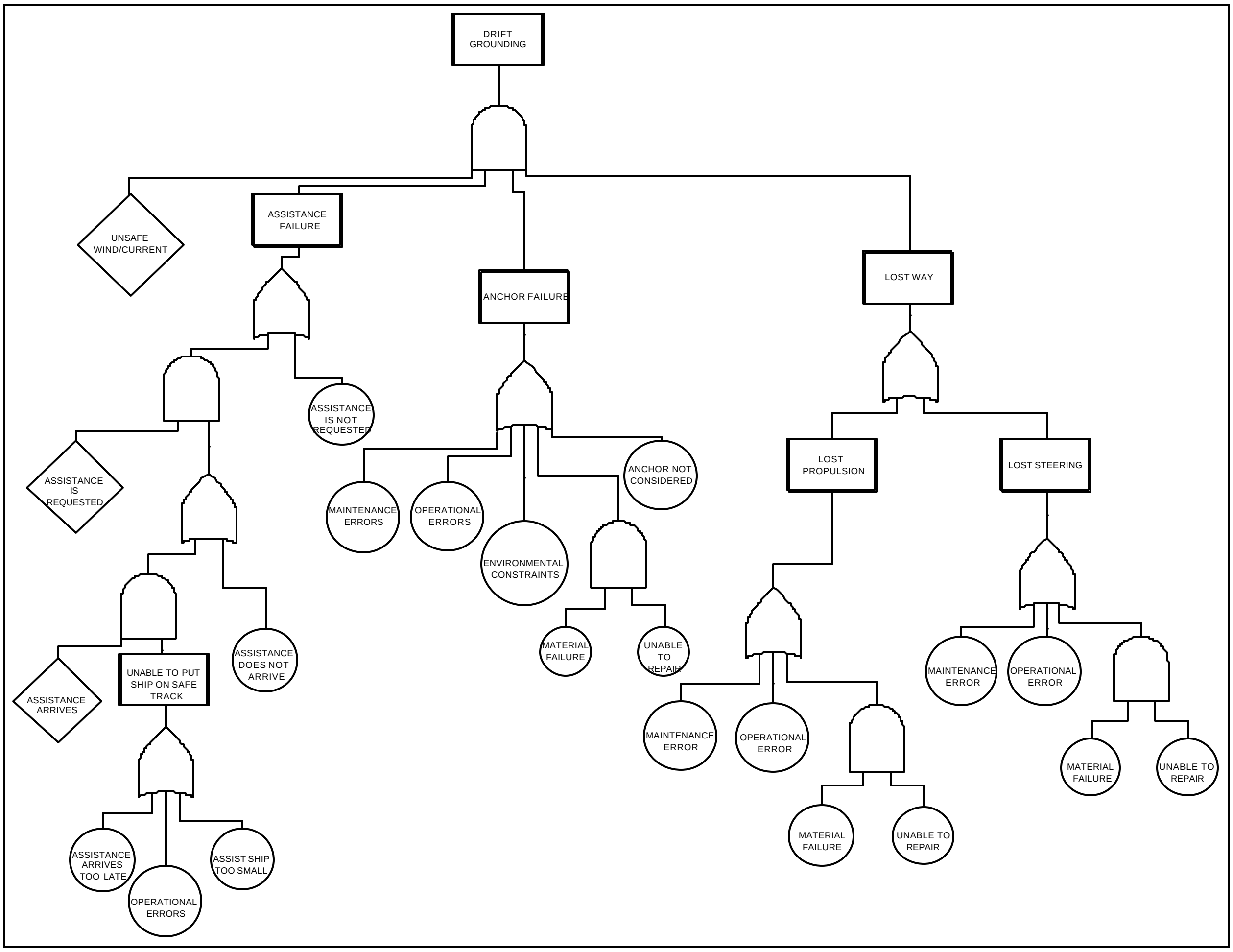

Figure 9 - Drift Grounding Fault Tree

Wind and Current

In order to properly assess the wind and current impact, there must be an analysis of the prevailing winds and currents in the area of concern. The data are dependent upon location. For this analysis, the probability is conservatively assumed to be equal to **1.0**. That is, the wind and current always force a drifting vessel towards a shoal.

