The Washington State Ferries Risk Assessment

Appendix III:
Detailed Discussion of Modeling Methodology and Assumptions.

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Section 1: Overview of the Collision Risk Models

Accidents involving Washington State Ferries are rare events. However, low probability, high consequence events lead to difficulties in the risk assessment process. Due to the infrequent occurrence of such accidents, large accident databases are not available for a standard statistical analysis of the contribution of perceived risk factors to accident risk. In the WSF Risk Assessment, a constructive modeling approach, combining System Simulation, Expert Judgement and available data, was used to allow for estimation of the contribution of risk factors to accident risk.

If there is a Washington State ferry underway, then there is a possibility, however unlikely, that something could go wrong. This is a fact inherent in many of the activities found in our day to day lives. A day to day situation in the running of the WSFS Ferry System is called an Opportunity for Incident (OFI). Obviously some situations are more "risky" than others. As an example, a ferry traveling on a clear day with no other traffic nearby is at a lower "risk" than a ferry in foggy conditions with many other vessels nearby. This variability in "risk" levels across situations requires that the following questions are answered in order to model collision risk in the WSF system:

- How often do the various OFI's occur?
- For a particular OFI, how often do triggering incidents occur?
- If a triggering incident occurs, how likely is a collision?
- If a collision occurs, what damage can be done to the ferry?
- If the ferry is damaged, what response time is required to avoid additional casualties?

Figure 1 shows a taxonomy of the models developed to answer these questions

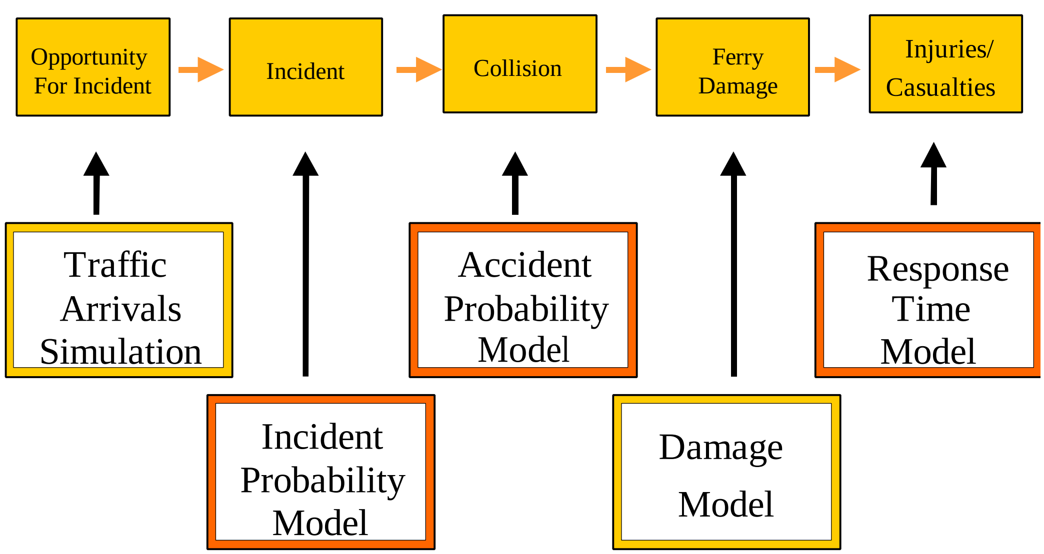


Figure 1. The overall framework of the model used in the WSF Risk Assessment

For each OFI, there are associated variables that may be considered contributing risk factors to that situation. The variables considered in the WSF Risk Assessment are listed in table 1.

Table 1. The variables considered in the Collision Risk Model

Variable Name	Possible Values
Ferry Route	Seattle-Bremerton, Anacortes-Sidney
Ferry Class	Issaquah, Jumbo, Chinook
Interacting Vessel Type	Container, Bulk Carriers, Other Ferries
Type of Interaction	Crossing, Meeting, Overtaking
Proximity of Interacting Vessel	Less than 1 mile, From 1 to 5 miles
Wind Speed	0 knots, 10 knots, 20 knots
Wind Direction	Perpendicular to Ferry, Along Ferry
Visibility	Less than half a mile, More than half a mile

The first question that must be answered to assess the system-wide risk is how often do the various possible situations, as defined by the variables considered, occur, i.e. what is the frequency of the various possible OFI's? Data is available from the United States Coast Guard logging arrivals of deep-draft vessels to the Puget Sound area and ferry schedules are published by the Washington State Ferry Service, but this does not tell us how often interactions between these vessels occur and in what conditions. Thus a computer simulation was built to model the movement of maritime traffic in the area pertaining to where the Washington State Ferry System.

The simulation was built to accurately represent the operation of the Washington State Ferries, the other vessels in the area and the environmental conditions at any given time. Using this simulation, a counting model was developed that observed and recorded snapshots of the study area at regular intervals and counted the occurrences of the various OFI's. The simulation is called the OFI generator and the counting model is called the OFI Counter. The simulation and the data used to create it are discussed in section 2.

The next step is to assess the likelihood of triggering incidents and collisions given the variables describing a particular OFI. The preferred method for estimating these probabilities is through data. Due to the safety record of the Washington State Ferry System, there was insufficient accident data to effectively estimate the contributions of the variables in table 1 to parameters of the collision probability model. In addition, typically the level of detail in accident/incident data bases does not allow for frequency estimation at the level of detail indicated by Table 1. Cooke (1991) cites the use of expert judgment in areas as diverse as aerospace programs, military intelligence, nuclear engineering, evaluation of seismic risk, weather forecasting, economic and business forecasting and policy analysis. Pate-Cornell (1996) discusses the necessity of using expert judgment when sufficient data is not available, while Harrald et al (1992) proposed the use of expert judgment in the analysis of risk in ports and waterways.

In the WSF Risk Assessment, expert judgement was obtained from Washington State ferry captains, United States Coast Guard personnel and members of the Puget Sound Pilots Association. This expert judgment was combined with the accident and incident data available and used to model the accident and incident probabilities. The incident and accident probability models are discussed in section 3.

The final step of the accident event chain is the consequences. Engineering models of collision impact damage scenarios were used to assess the damage to each ferry class in various collision scenarios. The method used for damage calculations is the Minorsky method (See for example Minorsky, 1959). The Minorsky method determines damage size as a function of the collision energy, the colliding vessel bow angle and the effective deck thickness of the Washington State Ferries. The collision energy is calculated using the masses of both the struck ship (ferry) and the striking ship. The damage calculation results in a damage penetration and damage width for every collision scenario. The damage model is discussed in section 4.

Structural plans of the ferries were used to estimate the damage to bulkheads given the damage calculations. In case of damage below the waterline of the ferry and damage of enough bulkheads, flooding of multiple compartment of the ferry is possible. To help addressing the response time question given the potential flooding of multiple compartments, the concept of Maximum Required Response Time is introduced:

Maximum Required Response Time (MRRT) =
The amount of time beyond which additional casualties
may result due to a failure to respond in time.

In the event that the possible number of flooded compartments is lower than the design limit of the ferry, the MRRT is judged to be long. Vice versa, if the possible number of flooded compartments is higher than the design limit, the MRRT may be judged to be short. More specific assumptions regarding the MRRT in case of ferry damage are discussed in the section 5.

Section 2: The Simulation and OFI Counting Models

2.1 The Simulation

The approach used in the WSFS Risk Assessment relies upon the premise that risk is a dynamic property of the system. Harrald et al (1992) discussed the need for dynamic modeling in the assessment of risk in the maritime area. The system risk at any given time is the summation of the risk posed by each of the vessels in the system. As vessels pass through the system, the waterway and organizational characteristics of the vessels (i.e. the **OFI**s) in the system change with time, thus changing the level of risk in the system. To be able to estimate the risk of the system over time, a model must capture the dynamic nature of the transportation system.

Banks et al (1996) state that "a simulation is the imitation of the operation of a real-world process or system over time." The behavior of this system as it evolves over time is studied through the development of what is termed a simulation model. Such a model allows for the examination of variations to the present system without disruption of the current system. Proposed risk interventions that change the dynamics of the current system can be evaluated in the simulation rather than tested in real life. When studying systems in which risk is a key component, this ability is a major benefit.

Figure 2 shows the flow of data and other information into the simulation. A variety of data from a number of sources was used to simulate the movements of both the ferries and other vessel types. In addition, environmental data was used to include wind speed and direction as well as visibility conditions into the simulation.

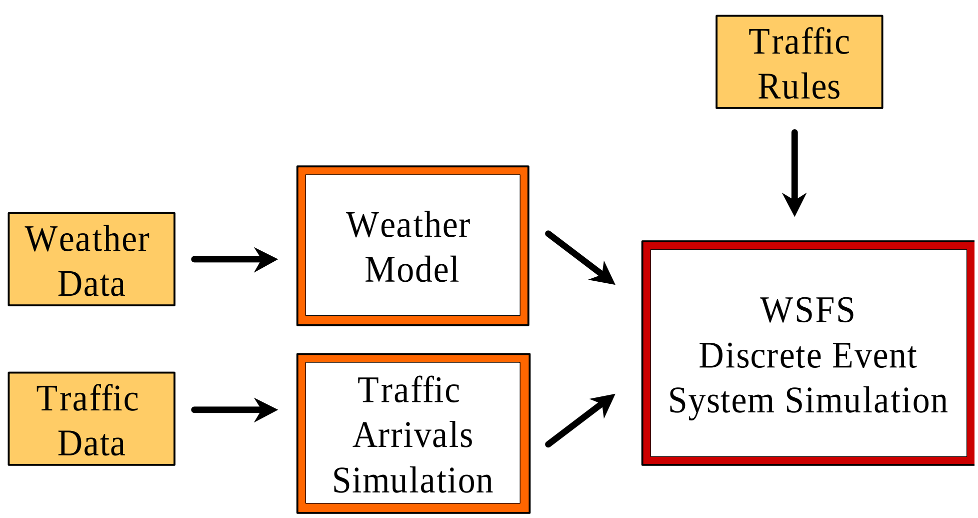


Figure 2. The WSF Simulation Data Inputs

2.1.1 Modeling the Simulation Area

The simulation region was defined using NOAA Electronic Nautical Charts for the Pacific Northwest: Puget Sound to Canadian Border, Region 15. Figure 3 shows the section of the chart including the Seattle, Bremerton and Bainbridge Island ferry terminals.

Figure 3. A section of the nautical charts used in the simulation

2.1.2 Modeling Ferry Traffic

The movements of the Washington State Ferries were drawn from the Fall, Spring and Summer schedules for 1997. The class of ferries used for each scheduled run were taken from the WSFS Vessel Assignments for 1998. The speed of movement of each ferry class was taken from the vessel specifications in conjunction with ferry service rules. As an example, to reduce wake damage in Rich Passage the Chinook must increase its speed to near maximum. The vessel speeds were verified in ship rides with the ferry captains. A group of 6 relief captains, each with over 20 years of experience, met with the consultant team. In this meeting, the ferry routes were drawn on nautical charts and possible route deviations discussed for bad weather conditions. These routes were used as inputs to the simulation.

Under certain conditions, scheduled ferry runs may be canceled. The primary cause of cancelations is mechanical problems on the scheduled ferry. The ferry cancelation logs for 1997-1998 were supplied and analyzed to determine a probability of cancelation for each ferry class. Cancelations resulting from mechanical failure were programmed to occur randomly in the simulation in accordance with the frequencies experienced by the Washington State Ferries in 1997-1998. Cancelations can also be caused by the wind and sea conditions. The ferry captains interviewed gave the risk assessment team possible scenarios in which a captain might decide to cancel a trip. These scenarios were programmed into the simulation and used as environmental cancelation rules.

2.1.3 Modeling Commercial Traffic

To simulate the movements of other traffic types, vessel arrivals logs were analyzed. The Canadian Coast Guard operate a Vessel Traffic Service (VTS) at Tofino. This service monitors and logs the transits of deep-draft traffic entering and leaving the Straits of Juan de Fuca. The Tofino traffic arrivals logs for 1994 to 1997 were obtained from the Washington State Department of Ecology. These logs contained some 67,000 recorded transits. The transits were grouped by vessel type, departure location and destination. All transits from or to locations outside the study area were assumed to be through the Straits of Juan de Fuca or the Straits of Georgia depending on the location. With the specific vessel types on specific routes grouped, a statistical analysis was performed to infer an arrival process that could be used to model the arrivals in the simulation. The arrivals of each vessel type were analyzed for effects of the time of day and seasonal variation. No such effects were indicated, thus the arrival process was assumed to be a renewal process, see Ross (1997). 246 separate arrival processes were modeled to represent the arrivals of commercial vessels into the study area.

The United States Coast Guard (USCG) also has a Vessel Traffic Service in Seattle that covers the Puget Sound and San Juan Islands. The traffic logs for 1994 to 1998 were supplied to the risk assessment team and were used to verify the completeness of the Tofino data.