Rescue and Assistance

Under the 1989 International Convention on Salvage, the 1990 International Convention on Oil Pollution Preparedness, Response and Cooperation, and OPA 90, greater emphasis is placed on dealing with the problem of pollution prevention, but the worldwide spread of salvage hardware is patchy [27], leaving a questionable availability in some areas should a crisis occur. Currently, few dedicated tugs exist worldwide for vessel rescue [2]. In most areas, the industry is constrained by a system that relies upon "tugs of opportunity" to provide assistance. This system is bounded by the availability, capability, and expertise of the tugs within a response area [2]. To address the system constraints, there is a momentum towards legislating dedicated rescue tugs and/or escort tugs.

Escort vessels can be the last line of defense in preventing a tanker spill accident resulting from either a loss of power or steering. The fundamental event tree for a ship requiring assistance is as follows:

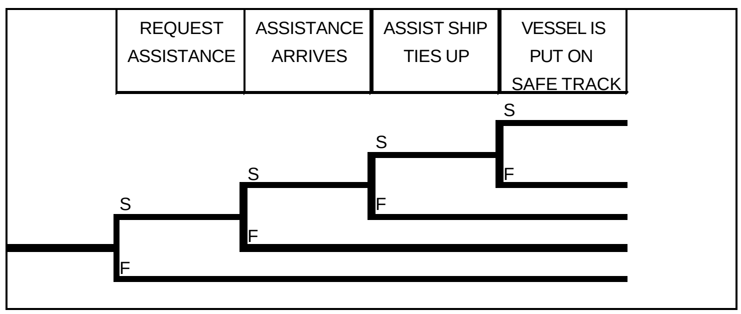

Figure 10 - Assistance Event Tree

Potentially, the largest contribution to an assistance failure is the failure to request assistance in time. Once the bridge team recognizes that assistance is required, the stress level is extremely high. History has shown that captains will take calculated risks by delaying contacting assistance in hope of remedying the situation with organic assets. Well known accidents such as the *Amoco Cadiz* and the *Transhuron* typify the concerns of many captains when faced with a situation in which they perceive the receipt of a "bad mark" if they call for assistance when the possibility of restoring the ship to a safe condition still exists in their minds. Reference [17] documents the probability of error for extremely high stress as being **0.25**. Since data are not available to determine the probability for assistance arriving and tying up correctly, the **0.25** value is used.

Currently, escort tugs are required for loaded tankers in Prince William Sound, Puget Sound and San Francisco Bay. Escort by means of a tug tethered to the stern of a tanker to permit rapid response to a steering or propulsion casualty is the typical implementation of the escort legislation [28]. The preventive measure of having a suitable tug tied to the stern of a tanker removes the system boundaries of availability and capability. The event tree reduces to the probability of the escort tug being able to keep the tanker on a safe track.

The application of escort tugs is for restricted waters. For approaches to restricted waters, tankers do not have an escort. To address the issues of availability and capability, some regions have implemented a dedicated rescue tug. A dedicated rescue tug remains on station in the area of concern. By being on station, the tug is always available. It is able to respond to a tanker in distress within a reasonable time frame.

A study by Robert Allan Ltd. [29] estimates the effectiveness of escort tugs in preventing accidents. The study surveyed casualty databases of Canada and the U.S. to determine accidents involving the interaction of tugs with ships greater than 5,000 gross tons.

Table 5 summarizes the accidents listed in reference [28] that resulted in groundings to determine the accident quotients. From the table, the failure of a dedicated escort tug in preventing a grounding is $\mathbf{5.1 \times 10^{-5}}$. Based on this limited analysis, the difference in the probability of an assistance failure varies from $\mathbf{2.5 \times 10^{-1}}$ without dedicated rescue tugs to $\mathbf{5.1 \times 10^{-5}}$ with dedicated rescue tugs.