The VTS personnel that monitor traffic in the study area have necessarily developed a detailed knowledge of the movements of traffic in this area. VTS personnel assisted the risk assessment team in developing route specifications for all deep-draft traffic. In addition, federal regulations requires the use of a Puget Sound Pilot on any transit of a deep-draft vessel beyond Port Angeles. Thus each deep-draft vessel in the simulation area is under the control of one of the pilots. As a result, members of the Puget Sound Pilots Association were utilized in developing data on the speed of movement in the various areas of the Puget Sound and the San Juan Islands as well as to verfiy the vessel routes.

2.1.4 Modeling Naval Traffic

The US Navy supplied yearly counts of the number of transits performed by various types of naval vessels from each of the sites used in the study area. Upon discussion with Naval personnel, it was discovered that for security reasons the departures of naval vessels are purely random. Thus arrivals totaling the counts supplied were sampled at random throughout a simulated year. Specifically, the inter-arrival times were assumed to be exponentially distributed with a mean rate equal to the counts supplied per year. Refer to Ross (1997) for details of the exponential distribution.

2.1.5 Modeling Wind and Visibility

Figure 4 shows the locations of the various data sources used in modeling environmental conditions. National Oceanographic and Atmospheric Administration (NOAA) weather buoys are located at Smith Island, near the entrance to Admiralty Inlet, and at West Point, near Seattle. These weather buoys record wind speed and direction at one-hour intervals. Their location is of importance to ensure the accuracy of the readings for specific areas, so the readings taken reflect the wind experienced on the water at a given location.

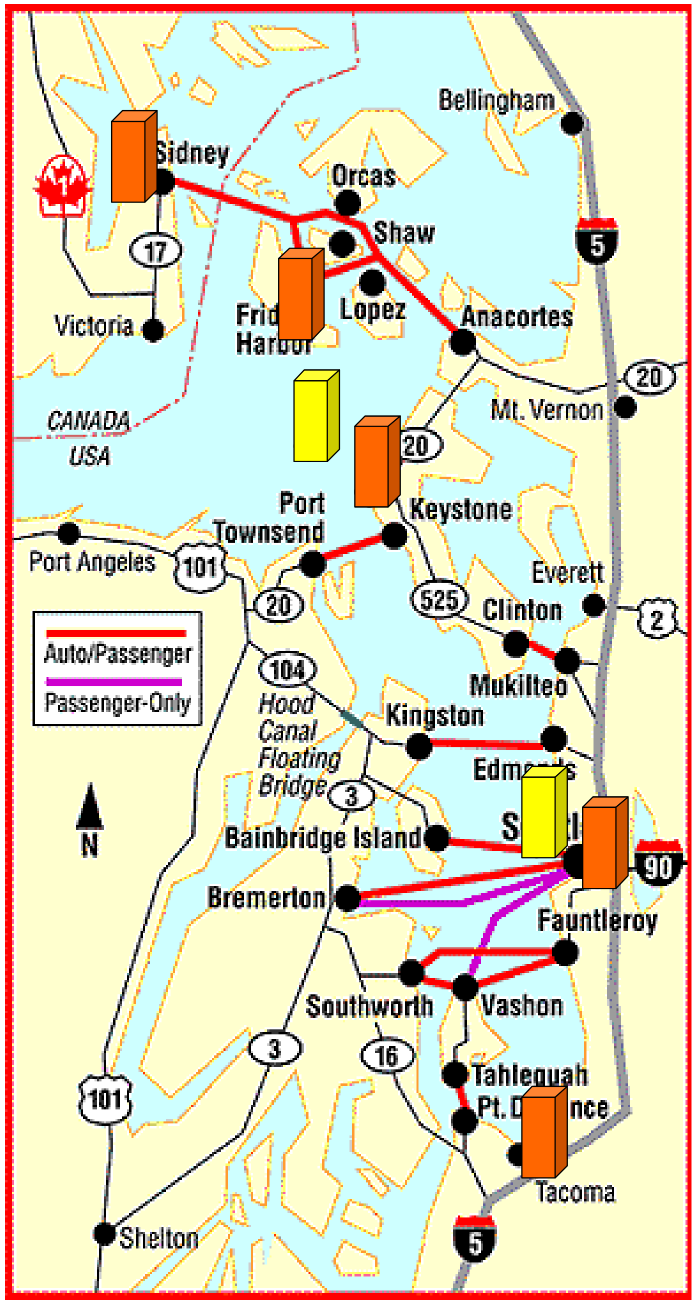


Figure 4. The locations of the environmental data sources

The data sources at Sidney, Friday Harbor, Keystone, Seattle and Tacoma come from airports. These readings include the wind speed and direction along with visibility information. However, the readings are taken at various intervals with some lengthy gaps. Five years of data was obtained from each location (1993 through 1997). This data was then used in the simulation to replicate the weather conditions historically observed. In the simulation, weather conditions at a specific location were determined by assigning that location to the nearest weather data source. Missing observations in the data were handled by defaulting to the nearest alternative location.

The simulation was validated visually by ferry captains, VTS personnel and Pilots. Several suggestions made by these persons were used to improve the accuracy of the simulation. Each group stated that for the simulated period observed, the situations observed could well have been taken from real life. This is a major test for a simulation.

2.2 The OFI Counter

The simulation itself does not tell us how often each possible situation occurs. A snapshot of the simulation is taken every 2½ minutes and the OFI's observed recorded in an event database. This data recording process is coded into the simulation program itself. Figure 5 shows a snapshot of Elliott Bay in the simulation.

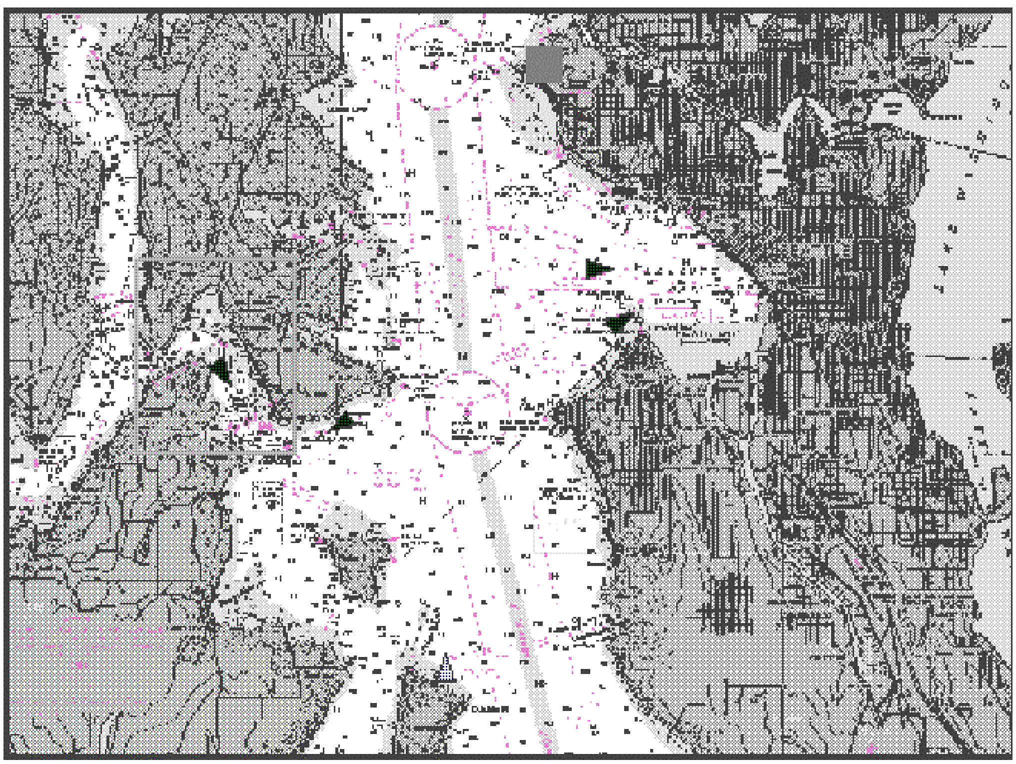


Figure 5. A snapshot of the WSF Simulation Program

To count OFI's that can lead to a collision, we need only consider interactions between ferries and other vessels (including other ferries). In figure 5, there are 4 moving ferries represented by the green triangles. Which pairs of ferries could be considered an interaction? This depends on the time until the vessels meet and the type of interaction. We are also interested in distinguishing between different types of interactions, as they will affect the risk of a collision.

More specifically, if a ferry is within 15 minutes of another vessel and (1) the vessel crosses the ferry track within 1 mile in front of the ferry, or (2) the vessel crosses the ferry track within 0.5 miles behind the ferry, an interaction is counted. If the previous scenario does not hold, but the current distance between the vessel and the ferry is less than 1 mile, an interaction is counted. This counting model is based on a Closest Point of Approach (CPA) type arguments and stems from the considerations that a ferry captain will make when considering interactions with other vessels. In addition, vessels close in at different speeds, thus in evaluating a situation involving other vessels, the captain is interested in which will arrive first, not necessarily which is closest. Experts with maritime experience outside the ferry service and a group of ferry captains from the Washington State Ferry Service provided input for this methodology.

2.2.1 Defining Types of Interaction

Figure 6 shows the various types of interactions as defined by the course the other vessel in relation to the ferry.

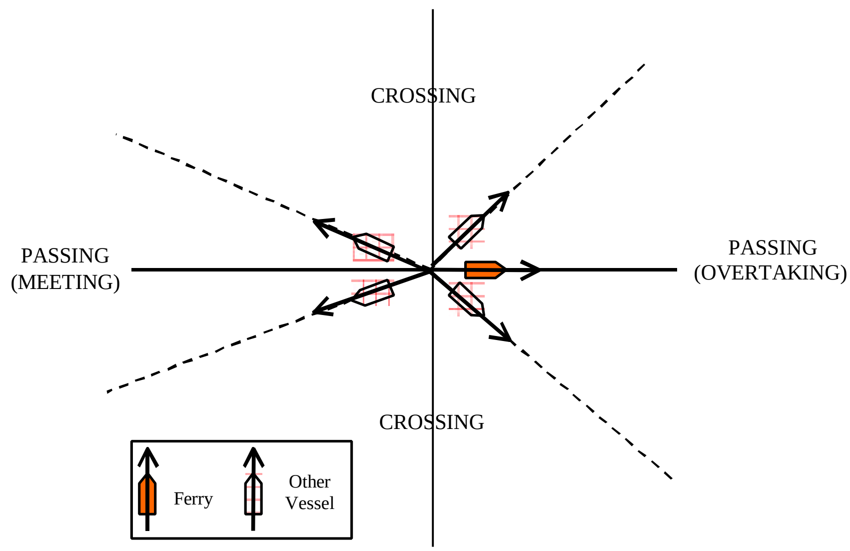


Figure 6. The type of interaction defined by interacting angle

If the other vessel is moving in the opposite direction from the ferry then it will be a meeting situation. If the other vessel is moving in the same direction as the ferry, it will be an overtaking situation (this means the other vessel is moving faster than the ferry). If the vessel is coming from either side and crossing the path of the ferry, in front or behind, then it will be a crossing situation.

2.2.2 Recording Vessel and Waterway Attributes

Within the simulation program, the snapshot of the simulation at a specific time is analyzed to determine whether an interaction is occurring. For each interaction determined, the information in table 2 is recorded.

Table 2. Vessel and waterways attributes recorded in an OFI

VESSEL ATTRIBUTES	WATERWAY ATTRIBUTES
Ferry Class	1st Interacting vessel type
Ferry Route	1st Interacting vessel type proximity
	Type of interaction with 1st vessel
	2nd Interacting vessel type
	2nd Interacting vessel type proximity
	Type of interaction with 2nd vessel
	Wind speed
	Wind direction
	Visibility

Notice that the vessel closest to the ferry is recorded as well as the second closest vessel, as this is a complicating factor in the interaction with the first vessel. Each OFI is recorded in an OFI database. The factors recorded for each OFI are the factors that determine the probability of a triggering incident and the probability of a collision in the incident and accident probability models.

2.2.3 Calculating Collision Frequencies

A specific OFI is defined by the factors in table 2. By counting the number of times each OFI occurs in ten years of simulation, the frequency of occurrence of each OFI may be determined. By multiplying this frequency by the probability of a collision for that OFI, calculated from the accident probability model, the statistical frequency of collisions with a specific set of attribute values (= risk factors) is determined. By adding together the statistical frequencies of collisions with specific sets of attribute values, the overall statistical frequency of collisions can be determined.

However, although the total frequency of collisions per year is of interest, the power of the model comes from the inclusion of risk factors in the model. As an example, suppose we wished to compare the statistical frequency of collisions across ferry routes. To determine the frequency of collision involving ferries on the Seattle-Bainbridge Island route, for instance, we can add together the collision frequencies for collision caused by all OFI's where the route is Seattle-Bainbridge. A similar calculation can be performed for each of the other routes and thus a comparison of collision frequencies by ferry route can be made. A similar comparison can be made sorting by ferry class, 1st interacting vessel type or any combination of the attributes in table 2.