Table 5: Tanker-Tug Grounding Accidents [29]

Area	Approximate Number of Vessel Movements	Number of Groundings	Accident Quotient
Strait of Jan de Fuca	500,000	2	4.0×10^{-6}
St. Lawrence River	100,000	5	5.0×10^{-5}
Bay of Fundy	60,000	6	1.0×10^{-4}
Distance-Weighted Mean			**5.1×10^{-5}**
Standard Deviation			**4.8×10^{-5}**

$$\textbf{Accident Quotient} = \frac{\textbf{Number of Groundings}}{\textbf{Number of Vessel Movements}}$$

Anchor Failure

Tankers typically have two anchors. Anchors on large tankers can weigh as much as 50,000 pounds. Unfortunately, as ships have gotten larger, the proportionate sizes of anchors have decreased. The ratio of the anchor weight to the deadweight tonnage has dwindled from about 0.6 to 0.2 [30]. The anchors of large tankers are suitable for anchorage in designated areas, but with any significant way on the ship when dropping anchor, the momentum can become too great for the anchor system. According to reference [18], for a large vessel, speed is the most significant factor to consider if an anchor system is used to stop the ship. DNV [18] concludes that at speeds greater than 1 knot, the anchor system will fail if it is deployed.

It is difficult to ascertain any valid statistical data relating to anchor failure. A query of the CASMAIN database [23] reveals 58 vessel casualty reports between the years 1981 and 1991 where a cause was attributable to a dragging anchor. This represents less than 0.1 percent of all the vessel casualties recorded. Of these 58 vessels, only 12 are tankers. The nature of the query limits causality to post letting-go anchor failure, where the nature of the failure can be attributed to unfavorable environmental constraints. An additional query of ground-tackle material failure revealed another 15 tanker accident reports. These failures give an indication of the material failure rate of tanker anchor system.

It is difficult to assign any failure data to either maintenance or operational errors. Based on 4 of the total 27 tanker accidents, attributed to some form of failure of the anchor system, which took place in the New Orleans/Baton Rouge waterway over the 11 year coverage of the CASMAIN database [23], a rough order of magnitude estimate of anchor failure rate is assumed. The average number of tanker trips in the New Orleans/Baton Rouge waterway over the years 1986-1990 was 2,765 trips. If this average is assumed for the 11 years for which the database covers, a total of 30,415 trips results. If this value is divided into the 4 anchor failure accidents occurring in this waterway, then an accident quotient of 1.3×10^{-4} results. This estimate is quite conservative, and based solely on the traffic within the New Orleans/Baton Rouge waterway.

Unfortunately, it is more difficult to extract from the database those cases where an accident occurred because the anchor was not considered. The grounding of the *Braer* is clear example where consideration for dropping the anchor could have significantly effected the results. Failure to consider dropping the anchor is a failure related to administrative control in reference [17]. This refers to the organizational structure, both real and perceived, that motivates the operator to make the right decisions and to follow policy and procedures. The situation that may require dropping the anchor is stressful. Based on an extremely high stress level, an HEP value of **0.25** is assigned to this basic fault.

The probability of an anchor failure is dominated by the HEP value of 0.25 for considering the anchor in time to be effective. Therefore, the probability used for anchor failure is **0.25**.

Lost Way

The loss of way is broken down into two categories: loss of propulsion, and loss of steering. Like the operations on the bridge, many of the failures related to loss of propulsion and loss of steering can be traced to human failure and individual error. Figure 11 shows the number of lost way incidents per year from 1981 through 1991 [23]. In order to estimate the probability of a loss of way incident, the number of incidents over a given time period is compared to the number of tanker transits. Table 6 summarizes the results.