Section 3. The Triggering Incident and Collision Probability Models

Thus far we have discussed the simulation and counting models used to estimate the frequency of various different situations that may lead to a collision. However, we do not know the likelihood collisions in these situations. To estimate the collision probabilities in each possible situation, expert judgement data was combined with the historical accident and incident data.

Expert judgment was used in the WSF Risk Assessment to assess the relative probabilities of human error incidents on the various ferry routes and the relative probabilities of accidents for different sets of waterway attributes and triggering incidents. This approach relies upon the premise that the judgments of the experts that have a deep understanding of the system provide a basis for the calculation of risk in case of sparse, and possibly unreliable, data. It must be noted, however, that all available, reliable data was used in the estimation and calibration of the conditional collision probabilities.

There were two levels to this part of the model. First, the likelihood of a triggering incident was assessed and then the likelihood of an accident given the occurrence of that triggering incident was assessed. In the next section, we shall discuss the estimation of the frequencies of the 5 types of triggering incidents: propulsion failures, steering failures, electronic or navigational aid failures and human errors. In the following section, the estimation of the 5 conditional collision probability given the occurrence of any of the 5 triggering incidents terms, is discussed. The 5 conditional probability terms are:

- the probability of a collision given a propulsion failure on the ferry.
- the probability of a collision given a steering failure on the ferry.
- the probability of a collision given a electronic or navigational failure on the ferry.
- the probability of a collision given a human error on the ferry.
- the probability of a collision given a mechanical or human error on the interacting vessel.

The calibration of the collision probability model is then discussed, followed by a discussion of uncertainty and bias in the use of expert judgment.

3.1 Estimating Frequencies of Triggering Incidents

As discussed in Appendix 1, data on the occurrence of mechanical failures on Washington State Ferries for the period 1988 to 1998 was collected from a variety of data sources. This data was used to estimate the frequency of the first 3 types of triggering incident: propulsion, steering and electronic failure. These are the 3 major types of mechanical failures experienced by ferries. The frequencies of these 3 types of mechanical failure were assumed to depend on the class of ferry.

Figure 7 shows the estimated frequencies of the 3 types of mechanical failures for each ferry class. Examining figure 7, the frequency of propulsion failures on the Chinook appears relatively high. This is due to a difference in classification for this design of ferry.

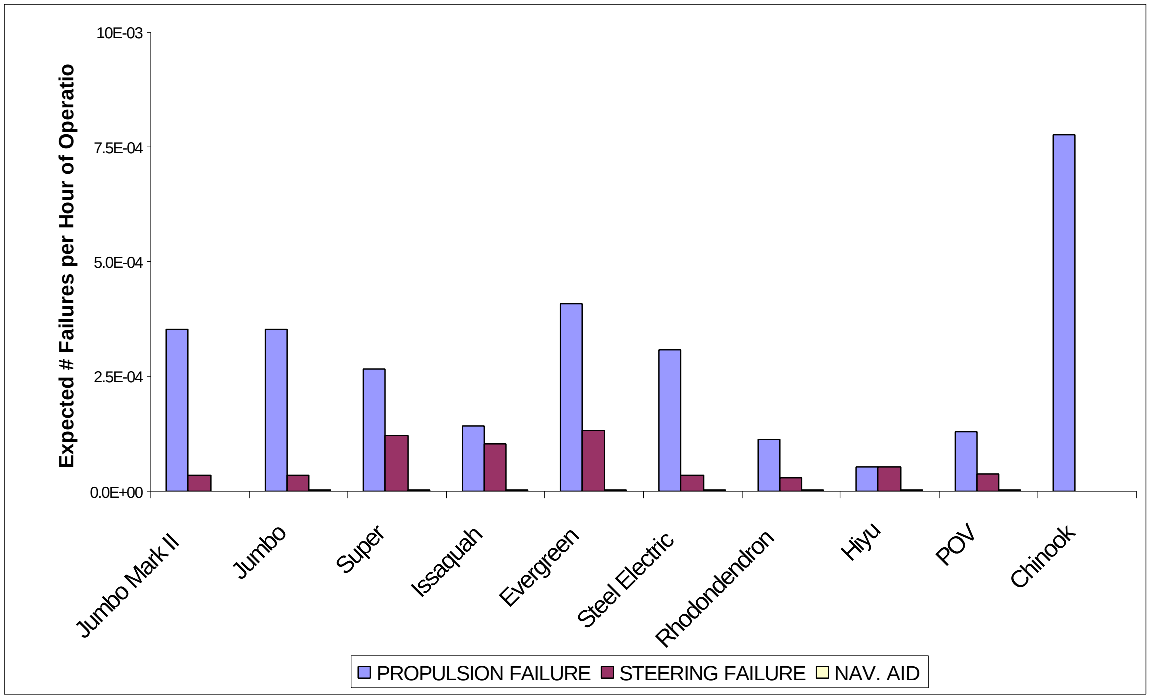


Figure 7. The estimated frequency of mechanical failures for each ferry class

The propulsion and steering systems on the Chinook are combined, leading to a problem in classifying propulsion and steering failures separately. In figure 7, all failures of the combined propulsion/steering system of the Chinook are shown as propulsion failures.

The occurrence of human errors is more difficult to assess. The Washington State Ferry Service does not formally collect data on the occurrence of human errors. Even in cases where human error data is collected, problems with definition and classification lead to difficulty in its analysis, see Harrald et al (1998). The ferry captains were asked to compare pairs of ferry routes and determine which route posed a greater opportunity for human error considering only characteristics specific to the routes being compared and not vessel characteristics. Using the Bradley-Terry pairwise comparison technique, see Bradley and Terry (1952), these comparisons were combined to estimate the probability of a human error occurring on a particular ferry route given the occurrence of a human error in the WSF system. Figure 8 shows the distribution of human errors across the ferry routes estimated using this expert judgment technique.

Even with the above distribution of human errors by ferry route, it is still necessary to find the overall frequency of human errors. Harrald et al (1998) states that "most studies in transportation related accidents have concluded that human errors cause approximately 80% of all accidents". In the absence of better information, this 80% figure is often assumed. In an effort to improve on this assumption, narrative descriptions were obtained from the United States Coast Guard of the accidents that have occurred since 1989 involving Washington State Ferries. An event analysis of the 46 Washington State Ferry accidents that occurred between 1988 and 1998 was conducted in order to assess the role of human and organizational error in events in the Puget Sound marine transportation system.

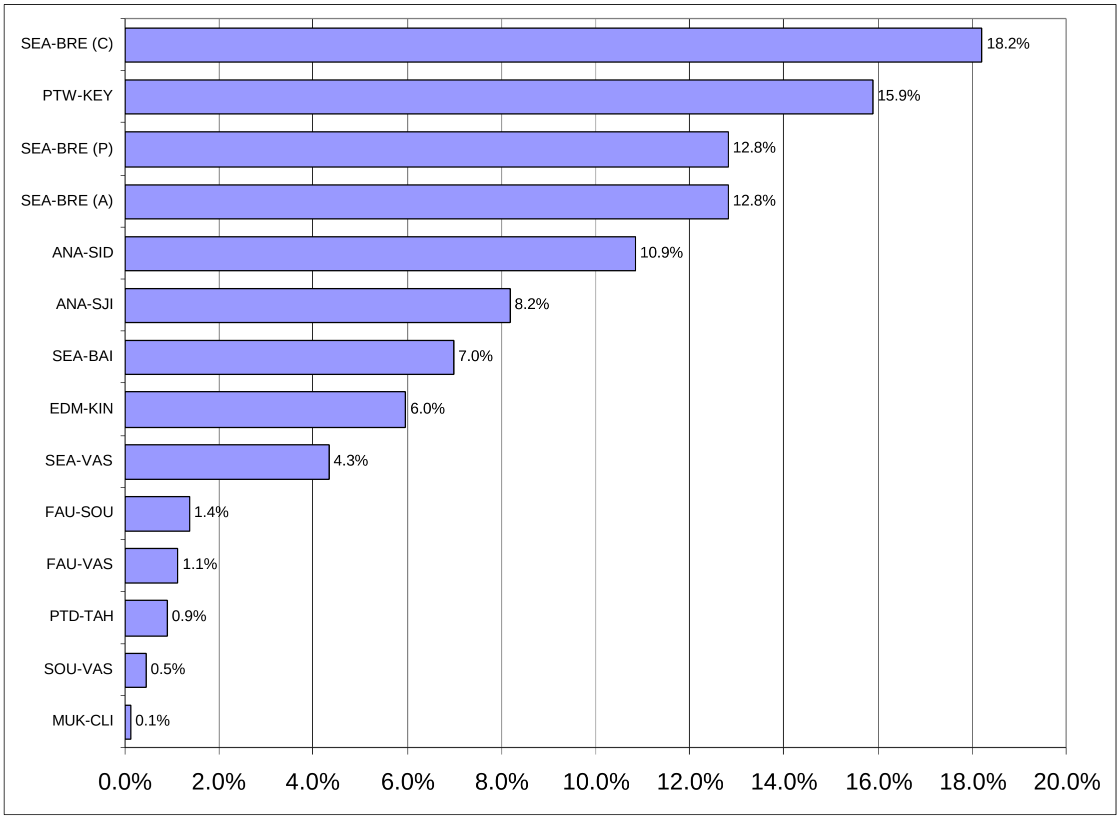


Figure 8. The estimated distribution of human errors across the ferry routes

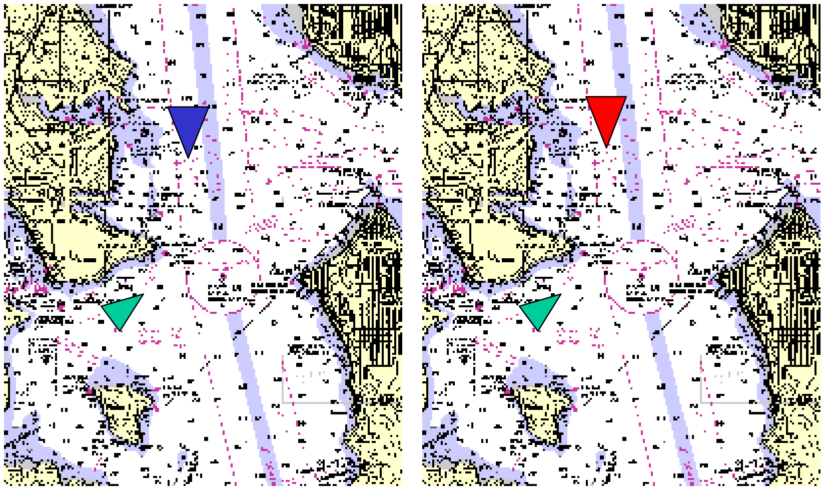
During this analysis, a total of 51 errors were identified. 35 (68.6%) of the errors were categorized as human error, and 16 (31.4%) of the errors were categorized as mechanical errors. This data provides an interesting contrast to the oft-quoted 80% human error figure used in many maritime studies. Thus, in this study, approximately two-thirds of the accidents were caused by human error, so it was assumed that the frequency of human error incidents is twice that of mechanical failure incidents.

3.2 Estimating the Probability of a Collision given a Triggering Incident

Once a triggering incident has occurred, the likelihood of a collision is affected by the factors that define the situation. The probability of a collision was assumed to depend on the factors listed in table 1. To assess the probability of a collision, experts were asked to compare two interaction situations, as shown in figure 9.

The questions ask the expert to consider two situations between which only one factor has changed. The basic situation in figure 9 is an Issaquah class ferry traveling from Bremerton to Seattle on a clear day with no wind. There is another vessel that will be crossing the bow of the ferry within the next 15 minutes but the other vessel is currently more than 1 mile away. In the situation on the left-hand side, the other vessel is a Navy vessel, while on the right-hand side, it is a product tanker.

Issaquah class ferry on the Bremerton to Seattle route in a crossing situation within 15 minutes, no other vessels around, good visibility, negligible wind.



Other vessel is a navy vessel   Other vessel is a product tanker

Figure 9. An example of the type of question used in the expert judgement

The experts were asked to complete a booklet with 60 such questions in a session. The questions were asked in the format of figure 10.

Question: 1 89

Situation 1	**Attribute**	**Situation 2**
Issaquah	**Ferry Class**	-
SEA-BRE(A)	**Ferry Route**	-
Navy	**1st Interacting Vessel**	Product Tanker
Crossing	**Traffic Scenario 1st Vessel**	-
0.5 – 5 miles	**Traffic Proximity 1st Vessel**	-
No Vessel	**2nd Interacting Vessel**	-
No Vessel	**Traffic Scenario 2nd Vessel**	-
No Vessel	**Traffic Proximity 2nd Vessel**	-
> 0.5 Miles	**Visibility**	-
Along Ferry	**Wind Direction**	-
0	**Wind Speed**	-
	Likelihood of Collision Avoidance	
	9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9	

Figure 10. An example of the question format

The responses were given on the scale at the bottom of figure 10. The scale is not an absolute scale, i.e. if the expert circles 2 one may not conclude that one event is twice as likely as the other; rather the scale is a "free floating" scale. An "average" calibration constant for the group of experts is calculated using accident data to convert the "free floating scale" to an absolute scale. Details concerning the calibration methods are discussed in a section below.

Five different questionnaires were designed, one for the conditional probability of a collision given each of the five triggering incidents. Table 3 shows the five questionnaires.

Table 3. The five collision questionnaires

Questionnaire	Likelihood of collision given a
7A	Propulsion failure on the ferry
7B	Steering failure on the ferry
7C	Navigational aid failure on the ferry
7D	Human error on the ferry
7E	Mechanical failure or human error on nearby vessel

Each questionnaire consisted of 60 comparisons. The results from the expert judgment sessions were analyzed using a technique known as statistical regression. The questionnaires were designed to collect the maximum amount of information from the 60 questions. This was to ensure that the experts could complete the entire booklet without tiring.

As an example, we shall examine the questionnaire for the likelihood of a collision given a propulsion failure. The model assumed took the form of a proportional probabilities model. This model has been used previously in the Prince William Sound Risk Assessment (Harrald et al 1998) and Roeleven (1991). Let $\underline{X}$ denote the vessel and waterway attributes for a particular OFI. The conditional probability of a collision (given that a propulsion failure has occurred in the OFI defined by $\underline{X}$) is assumed to be

$$P(\text{Collision} \mid \text{Prop. Fail.}, \underline{X}) = p_0 \exp\{\underline{b}^T \underline{X}\},$$

where $\underline{b}$ is a vector of parameters and p_0 is a baseline probability parameter. The convenience of this form is revealed by examining relative probabilities. Consider two situations defined by the vessel and waterway attribute vectors $\underline{X}$ and $\underline{Y}$. The relative probability is the ratio of the collision probabilities, specifically

$$\frac{P(\text{Collision} \mid \text{Prop. Fail.}, \underline{X})}{P(\text{Collision} \mid \text{Prop. Fail.}, \underline{Y})} = \frac{p_0 \exp\{\underline{b}^T \underline{X}\}}{p_0 \exp\{\underline{b}^T \underline{Y}\}} = \exp\{\underline{b}^T (\underline{X} - \underline{Y})\},$$

where $(\underline{X} - \underline{Y})$ denotes the difference vector for the two vessel and waterway attribute vectors.

Thus, in this probability model, the relative probability of a collision given propulsion failures in 2 situations depends solely upon the difference between the two situations and the parameter vector $\underline{b}$. Recall the format of the questionnaires demonstrated in figure 9. Each question asked the experts to assess the relative likelihood of a collision given a propulsion failure in two situations. Thus the format of the questionnaires allows the estimation of the parameter vector $\underline{b}$ without considering the absolute level of collision likelihood (given by the baseline parameter vector p_0).

Multiple experts are used for each questionnaire, so there are multiple responses to each question. Let the questions be indexed by $k \ (=1,\ldots,n)$ and the experts be indexed by $l \ (=1,\ldots,m)$, so the experts' responses can be denoted $e_{k,l}$. To pool the expert responses for a given question, the geometric mean of the expert responses is taken to obtain

$$\bar{e}_k = \left(\prod_{l=1}^{m} e_{k,l} \right)^{1/m}.$$

The geometric mean is appropriate as the responses represent ratios of probabilities. Thus we now have that $\bar{e}_k$ is the grouped expert estimate of the relative probability for the k-th question, while the model gives this relative probability as $\exp\{\underline{b}^T \underline{Z}_k\}$, where $\underline{Z}_k$ is a vector representing the difference between the two situations in question k. This gives the basis for the regression equation used, specifically

$$\ln(\bar{e}_k) = \underline{b}^T \underline{Z}_k + e \ ,$$

where e is the residual error term.

Assuming that e is normally distributed, this equation is a standard multiple linear regression, where the grouped expert response is the dependent variable, $\underline{Z}_k$ is the vector of independent variables, $\underline{b}$ is a vector of regression parameters and e is the error term. Using a standard inference procedure for multiple linear regression, estimates for the parameter vector $\underline{b}$ are obtained, denoted $\underline{\tilde{b}}$.

Recall from figure 10, that the scale of the experts' responses was allowed to be "free floating". Thus the experts were not asked to actually assess that one situation was twice as likely as another. Each expert was allowed to choose his or her own implicit scale on which to respond. Thus the expert responses required scaling to convert them to a meaningful scale. Let $\bar{c}$ denote the implicit scaling constant for the expert group, and let $\bar{e}_k^* = \bar{e}_k^{1/\bar{c}}$ represents the calibrated relative probability of a collision in the two situations assessed by the expert group for the k-th question. Thus the regression equation becomes

$$\ln(\bar{e}_k) = \ln(\bar{e}_k^{*\bar{c}}) = \underline{b}^T \underline{Z}_k + e_k$$

or

$$\ln(\bar{e}_k^*) = \frac{\underline{b}^T}{\bar{c}} \underline{Z}_k + \frac{e_k}{\bar{c}}.$$

Thus the estimate $\underline{\tilde{b}}$ obtained from the statistical regression must be scaled using $\bar{c}$ to calibrate the 'free floating' scale of the questionnaires to an absolute scale. As $\bar{c}$ is unknown, it must be estimated in the calibration procedure using historical accident data.

Returning to our example of the probability of a collision given a propulsion failure, the parameter estimates obtained from the statistical regression equation are given in table 4.

Table 4. Results of the statistical regression for the probability of a collision given a propulsion failure on the WSF vessel

Waterway Attribute	Parameter Estimate	Standard Deviation
1st Interacting vessel type	1.503	0.209
Type of interaction with 1st vessel	0.642	0.299
1st Interacting vessel type proximity	3.330	0.311
2nd Interacting vessel type	0.606	0.467
Type of interaction with 2nd vessel	1.177	0.325
2nd Interacting vessel type proximity	2.736	0.310
Visibility	3.343	0.310
Wind speed	1.775	0.310
Wind direction	3.737	0.621

The R^2 value for a statistical regression gives an indication of the fit of the model to the data. For this regression, an R^2 value of 76.5% was achieved (indicating a good fit) which indicates that 76.5% of the variation in the answered is explained by the model. The other questionnaires resulted in similar R^2 values.

Prior to the regression the ranges of values of the independent variables were normalized. The normalization allows for interpretation of the parameter estimates, i.e. which variables are most important in determining the conditional probability of a collision given a triggering incident. Figure 11 shows the relative contribution of each variable. Recall that this regression determines the conditional probability of a collision given that a propulsion failure has occurred. The 4 most important variables in determining this probability are shown, in figure 11, to be the proximity of the closest vessel, the proximity of the second closest vessel, the wind speed and the visibility. This result is intuitive, as the propulsion failure would disable the ferry and the avoidance of a collision would be up to the closest vessels. In addition, bad visibility and high winds would cause significant problems in case of a disabled ferry due to loss of propulsion.

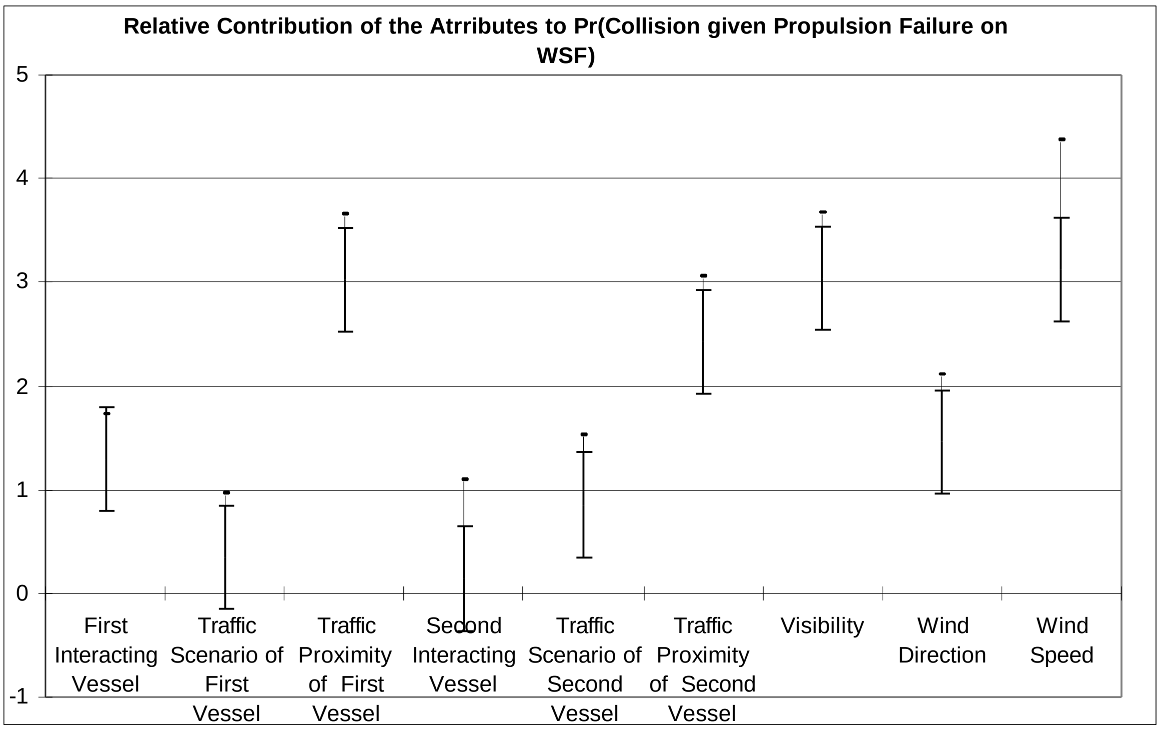


Figure 11. Relative contribution of the variables for the collision probability given a propulsion failure on the WSF vessel.

3.3 Calibration of the Collision Probability Model

The questions asked in the questionnaires concerned comparisons of different scenarios. Thus the results of the expert judgment sessions allows us to estimate, for example, that a meeting situation involving two Jumbo Mark II ferries on a clear day is a certain factor safer than a meeting situation involving a Jumbo Mark II ferry and a container vessel in poor visibility. However, this does not give the likelihood of a collision in either situation. To turn the relative comparisons into accident frequencies, the relative results have to be calibrated to accident data. As discussed previously there was also the problem of calibrating the scale of the expert responses.

The calibration procedure began once the simulation was run to obtain the frequencies of the various OFIs, the statistical regressions on the expert judgments were completed and the statistical frequencies of the various triggering incidents were estimated. The parameters that remained to be estimated were the baseline probabilities, denoted by p_0 in the regression equation discussed above, and the implicit scaling constant, previously denoted $\bar{c}$.

To find these calibration constants, historical accident data was used along with certain arguments of symmetry that were logically required. The calibration constants were set so that the following constraints were satisfied:

1. The baseline probability of a collision given a propulsion failure, a steering failure and a navigational aid failure are all equal. This is a symmetry argument. The baseline probability is the probability of a collision in the lowest probability situation. The lowest probability situation is an interaction between two large ferries over a mile apart on a clear day with no wind. In this situation one could argue that the course of action would be the same if any of these three triggering incidents occurred, e.g. to stop and radio the other ferry. Thus, the probability of a collision in this situation is judged to be the same for each triggering incident.
2. The statistical frequency of collisions caused by human error incidents was twice that of collisions caused by mechanical failures, specifically the total frequency of propulsion failures, steering failures and navigational aid failures. This reflects the historical data where two-thirds of the accidents in the period 1988 to 1998 were attributed to human error.
3. The statistical frequency of collisions between two ferries due to mechanical failures or human errors on one of the ferries involved was equal to the statistical frequency of collisions between two ferries due the nearby vessel, i.e. the other ferry. This is a symmetry argument.
4. The statistical frequency of collisions between two ferries was equal to the statistical frequency of collisions between a ferry and a non-WSF vessel. This reflects the historical data in the period 1988 to 1998, where one collision occurred between two ferries and one collision occurred between a ferry and a non-WSF vessel.
5. The total statistical frequency of collisions was equal to 2 in 11 years. This reflects the historical data, where 2 collisions occurred in the period 1988 to 1998.

The calibration constants were set to satisfy these necessary conditions. This required multiple iterations to ensure that each necessary conditions was simultaneously satisfied. Each of these facts were checked once the calibration process was completed.

3.4 Limitations of Expert Judgment

At this point some limitations of the use of expert judgment should be mentioned. As with the analysis of rare events using classical statistical methods, the results obtained from the encoding of expert judgment should not be considered free of error. As stated by Harrald et al (1992), the experts must be evaluated for bias and for overconfidence in their own judgment.

Each expert filled out the questionnaires independently and the responses of each expert were compared. Although, there were differences of opinion on some questions, the overall agreement of the experts was remarkable. The experts were allowed to use a "free floating" scale to minimize anchoring bias. The scale was then calibrated to historical data. The questions were asked in random order. The randomization of the questions meant that deliberate attempts to bias the results were almost impossible. Tests on the responses were performed to ensure that the experts' responses were not effected by fatigue.