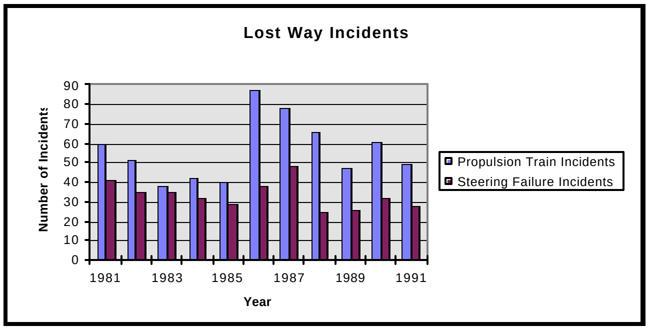

Figure 11 - Tanker Lost Way Incidents (1981-1991) [23]

Table 6: Lost Way Accident Quotients [23]

Port	Tanker Transits	Propulsion Failures	Propulsion Failure Accident Quotient	Steering Failures	Steering Failure Accident Quotient	Approximate Transit Miles
Valdez	8708	5	5.74×10^{-4}	1	1.15×10^{-4}	100
San Francisco Bay	10,133	3	2.96×10^{-4}	1	9.87×10^{-5}	40
New Orleans/ Baton Rouge	13,825	28	2.03×10^{-4}	12	8.68×10^{-4}	200
Total	**32,666**	**36**	$\mathbf{1.10 \times 10^{-3}}$	**14**	$\mathbf{4.29 \times 10^{-4}}$	

$$\textbf{Lost Way Accident Quotient} = \frac{\textbf{Number of Lost Way Incidents}}{\textbf{Number of Transits}}$$

Since the failure rate is dependent on the time of transit and transit length, a rough estimate of the near-land transit length for each port is included in Table 4. The aggregate failure probabilities are divided by the total number of transit miles (340 mi.) to approximate the failure probability per mile. The probability per mile of having a loss of way accident is the sum of the probabilities for propulsion and steering casualties (assuming independence and the rare event approximation) or **4.5×10^{-6} accidents per mile.** Multiplication by the ships speed, s, results in a hazard rate and unavailability function. The behavior of the unreliability over time is:

$$F(t) = 1 - e^{(-l\,t)} = 1 - e^{-0.0000045st} \qquad (3)$$

or approximately **4.5×10^{-6} st**.

Summary of Probabilities and Sensitivity Analysis

The probability values determined from fault trees, event trees and historical data are summarized in Table 7:

Table 7 - Summary of Grounding Probabilities (transit time = t hours)

Powered Grounding:	

Faulty Passage Plan	7.005×10^{-5}
Faulty Planning Information	1.0×10^{-4}
Piloting Error	1.95×10^{-4} t
Drift Grounding:	
Sufficient Wind/Current	1
Assistance Failure	0.25
Anchor Failure	0.25
Lost Way:	4.5×10^{-6} st

The grounding fault tree has been inductively and deductively constructed for clarity in order to determine the basic faults of grounding accidents. Using Boolean identities, the fault tree provides expressions for powered and drift grounding:

$$\textbf{P(powered grounding)} = 7.005 \times 10^{-5} + 1.0 \times 10^{-4} + 1.95 \times 10^{-4}\, t \qquad \textbf{(4)}$$

$$\textbf{P(drift grounding)} = 1.0 \times 0.25 \times 0.25 \times 4.5 \times 10^{-6}\, st \qquad \textbf{(5)}$$

The total probability of grounding is approximated as the sum the probabilities for drift grounding and powered grounding. For typical transit times, powered grounding dominates the contribution to the probability of grounding such that a final approximate expression for the probability of grounding is:

$$\textbf{P(grounding)} = 1.7 \times 10^{-4} + 1.95 \times 10^{-4}\, t \qquad \textbf{(6)}$$

where t is the time of near-shore transit in hours.

Sensitivity analysis is used to assess the relative importance of the different failures effecting a grounding over their range of variation. Reference [17] probability ranges are used to assess the change in human error probabilities and the resulting grounding probability.