The main pool of experts used in the study was the ferry captains that worked relief. This ensured that the experts had a thorough knowledge of the entire system, not just a specific route. Each of the experts used had over 20 years of experience with the Washington State Ferries. To assess the possibility of a group bias, questionnaires were also given to personnel from the USCG Vessel Traffic Service in Seattle and to members of the Puget Sound Pilots Association. The level of agreement between the ferry captains and the two other groups of experts was considerable and served as evidence against the presence of a group bias.

Section 4. Damage Model

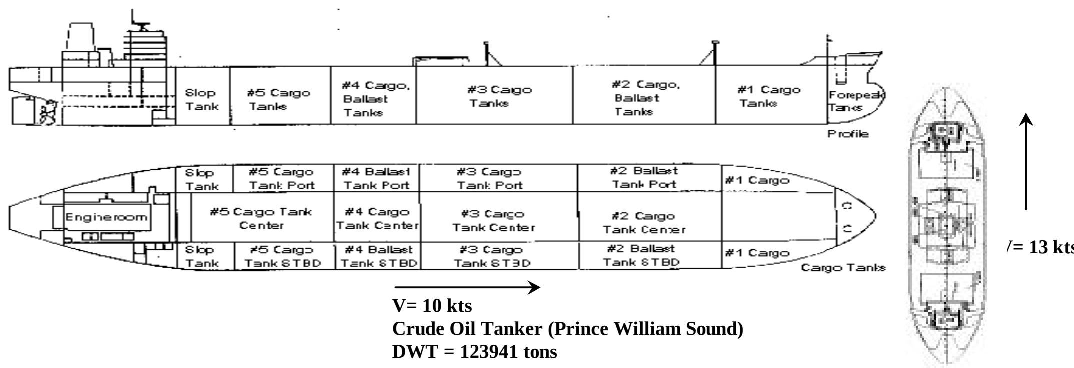
Collision is a major potential threat to Washington State Ferries. Car ferries are designed to survive most collisions. However, a few collision scenarios involving certain classes of car ferries and large, fast vessels, and almost all scenarios involving passenger only ferries could result in potentially catastrophic consequences.

Of key interest in assessing risk associated with the Washington State Ferry System is the assessment of the required time to respond such that no additional casualties occur due to a failure to respond in time. The first step in the model was to assess the possible damage to the ferry from a collision. Damages to ship structure incurred in collisions can be described as sharp and localized cuts of the side plating by a sharp wedge. Studies of these damage scenarios (Minorsky, 1959) have led to development of techniques for the extent of damage. Using those standard techniques, estimates of the extent of damage size have been calculated for each ferry class. The initial set of calculations assume a perfectly inelastic, midship, right angle collision and a rigid, wedge-shaped bow on the striking ship extending from baseline to deck edge on the struck ship.

The damage size is a function of the collision energy, the colliding vessel bow angle and the effective deck thickness. The collision energy is calculated using the masses of both the struck ship (ferry) and the striking ship. To simplify the procedure during this initial set of calculations, a right collision angle was assumed. The mass of the ferry, mass of the striking vessel and square of the closing speed are directly proportional to the size of the damage. Due to proportionality to the square of the closing velocity of the striking vessel, velocity is a determining factor in damage calculations. Figure 12 shows a collision scenario –a large crude oil tanker striking a medium size car ferry- based on a possible interaction. Another potential collision scenario is shown on Figure 13, a mid-ship collision with a much faster vessel, a navy cruiser. Notice that the damage width and the damage penetration caused on the ferry by the navy cruiser is twice as large as the damage penetration caused by a tanker which is 12 times heavier. This means that speed has a much greater impact on the extent of damage than mass.

For non-WSF vessels the collision speed is set to 80% of the travelling speed to account for a speed reduction due to the awareness of a dangerous course, though too late. For WSF vessels the collision speed is set at 50% of the traveling speed. The difference between WSF vessels and non-WSF Vessels was argued due to size differences between WSF vessels and non-WSF vessels and the different layout of the propulsion systems of WSF Vessel relative to typical non-WSF vessels. The approach here was to use a reasonable assumptions rather than a worst case assumption and perform sensitivity analysis by changing this assumption to the worst case assumption, i.e. the collision speed of the striking vessel equals the travelling.

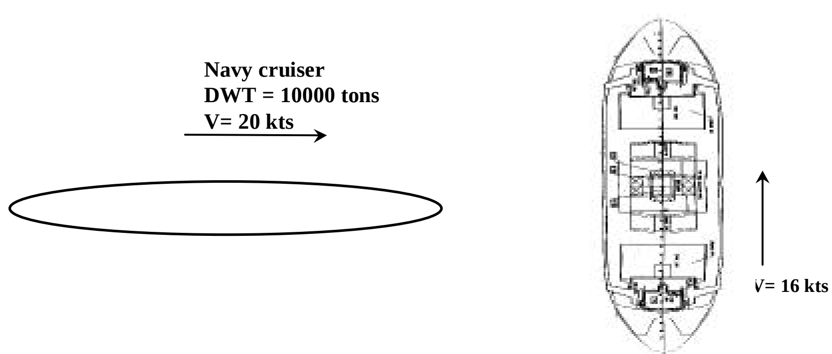
Evergreen State Ferry - Crude oil Tanker



Vessel Class	Name	Route	Length (ft)	Beam (ft)	Speed (knots)	# of compts.	Damage width (ft)	Damage Penetration (ft)
Evergreen State Ferry	Tilikum	Anacortes-San Juans-Sidney	310' 2"	73'	13	2	33	21

Figure 12. A collision damage calculation based on a collision scenario with a crude oil tanker

Issaquah Class - Navy cruiser



Vessel Class	Name	Route	Length (ft)	Beam (ft)	Speed (knots)	# of compts.	Damage width (ft)	Damage Penetration (ft)
Issaquah	Chelan	Mukilteo-Clinton	328'	78' 8"	16	2	63	40

Figure 13. A collision damage calculation based on a collision scenario with a navy cruises

The results of the method described above are conservative in that they assume a 90 degree vertical bow angle on the striking ship which implies that the estimated damage penetration extends from the baseline to the deck edge on the struck ship. Analyses were performed which take into account other vertical bow angles on the bow of the striking ship as shown figure 14. In addition, these analyses take into account the hull shape of the ferry to calculate whether damage penetration below the waterline occurs or not. These analyses are less conservative in terms of damage penetration below the waterline.

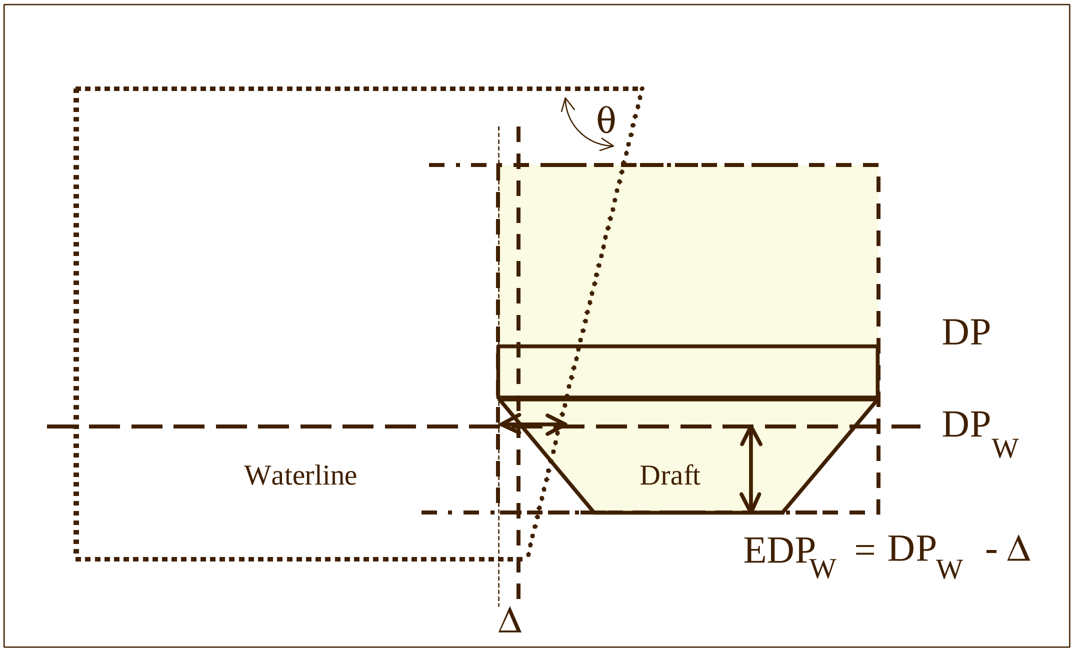


Figure 14. Modified Analysis due to Vertical Bow Angle and Washington State Ferry Hull shape

Table 5 contains example a set of damage calculations where the struck vessel is a Jumbo Mark II class ferry. A set of damage width calculations and damage penetration calculations, below and above the waterline, were calculated for each ferry class using the above modeling approach. Typical displacement sizes were assumed for vessels travelling in the WSF system as indicated in Table 5. The same holds for horizontal bow angles and vertical bow angles. Again, the approach was to use reasonable assumptions rather than worst case assumptions and perform a sensitivity analysis on these assumptions. The travelling speed for the different vessel types in different locations were taken from the WSF simulation and were obtained through interviews with pilots, VTS coast guard personnel, and WSF captains.

In later stages of modeling, a modified-Minorsky analysis was performed which considered the collision angle and the struck ship speed. The changes in collision forces and velocities were modeled as appropriate. The conclusion from these modified-Minorsky analysis is that a right collision angle assumption may underestimate the amount of damage width but overestimate damage penetration. Both damage penetration and damage width are input parameters for the response time model.

Table 5. A set of damage calculations for the Jumbo Mark II

Striking Vessel	Tavelling Speed (Knots)	Reduction Factor	Collisions Speed (Knots)	Ship Displacement (lton)	1/2 Horizontal Bow Angle	Vertical Bow Angle	Average Damage Penetration (ft)	Waterline Damage Penetration (ft)	Damage Width (ft)
Passenger, Loc 1-3	18	80%	14.4	20000	33	90	35.44	26.77	46.03
Passenger, Loc 4-5	14	80%	11.2	20000	33	70	25.96	14.20	33.72
Tug/Barge	13	80%	10.4	15000	33	70	21.73	9.97	28.22
Freight_Ship, Loc 1-3	15	80%	12	32000	33	70	30.95	19.19	40.20
Freight_Ship, Loc 4-5	14	80%	11.2	32000	33	70	28.40	16.64	36.88
Container, Loc 1-4	22	80%	17.6	32000	33	70	48.06	36.30	62.43
Container, Loc 5	16	80%	12.8	32000	33	70	33.46	21.70	43.46
Bulk_Carrier, Loc 1-3	15	80%	12	52000	33	70	32.88	21.12	42.71
Bulk_Carrier, Loc 4-5	14	80%	11.2	52000	33	70	30.23	18.47	39.27
Refr_Cargo, Loc 1-3	15	80%	12	32000	33	70	30.95	19.19	40.20
Refr_Cargo, Loc 4-5	14	80%	11.2	32000	33	70	28.40	16.64	36.88
Tanker, Loc 1-5	11	80%	8.8	140000	33	70	23.74	11.98	30.84
Product Tanker, Loc 1-3	15	80%	12	52000	33	70	32.88	21.12	42.71
Product Tanker, Loc 4-5	15	80%	12	52000	33	70	32.88	21.12	42.71
Other	10	80%	8	5000	33	70	2.53	0.00	3.29
Ro-Ro, Loc 1-5	18	80%	14.4	34000	33	70	38.73	26.97	50.30
Naval	20	80%	16	10000	33	70	33.69	21.93	43.76
Misc	10	80%	8	500	33	70	0.00	0.00	0.00
Jumbo Mark II	18	50%	9	6072	33	90	10.21	1.54	13.26
Jumbo	18	50%	9	4955	33	90	8.00	0.00	10.40
Super	17	50%	8.5	4163	33	90	2.22	0.00	2.89
Issaquah	16	50%	8	3543	33	90	0.00	0.00	0.00
Evergreen	13	50%	6.5	3086	33	90	0.00	0.00	0.00
Steel Electric	12	50%	6	2113	33	90	0.00	0.00	0.00

Section 5. Response Time Model

5.1 Emergency Evacuation Plan (EEP) on SOLAS Ferries

The Emergency Evacuation Plan (EEP) used by the WSF is divided into the following three distinct stages of egress[1]:

Stage 1 Egress: Muster of passengers and crew at Evacuation Zones and Assembly Stations[2]
Stage 2 Egress: Moving passengers and crew from Evacuation Zones and Assembly Stations to the Embarkation Stations
Stage 3 Egress: Moving passengers and crew from the Embarkation Stations to other points of safety away from the vessel.

The reason why the EEP is divided into separate stages is that it allows the master to prepare the passengers for the abandonment and to stop the abandonment process if the master determines that it is safer for the passengers to remain aboard the vessel.

During Stage 1 Egress, the crew members' duties include; issuing life jackets, and instructing passengers while mustering them. During the same time, some crew members execute other duties that their muster list requires. These duties may include, fire fighting, damage control and deployment and use of rescue boats and survival craft. According to the EEP, actual deployment of rescue boats, evacuation slides and survival craft must occur at the end of stage 1 Egress, just before Stage 2 Egress commences, as directed by the master. This portion of the EEP is used during fire and rescue emergencies. In many emergencies, it is usually not necessary to proceed beyond this point.

When the order to proceed to Stage 2 Egress are given by the master, the crew's duty is to move passengers down stairwells and through vehicles to the Embarkation stations on the car deck. If it is decided as unneccessary to proceed beyond this point, the passengers remain at the evacuation zones or assembly stations until the emergency conditions get resolved.

Stage 3 Egress requires the passengers to abandon the vessel via the car deck, overhead walkways, evacuation slides or other means to the shore, other vessels or survival craft. Depending on the type of emergency, say collision and/or fire; the passengers might also be mustered at the upper decks if the embarkation stations on the car deck are blocked. It is required that the embarkation stations be accessible under all loading conditions. Actual abandonment only should commence under direct orders from the Master using the PA system.

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[1] Vessel Emergency and Safety Preparedness- Solas Vessels, p.4-1
[2] Assembly Stations are currently being used on the Elwha and Evergreen State and are established inside evacuation zones at ends of the main passenger cabin.

5.2 Passenger behavior in maritime emergencies

It is difficult to estimate the total time required to abandon a ferry. There are numerous factors affecting the duration it takes to completely get the passengers out of the ferry. One reason is that the passenger behavior and the interaction of passengers and crew in crisis situations are complex. The following figures are taken from a report that studies the importance of passenger behavior in safety at sea[3]. Two stages for passenger behavior are discussed in the report: an acceptance stage and a reaction stage.

The acceptance stage in Figure 15 shows that in the initial phases of an accident, people have difficulty in accepting the danger of a situation under development. They either neglect the indications or they look for other signs that an accident is about to take place. 60% ignore or neglect even the most obvious signs that something is wrong. 30% investigate the incident and only 10% immediately accept the presence of danger. In some types of accident, the acceptance phase does not take place because of the obvious nature of the danger.

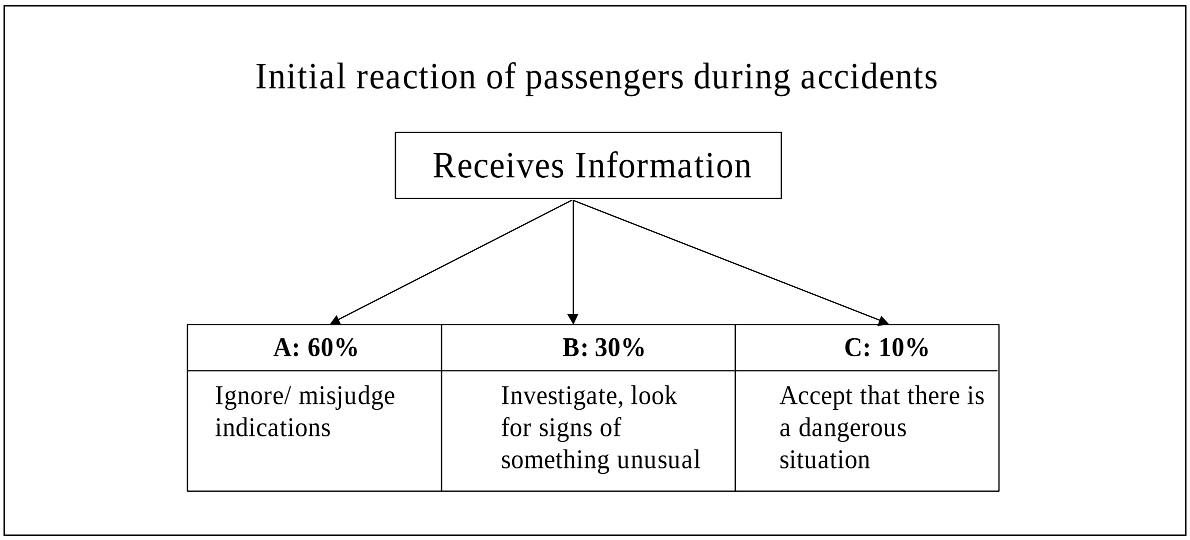


Figure 15. Acceptance Stage : The initial reaction in the first phase of a crisis.

As the signs of the crisis become stronger, Group A moves to Group B and Group C. As soon as Group B has received several signs, it will move over to Group C. Passengers' reaction behavior, once they accepted the danger, is also surprising. 25% act rationally, 60% await the initiatives of others and the final 15% seem totally paralyzed by the seriousness of the situation as indicated by figure 16.

[3] Prize Dissertation given by the Danish Investment Foundation of July 1, 1976, p.1-7.

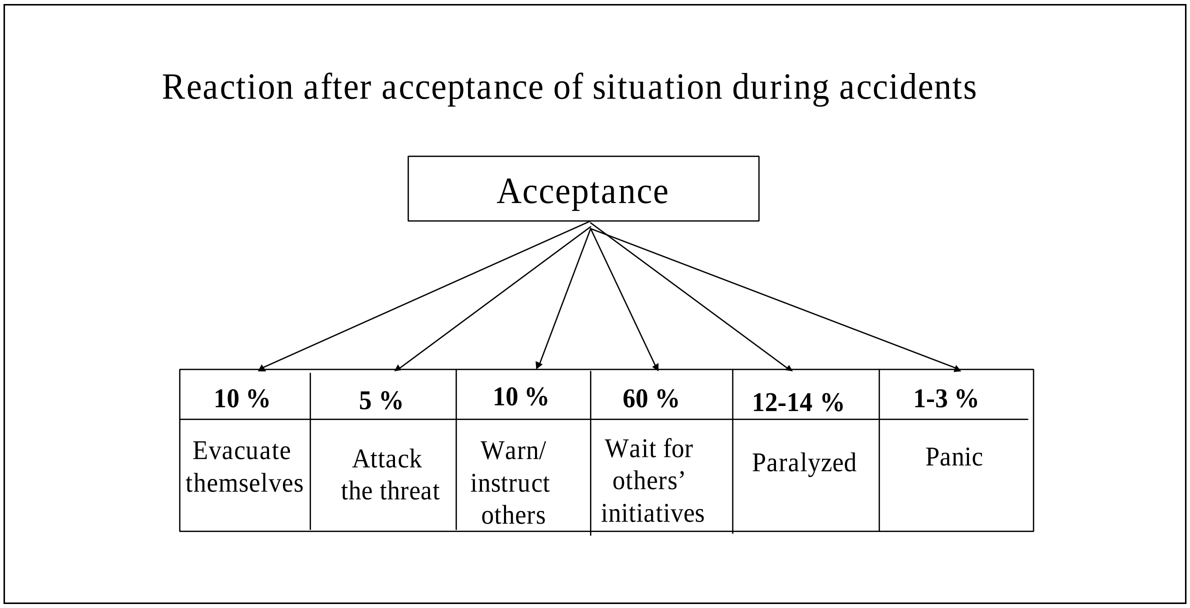


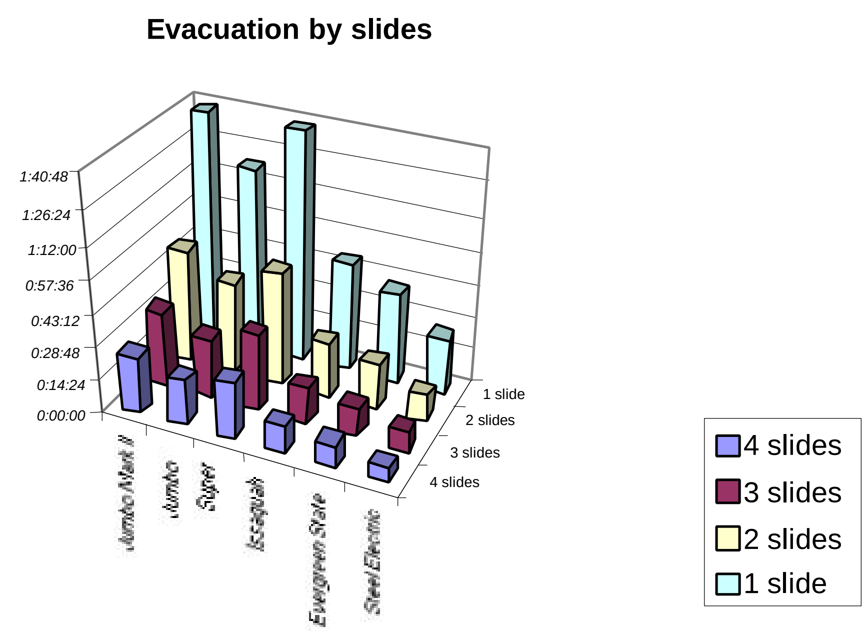
Figure 16. Reaction Stage: The second reaction in the first phase of a crisis.

5.3 Estimation of stage 3 egress by evacuation slides off car ferries

Although it is quite complicated to estimate the duration of Stage 1 and Stage 2 egress, it is possible to calculate an estimate of length of time it takes to get passengers off the ferry once they all have mustered at the embarkation stations. An analysis was done for this purpose. The analysis assumes the following optimistic assumptions:

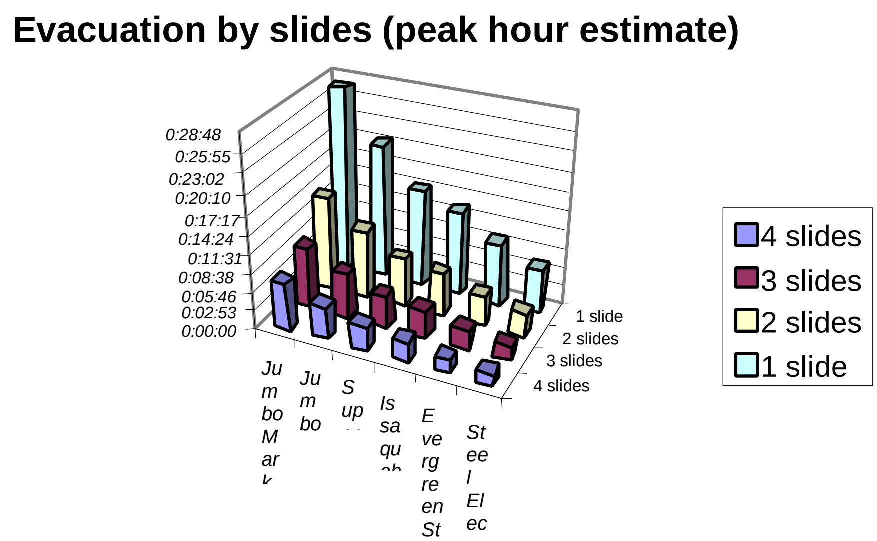
- The evacuation slides were designed to evacuate 200 people using 4 slides, in 2 minutes.
- The passenger behavior is ignored; i.e. it is assumed that passengers are in perfect shape, no panic involved, and all passengers are ready to go off the vessel without any delays for any reason.
- Equal number of passengers clustered at each embarkation station.
- The survival craft are enough for all passengers aboard, have already been marshalled and brought near each side of the platform.
- Rescue boats have already been launched.

Before doing the analysis, one debate was on the assumption of the number of passengers on board. Should this type of an analysis consider 100% passenger capacity in order to fulfill the worst case scenario approach or would it be an overkill since the ferries seldom operate full capacity? As a result, two separate calculations were made. The results from these calculations are presented in Figure 17 and Figure 18. Figure 17 contains the Stage 3 egress completion times for the full passenger capacity. Figure 18 contains the Stage 3 egress completion times for a more typical peak hour case. In the typical peak hour case it is assumed that the number of passengers on board equal twice the car capacity (thus, 2 passengers per car) plus the percent of people that walk-on. The walk-on percentages were taken from the Washington State Ferris System Plan for 1998-2018 published last year.