Table 8 provides sensitivity results for a planning fault (Desired Track Unsafe). From this table, the events that offer the largest potential for minimizing planning faults are: (1) Master's verification; (2) faulty waterway navigation information; (3) checking publications for changes in the waterway; and (4) properly determining the voyage waypoints. For voyage planning, it is essential to begin with the correct information by checking publications, incorporating the changes on the charts, and determining the correct waypoints, but the most important event is verification. While these factors offer the greatest potential for improvement over the range of uncertainty, they offer a greater potential for increasing the probability of failure if they are not performed correctly or at all. This emphasizes the importance of quality information, navigation fundamentals and the Master's role in verifying that the track is safe.

Table 8 - Planning Failure Event Tree Sensitivity Analysis

Mean Probability for Implementing a Faulty Track	**1.705E-4**					
Probability that is Varied Over the Uncertainty Range	**Probability of Implementing a Faulty Track at Low End of Uncertainty**	**Difference from Mean**	**Percent Difference**	**Probability of Implementing a Faulty Track at High End of Uncertainty**	**Difference from Mean**	**Percent Difference**

check publications for changes	**1.51E-04**	**-1.95E-05**	**-12%**	**2.40E-04**	**7.02E-05**	**41%**
incorporate changes	**1.65E-04**	**-4.52E-06**	**-3%**	**2.10E-04**	**4.02E-05**	**23%**
determine waypoints	**1.51E-04**	**-1.95E-05**	**-12%**	**2.40E-04**	**7.02E-05**	**41%**
lay down track	**1.70E-04**	**1.50E-07**	**negligible**	**1.73E-04**	**2.83E-06**	**1%**
recognize faulty track	**1.70E-04**	**5.00E-08**	**negligible**	**1.72E-04**	**1.84E-06**	**1%**
Master verify plan	**1.35E-04**	**-3.48E-05**	**-21%**	**3.62E-03**	**3.45E-03**	**2025%**
faulty information	**8.04E-05**	**-8.96E-05**	**-53%**	**1.07E-03**	**9.00E-04**	**528%**

Table 9 - Piloting Failure Event Tree Sensitivity Analysis

Mean Probability for Piloting Error	**2.95E-03**					
Probability that is Varied Over the Uncertainty Range	**Probability of Piloting Failure at Low End of Uncertainty**	**Difference from Mean**	**Percent Difference**	**Probability of Piloting Failure at High End of Uncertainty**	**Difference from Mean**	**Percent Difference**
a difference error is generated	**2.00E-03**	**-9.47E-04**	**-32%**	**3.00E-03**	**-4.97E-05**	**2%**
fix is taken	**2.45E-03**	**-4.99E-04**	**-17%**	**6.94E-03**	**3.99E-03**	**135%**
fix is plotted	**2.95E-03**	**-3.00E-07**	**negligible**	**2.95E-03**	**-2.00E-07**	**negligible**
fix is verified	**2.95E-03**	**-3.00E-07**	**negligible**	**2.95E-03**	**-2.00E-07**	**negligible**
Master verifies fix	**2.95E-03**	**-3.00E-07**	**negligible**	**2.95E-03**	**-2.00E-07**	**negligible**
difference error is detected	**2.45E-03**	**-4.99E-04**	**-17%**	**6.94E-03**	**3.99E-03**	**135%**
correct course is ordered	**2.95E-03**	**-4.00E-07**	**negligible**	**2.95E-03**	**-5.00E-07**	**negligible**
course is verified	**2.95E-03**	**-4.00E-07**	**negligible**	**2.95E-03**	**-1.00E-06**	**negligible**
Master verifies course	**2.95E-03**	**-4.00E-07**	**negligible**	**2.95E-03**	**-1.00E-06**	**negligible**
helm responds correctly	**2.95E-03**	**-4.00E-07**	**negligible**	**2.95E-03**	**-5.00E-07**	**negligible**
helm response is verified	**2.95E-03**	**-4.00E-07**	**negligible**	**2.95E-03**	**-1.00E-06**	**negligible**
Master verifies helm response	**2.95E-03**	**-4.00E-07**	**negligible**	**2.95E-03**	**-1.00E-06**	**negligible**