	Jumbo Mark II	Jumbo	Super	Issaquah	Evergreen State	Steel Electric
4 slides	0:25:00	0:20:00	0:25:00	0:12:00	0:10:00	0:06:10
3 slides	0:33:20	0:26:40	0:33:20	0:16:00	0:13:20	0:08:13
2 slides	0:50:00	0:40:00	0:50:00	0:24:00	0:20:00	0:12:19
1 slide	1:40:00	1:20:00	1:40:00	0:48:00	0:40:00	0:24:38

Figure 17. Stage 3 Egress Completion Times (full capacity)



	Jumbo Mark II	Jumbo	Super	Issaquah	Evergreen State	Steel Electric
4 slides	0:06:56	0:05:07	0:03:43	0:03:14	0:02:19	0:01:44
3 slides	0:09:15	0:06:49	0:04:57	0:04:19	0:03:06	0:02:19
2 slides	0:13:52	0:10:13	0:07:25	0:06:29	0:04:38	0:03:29
1 slide	0:27:44	0:20:26	0:14:51	0:12:58	0:09:17	0:06:58

Figure 18. Stage 3 Egress Completion Times (peak hour estimates)

5.4 Response Time Model Logic

A surrogate measure termed *maximum required response time* (MRRT), was used to address the potential accident impact and the response time issue. The MRRT was defined as the maximum allowable time for response to avoid additional (post accident) injuries or fatalities due to a failure to respond in time. Three categories of MRRT were deemed appropriate: less than one hour, between one and six hours, and greater than 6 hours. Accidents in the first category will require an effective external emergency response to prevent additional injuries or fatalities since the time would probably not permit the launching of survival craft. This observation primarily follows from the discussions in Section 5.2 and the optimistic estimates of Stage 3 egress completion times in Section 5.3. For accidents in the second category, time is deemed available for evacuation to a safe haven. In order to meet subchapter W requirements, the WSF system will have to demonstrate that they either have the ability to mobilize evacuation vessels or plan to provide survival craft adequate for all passengers. For accidents in the third category, adequate response in all cases can be provided without evacuating the passengers from the ferry. It is assumed that all collisions involving a high speed ferry fall in the less than one hour MRRT category. The response time model below is applied to calculate the likelihood of the three MRRT categories given a particular collision scenario for all ferries, except the Chinook.

Given the damage width and damage penetration calculations following from the damage model in Section 4, the likelihood of the three MRRT categories needs to be assessed. Collisions can result in damage to the structure of the vessel above the water line. More significant however is the damage to the underwater portion of the ship which affects the watertight integrity of the vessel and permits flooding of interior compartments. The subdivision of the ship by watertight bulkheads from the deck edge to the baseline, is done to prevent the vessel from sinking due to collision or grounding. The subdivision is the optimization of the size of the watertight compartments to assure that after flooding they will still permit the hull to retain sufficient buoyancy. The proper arrangement of compartments and bulkheads avoid progressive flooding, that would tend to cause the vessel to go down by the bow or the stern, and also prevent asymmetric flooding, which would put too much weight on one side and cause capsizing. The USCG requires a one compartment standard for vessels below 45.7 m (150 ft) in length and a two compartment standard above. A one compartment ship means that one compartment in the ship can be flooded without the ship sinking below the margin line. A two compartment ship means, any two compartments in the ship can be flooded without the ship sinking below the margin line.

The USCG requirements pertaining to subdivision (compartmentation) are given in Title 46 of the Code of Federal Regulations (46 CFR 171) where the damage stability standards of ferries are required to comply with the requirements and Regulations 1 and 5 of the Annex to Resolution A.265 (VIII) of the International Maritime Organization. The regulations (46 CFR 171) allow some watertight bulkheads to be pierced with doors, ventilation ducts, or pipes. For the prevention of progressive flooding from endangering the ship, all such openings should be capable of being closed in a rapid manner. The retention of buoyancy may also require crew competency by prompt action of closing the watertight doors and openings and dewatering endangered compartments.

The response time model takes into account the above subdivision rules for the WSF ferries. The following table summarizes the classification of one compartment and two compartment vessels as used in the WSF Risk Assessment.

Table 6. Classification of WSF Ferries

WSF Class	Number of Compartments
Jumbo Mark II	Two Compartment
Jumbo	Two Compartment
Super	Two Compartment
Issaquah	Two Compartment
Evergreen	Two Compartment
Steel Electric	Special Case
Rhodondendron	One Compartment
Hiyu	One Compartment
POV (Skagit, Tyee)	One Compartment
Chinook	High Speed Ferry

It is clear from the table that the Steel Electric has been considered a special case. Using the USCG regulation, the Steel Electric does not meet the requirements of a two compartment vessel and is by default a one compartment vessel. However, review of the structural plans of the steel electric by Naval Architects resulted in the observation that parts of the steel electric satisfy one compartment characteristics and other parts satisfy two compartment characteristics. As the location of impact of a collision has been considered in the WSF Risk Assessment, this information has been taken into account in treating the steel electric as a special case. Details concerning the steel electric assumptions are described below.

5.4.1 Response Time model logic for two compartment ferries

Below follows a discussion of the modeling logic to calculate the likelihood of the three MRRT categories for two compartment ferries given damage penetration and damage width as calculated by the damage model in Section 4. Figure 15 shows the distribution of collision points along a ship (taken from Tanker Spills, NRC, 1991). Note that the majority of the collisions are bow-stern collisions. Using the approach displayed in figure 15 we may calculate the probability of bow-stern collision and a mid ship collision. In the event of a bow-stern collision the MRRT is judged to be more than 6 hours as indicated by figure 16.

In the event of a mid-ship collision and a Relative Damage Penetration (RDP = damage penetration/Beam) larger than a preset threshold the three MRRT categories are assumed to be evenly distributed as indicated by figure 17. The preset threshold is set at 50%. However, sensitivity analyses are performed to test the sensitivity of this assumption (See appendix II). Assuming a MRRT of more than 6 hours in case of an RDP larger than the threshold is judged too optimistic. Vice Versa, assuming a MRRT of 0-1 hours in the latter case is judged too conservative. Therefore, it is judged that, without a detailed structural analyses on the effect of an RDP larger than the threshold, an even distribution over the three MRRT categories is a reasonable assumption.

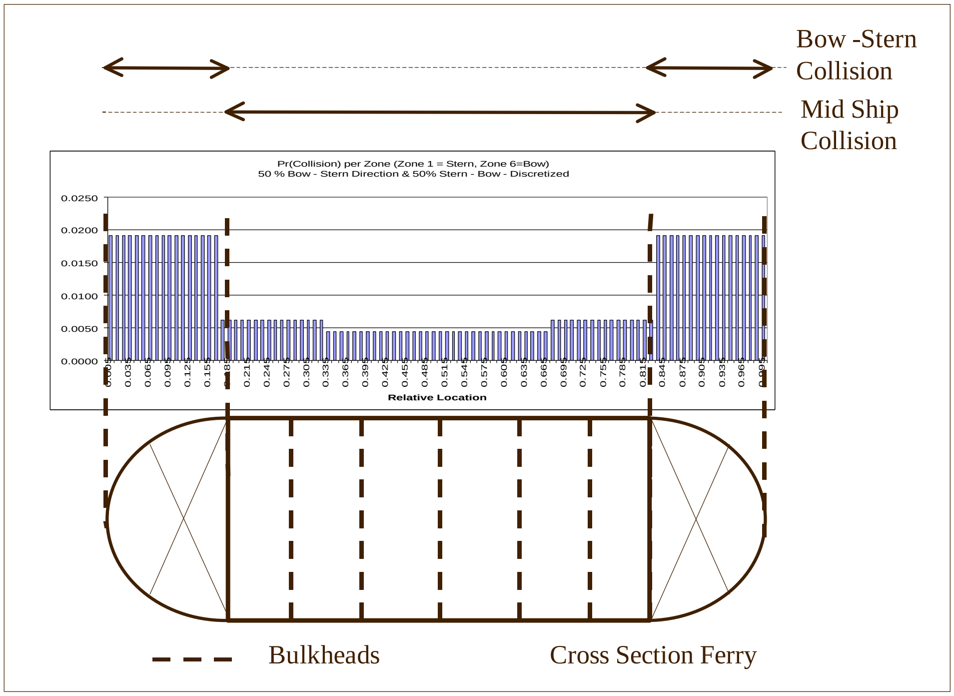


Figure 19. Probability calculation of Mid-Ship Collision and Bow-Stern Collision

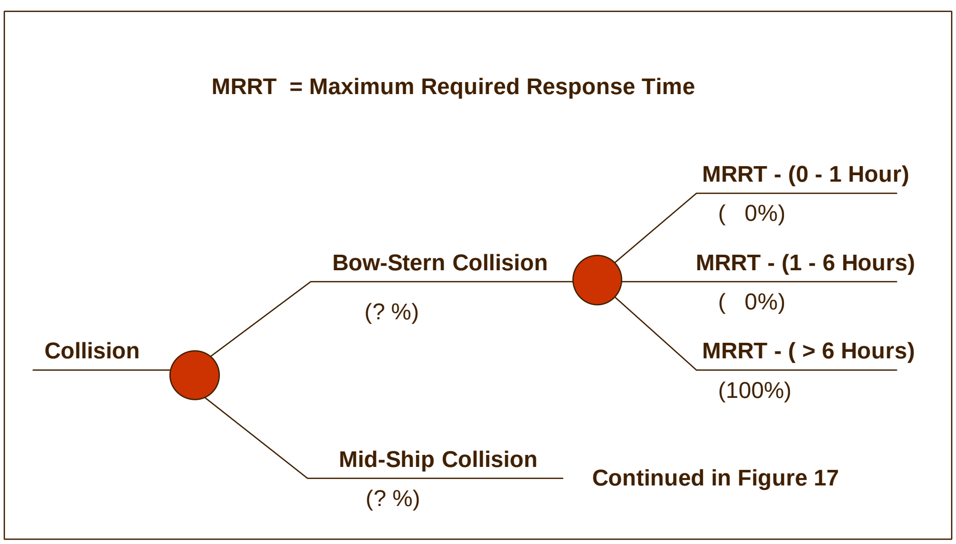


Figure 20. Response Time Model Logic

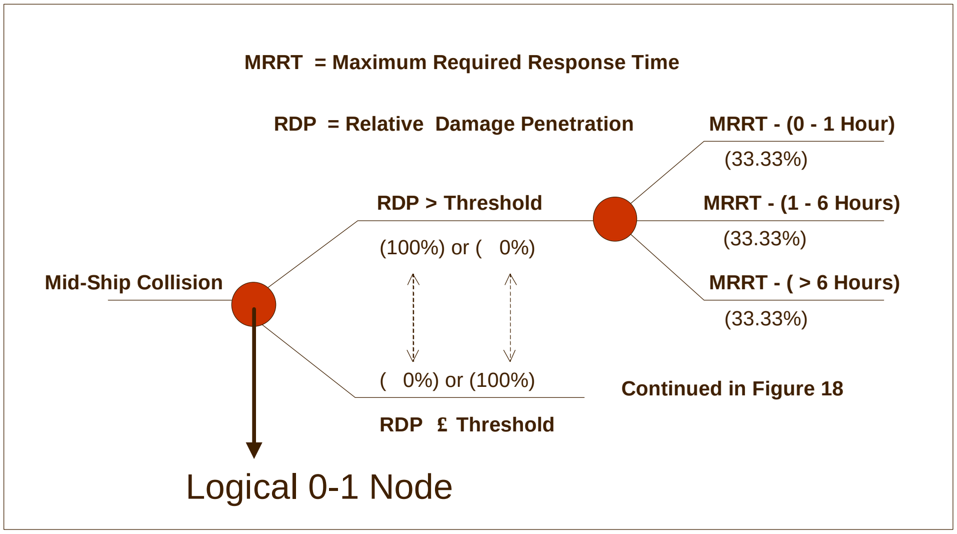


Figure 21. Response Time Model Logic (Continued)

In case of a mid-ship collision with an RDP less than the preset threshold and damage above the waterline, the MRRT is judged to fall in the more than six hours category as indicated in Figure 18.

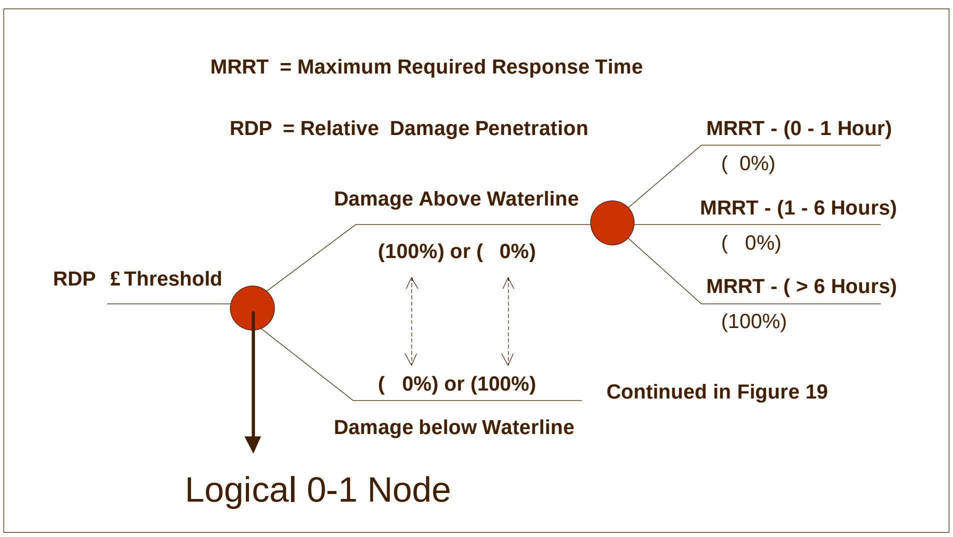


Figure 22. Response Time Model Logic (Continued)

In case of a mid-ship collision with an RDP less than the preset threshold and damage below the waterline, the distribution of the MRRT over the three categories is a function of the number of bulkheads damaged. In this case, and (1) if we are dealing with a two compartment vessel, and (2) if the number of bulkheads damaged is less than one, the MRRT is judged to fall in the more than six hours category. However, in the case of more than one bulkhead damaged, flooding of more than two compartments is possible and assuming a MRRT of more than 6 hours is judged too optimistic. Vice Versa, assuming a MRRT of 0-1 hours in the latter case is judged too conservative. Therefore, without detailed flooding analyses of individual ferries based on the assessed damage, it is judged that in the latter case an even distribution of the three MRRT categories is a reasonable assumption. This assumptions for the two compartment vessels given bulkhead damage scenarios are summarized in Figure 19.