Table 9 provides sensitivity results for a piloting fault (Course Deviates from Desired Track and Is Unsafe). From this table, the events that offer the largest potential for minimizing piloting faults are: (1) properly taking a fix; (2) detecting a difference error from the plotted fix and (3) the accuracy and reliability of the navigational equipment (a difference error is generated). Over the range of uncertainty, reliably detecting that a difference error exists between the actual and desired course offers the most potential to decrease the probability of a piloting error. These are the most basic of piloting skills. They are fundamental to good seamanship. It is not surprising, but very significant, that basic skills of good seamanship are most critical to tanker safety.

Based on the analysis of 100 accidents at sea, Groeneweg [30] concluded that 96 of the accidents were preceded by human failures. There were 345 necessary human failures identified. Out of all the identifiable and necessary human errors, 76 percent of these errors occurred on the bridge. Since the bridge is the controlling station for the ship, it is not surprising that the majority of contributing events preceding an accident are attributable to the actions taken on the bridge. “Therefore, programs to improve safety should look carefully at what happens on the bridge” [31]. The significance of the bridge and the actions taken there, is reflected in the number of marine accident causal factors attributed to this controlling station of the vessel. This is substantiated by the grounding fault tree. The resulting probability for grounding is dominated by the piloting process in the powered grounding mode of failure. This is confirmed by the CASMAIN database [23], which attributes only 15 cases of 716 tanker groundings to either steering failure, or propulsion failure.

Based on PRA and sensitivity analysis, avoiding failures resulting in powered grounding offers the greatest potential for risk reduction. Critical tasks include:

1. *Planning* - Check publications for changes, determine waypoints properly, Master verify the plan.
2. *Planning Information* - must be accurate.
3. *Piloting* - Take fixes properly, recognize difference errors, provide accurate and reliable navigation equipment.

Effective implementation of the Standards for Training, Certification and Watchstanding (STCW) and the International Safety Management (ISM) Code addresses the most important factors impacting these critical tasks including: bridge procedures, training, experience, morale, motivation, fatigue, substance abuse and maintenance. Besides sound seamanship, technology may also have a place in reducing tanker risk. The potential for Electronic Chart Display and Information Systems (ECDIS) to reduce planning errors is significant, if implemented properly and reliably.

Conclusion

Maritime culture, economics, and regulatory bodies all contribute to create a system that can be characterized as error-inducing. There has been little effort to characterize the system as a whole and to determine the areas that offer the greatest potential for risk reduction. The NRC has determined that maritime safety as a whole, could benefit from the increased use of quantitative and qualitative risk analysis to develop risk reduction strategies [20].

The outlined approach addresses the total tanker system [32] and has its foundations in the risk model and the event tree/fault tree methodology. Siu *et al*. [11], have argued that the event tree/fault tree approach provides a natural framework for treating oil spill scenarios.

When developing a PRA for oil spills it is important to recognize the areas of uncertainty. PRA is a discrete analysis. Therefore, it is unable to account for the infinite number of possibilities. Ideally, a PRA considers all the important aspects that lead to the undesired event, but there is the possibility that important contributions have been overlooked. Additionally, there are uncertainties due to the necessary approximations made in developing the model. Human failure factors, system complexity, and the subjective nature of the analysis, all present uncertainties that must be recognized. Despite the uncertainties, it is important to develop a PRA so that perceived risk does not produce either irrational behavior or reflex reactions. The performance of a PRA reduces the uncertainty concerning some of the elements of risk so that resources can be better allocated.

The performance of a risk analysis of and by itself can reduce risk as knowledge and awareness are gained [14]. Additionally, if the process of risk assessment is dynamic, the uncertainties can diminish with time as more knowledge is gained. Once the PRA is completed, allocating resources in the areas that are risk relevant, rather than trying to alleviate all conceivable hazards, allows for realizable risk reductions with limited resources.

There is momentum in the industry for change, and the outlined systematic approach offered by a PRA identifies the areas of change where industry can focus.

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