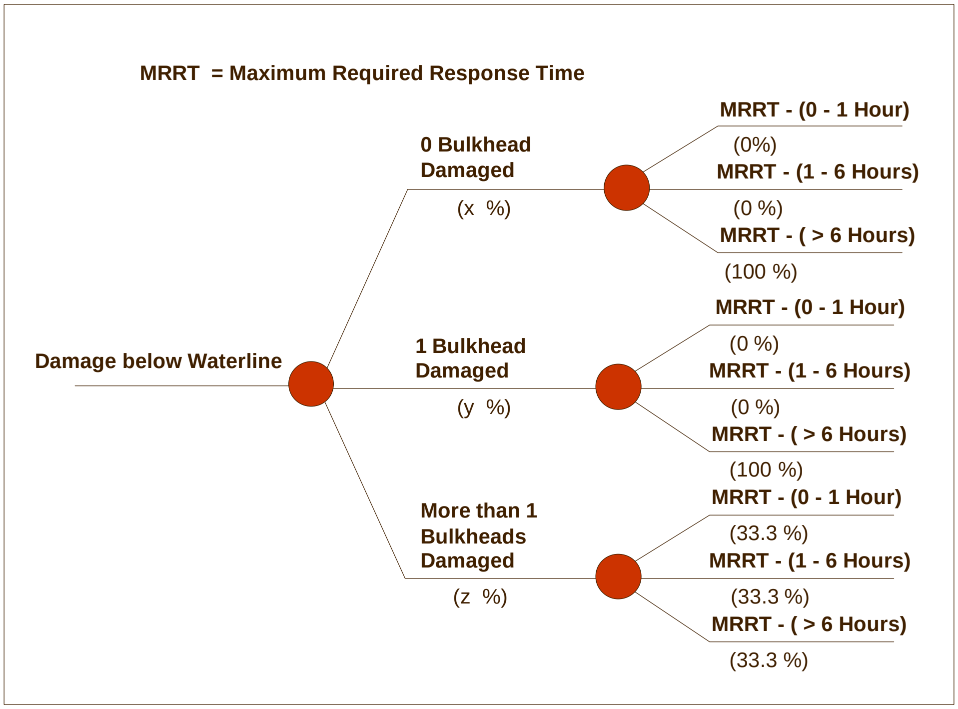


Figure 23. Response Time Model Logic (Continued)

Missing in Figure 19 is the actual probability of 0 bulkheads damaged, 1 bulkhead damaged and more than 1 bulkheads damaged. The calculation of these probabilities follow from the collision impact distribution, indicated in figure 15, and the actual calculated damage penetration and damage width, as indicated in figure 20. In figure 20, the probability of the actual point of impact can be read from the impact distribution. From the damage penetration and damage width calculation follows whether the RDP exceeds its threshold and the number of bulkheads damaged associated with this point of impact. By moving the point of impact along the length of the ferry and weighing these points of impact by their associated probabilities, the probabilities of 0 bulkheads, 1 bulkhead damaged and more than 1 bulkhead damaged can be calculated.

The assumptions concerning the distribution of the three MRRT categories for two compartment vessels given different damage scenarios are summarized in Table 7.

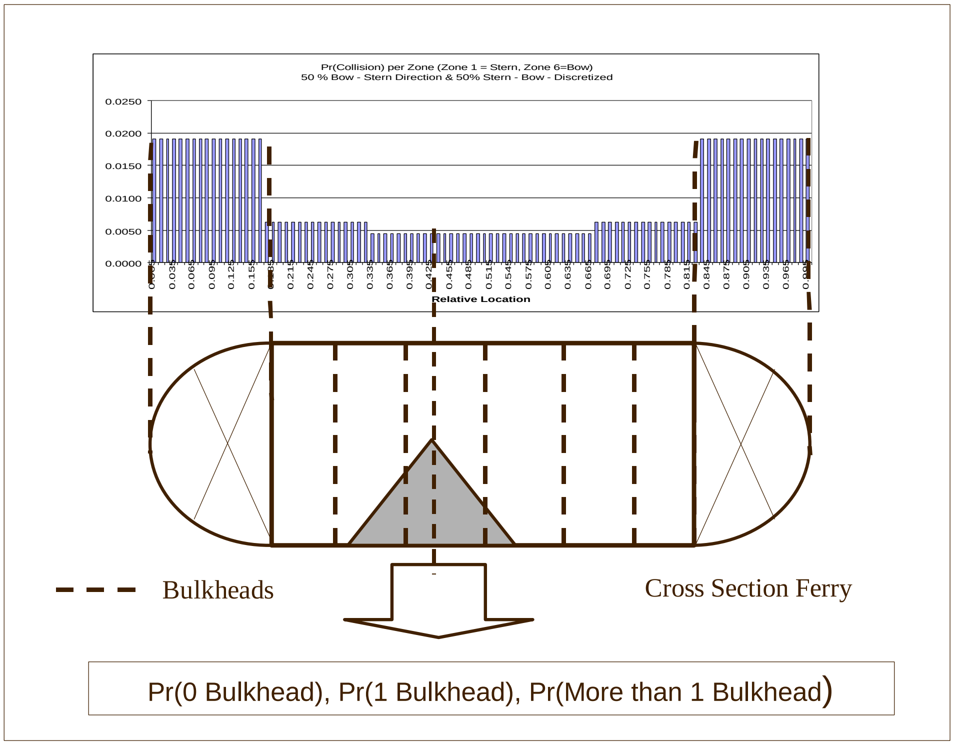


Figure 24. Probability calculation of Bulkhead Damage Scenarios

Table 7. MRRT assumptions for Two Compartment Ferries

	DAMAGE SCENARIO	MRRT 0-1	MRRT 1-6	MRRT > 6
Two Compartment Ferries	Bow-Stern Collision	0.00%	0.00%	100.00%

	DAMAGE SCENARIO	MRRT 0-1	MRRT 1-6	MRRT > 6
Two Compartment Ferries	Mid-Ship Collision, Relative Depth Penetration larger than threshold	33.33%	33.33%	33.33%

	DAMAGE SCENARIO	MRRT 0-1	MRRT 1-6	MRRT > 6
Two Compartment Ferries	Mid-Ship Collision,Relative Depth Penetration Smaller than threshold, damage above the waterline	0.00%	0.00%	100.00%
	Mid-Ship Collision,Relative Depth Penetration Smaller than threshold, damage below the waterline, less than 1 Bulkhead Damaged	0.00%	0.00%	100.00%
	Relative Depth Penetration Smaller than threshold, damage below the waterline, More than 1 Bulkhead Damaged	33.33%	33.33%	33.33%

5.4.2 Response Time model logic for one compartment ferries

The response time model logic if the same for one compartment ferries and two compartment ferries and differs only in terms of the distributions of the three MRRT categories given different damage scenarios. Table 8 contains the assumptions concerning the distribution of the three MRRT categories for one compartment vessels, except the Chinook, given different damage scenarios. The difference in assumptions in Table 7 and Table 8 stem from the difference between a one compartment vessel and two compartment vessel and the size of a typical one compartment ferry relative to a typical two compartment ferry.

Table 8. MRRT assumptions for One Compartment Ferries

	DAMAGE SCENARIO	MRRT 0-1	MRRT 1-6	MRRT > 6
One Compartment Ferries, except Chinook	Bow-Stern Collision	0.00%	0.00%	100.00%

	DAMAGE SCENARIO	MRRT 0-1	MRRT 1-6	MRRT > 6
One Compartment Ferries, except Chinook	Mid-Ship Collision, Relative Depth Penetration larger than threshold	100.00%	0.00%	0.00%

	DAMAGE SCENARIO	MRRT 0-1	MRRT 1-6	MRRT > 6
One Compartment Ferries, except Chinook	Mid-Ship Collision,Relative Depth Penetration Smaller than threshold, damage above the waterline	0.00%	0.00%	100.00%
	Mid-Ship Collision,Relative Depth Penetration Smaller than threshold, damage below the waterline, 0 Bulkheads Damaged	0.00%	0.00%	100.00%
	Relative Depth Penetration Smaller than threshold, damage below the waterline, 1 Bulkhead Damaged	33.33%	33.33%	33.33%
	Relative Depth Penetration Smaller than threshold, damage below the waterline, more than 1 Bulkhead Damaged	100.00%	0.00%	0.00%

5.4.3 Response Time model logic for Steel Electric Class

The Steel Electric ferry class has been considered a special case. Using the USCG regulation, the Steel Electric does not meet the requirements of a two compartment vessel and is by default a one compartment vessel. However, review of the structural plans of the steel electric by Naval Architects resulted in the observation that parts of the steel electric satisfy one compartment characteristics and other parts satisfy two compartment characteristics. Bulkheads in the "one compartment" part of the Steel Electric are designated as category 1 bulkheads. Bulkheads in the "two compartment" part of the Steel Electric are designated as category 2 bulkheads. The response time model logic is the same for the Steel Electric class and the two compartment vessels and differs only in terms of the distributions of the three MRRT categories given different damage scenarios. The assumptions concerning the distribution of the three MRRT categories for the Steel electric class given different damage scenarios are summarized in Table 9. However, as the steel electric classification is an issue of debate between leading naval architects in the field, sensitivity analysis has been performed to analyze the effect of treating the steel electric as a one compartment vessel and the associated MRRT assumptions in Table 8 (see Appendix II).

Table 9. MRRT Assumptions for the Steel Electric Class

	DAMAGE SCENARIO	MRRT 0-1	MRRT 1-6	MRRT > 6
Steel Electric Class	Bow-Stern Collision	0.00%	0.00%	100.00%
Steel Electric Class	Mid-Ship Collision,Relative Depth Penetration larger than threshold	33.33%	33.33%	33.33%
Steel Electric Class	Mid-Ship Collision, Relative Depth Penetration smaller than threshold, damage above the waterline	0.00%	0.00%	100.00%
	Mid-Ship Collision, Relative Depth Penetration smaller than threshold, damage below the waterline, 1 Category 1 Bulkhead Damaged	33.33%	33.33%	33.33%
	Mid-Ship Collision, Relative Depth Penetration smaller than threshold, damage below the waterline, 1 Category 2 Bulkhead Damaged	0.00%	0.00%	100.00%
	Relative Depth Penetration Smaller than threshold, damage below the waterline, More than 1 Bulkhead Damaged	33.33%	33.33%	33.33%

Table 10 contains a set of calculations combining the damage calculations in Table 5 with the Response Time model in this section, where the struck ferry is a Jumbo Mark II.

Table 10. Sample Calculations of the likelihood of the three MRRT Categories for the Jumbo Mark II Class

Striking Vessel	MRRT 0-1 hour	MRRT 1-6 hours	MRRT >6 hours
Passenger, Loc 1-3	9%	9%	81%
Passenger, Loc 4-5	2%	2%	96%
Tug/Barge	2%	2%	97%
Freight_Ship, Loc 1-3	6%	6%	88%
Freight_Ship, Loc 4-5	4%	4%	92%
Container, Loc 1-4	18%	18%	64%
Container, Loc 5	8%	8%	84%
Bulk_Carrier, Loc 1-3	7%	7%	85%
Bulk_Carrier, Loc 4-5	6%	6%	88%
Refr_Cargo, Loc 1-3	6%	6%	88%
Refr_Cargo, Loc 4-5	4%	4%	92%
Tanker, Loc 1-5	2%	2%	97%
Product Tanker, Loc 1-3	7%	7%	85%
Product Tanker, Loc 4-5	7%	7%	85%
Other	0%	0%	100%
Ro-Ro, Loc 1-5	12%	12%	76%
Naval	8%	8%	84%
Misc	0%	0%	100%
Jumbo Mark II	0%	0%	100%
Jumbo	0%	0%	100%
Super	0%	0%	100%
Issaquah	0%	0%	100%
Evergreen	0%	0%	100%
Steel Electric	0%	0%	100%

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