The Washington State Ferries Risk Assessment

Appendix II: Collision, Allision, Grounding and Fire / Explosion Results using the WSF Simulation

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Prepared for:

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1.1 Specific Findings from the Analysis in this Section

The following are specific findings from the Final Report that are justified by the results discussed in this section. The numbering of the findings is the same as that used in the final report to ensure tracability between the two documents.

The risk models demonstrate that potential accidents have serious consequences and identify the dominant potential accident scenarios.

5. Credible accident scenarios that should form the basis of response and consequence management were demonstrated. Collisions are the most likely accident type that could result in a significant number of injuries and fatalities. Several collision scenarios were developed that could have catastrophic consequences (passenger only vessel collisions--particularly high speed ferry collisions, automobile ferry collisions with large, high speed vessels such as container ships)

6. A surrogate measure, termed *maximum required response time* (MRRT), was used as the potential accident impact. 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 classes of MRRT were deemed appropriate: less than one hour, between one and six hours, and greater than 6 hours. A MRRT of more than 6 hours occurred in 68% of all the statistical expected number of collisions. In 7% of the predicted collisions a MRRT between 1 and 6 hours would be required, and the remaining 25% would require a MRRT of less than 1 hour.

7. The average return time (the average time between two consecutive events) for collisions involving Washington State Ferries (regardless of its severity) is 4½ years. However, the average return time of collisions requiring a MRRT of 1 to 6 hours is 67 years and the average return time of collisions requiring a MRRT of less than 1 hour is 18 years.

8. The routes, listed in order of collision potential account for 94% of the total statistical frequency of collisions:
   - Seattle-Bainbridge Island ferries (24.3%)
   - Seattle-Bremerton car ferries (22.1%)
   - Seattle-Bremerton passenger-only ferries (18.6%)
   - Edmonds-Kingston ferries (13.7%)
   - Fauntleroy-Vashon ferries (8%)
   - Seattle-Vashon passenger-only ferries (7.5%)

   The percentages indicated in the brackets are the percentage contribution of the route to the total statistical expected number of collisions per year.

9. Collisions that fall in the 1 to 6 hour MRRT category would also require the evacuation of passengers to a safe haven such as another ferry, a rescue vessel, or a survival craft

launched from the ferry. The following routes account for 95% of the total statistical frequency of collisions of this type:

- Edmonds-Kingston ferries (30.5%)
- Seattle-Bremerton passenger-only ferries (15.6%)
- Seattle-Bremerton car ferries (15.6%)
- Seattle-Bainbridge Island ferries (13.5%)
- Seattle-Vashon passenger-only ferries (11.7%)
- Fauntleroy-Vashon ferries (8.2%)

The percentages indicated in the brackets are the percentage contribution of the route to the total statistical expected number of collisions per year with an MRRT of 1 to 6 hours.

10. Collisions that fall in the less than 1 hour MRRT category require a fast and coordinated emergency response from the U.S. Coast Guard and the Washington State Ferries. The routes that account for 99% of the total statistical frequency of collisions of this type are:
    - Seattle-Bremerton passenger-only ferries (52.5%)
    - Seattle-Bremerton car ferries (17%)
    - Seattle-Vashon passenger-only ferries (10.7%)
    - Edmonds-Kingston ferries (8.2%)
    - Seattle-Bainbridge Island ferries (8.1%)
    - Fauntleroy-Vashon ferries (2.3%)

    The percentages indicated in the brackets are the percentage contribution of the route to the total statistical expected number of collisions per year with an MRRT of less than 1 hour.

11. The highest average collision probability per interaction is on the Edmonds-Kingston route. This is because a large proportion of the interactions is with non-WSF vessels. These interactions have a higher probability of leading to a collision and thus the average collision probability is higher. Other routes with higher average collision probabilities per interaction are the Seattle-Bremerton passenger-only ferries, the Seattle-Bainbridge ferries, the Port Townsend-Keystone ferries and the Seattle-Vashon passenger-only ferries.

12. A primary cause of collision risk in the system is the relatively high level of traffic congestion in the Central Puget Sound, particularly in Elliott Bay. Future increases in traffic in this area due to additional Ferry runs, excursion boats, and commercial shipping will increase the potential risk in this area.

13. A secondary cause of collision risk in the system is operations in conditions of high traffic and restricted visibility. The visibility model developed for the risk analysis determined that ferries operate in restricted visibility 12% of the time; 54% of the total statistical frequency of collisions were found to occur during periods of restricted visibility.

14. Over 90% of the statistical frequency of collisions requiring an immediate response would occur in the Central Puget Sound on the routes that carry 85% of the Washington State Ferry ridership.

15. The addition of the high speed (Chinook) class ferry to the schedule and the subsequent additional interactions in a high ferry to ferry interaction area has resulted in an increased statistical expected number of collisions. However, the average collision probability per interaction for the Chinook is less than that for the older passenger-only ferries. Since all collisions involving high-speed class vessels were assumed to require an immediate response, the introduction of the high-speed class ferries increases the statistical frequency of collisions requiring a MRRT of less than 1 hour by over 50%.

16. The Port Townsend-Keystone route was a cause of concern prior to the study due to its isolation and the single ferry assigned to the route during the winter months. The statistical expected number of collisions for this route is low relative to the central Puget Sound routes, but the average collision probability is the fourth highest. This is because a large proportion of the interactions is with non-WSF, commercial traffic. It should also be noted that collisions with such vessels could have an MRRT of less than 6 hours and thus require evacuation of the passengers to a safe haven. Emergency response planning should, therefore, be carefully considered for this route.

17. The international ferry to Sidney is also isolated from other WSF ferries and US Coast Guard response capabilities. Crossing Haro Strait, this ferry can interact with non-WSF, commercial traffic with which collisions can have an MRRT of less than 6 hours. However, this vessel is required to have life rafts for 110% of its passenger capacity by US Coast Guard SOLAS regulations.

Risk reduction interventions are required to maintain the current low likelihood of accidents and to reduce the potential consequences of accidents that could occur by increasing the effectiveness of emergency response.

27. Although the statistical expected number of collision with an MRRT of less than 1 hour on the Port Townsend-Keystone and Haro Strait transits are low relative to other routes, the isolation of these routes from other Washington State ferries and US Coast Guard response equipment is a cause of concern. Vessels making the Haro Strait transit are subject to international conventions and currently carry survival craft adequate for all passengers. Ferries on the Pt. Townsend– Keystone run are not required by current Coast Guard regulations to carry 100% survival craft.

1.2 Some Terminology

The results below are presented in the form of a statistical analysis. Thus several concepts should be discussed to avoid confusion in the interpretation of the results.

Number of Interactions per year:

In the discussion of the modeling techniques, the notion of an interaction was introduced. 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. By counting the number of interactions it is possible to examine the number of times a ferry interacts with other vessels in the system. Suppose we examine the number of interactions for each ferry route, we would be able to determine which route was the most congested according to the above definition of interactions. Moreover, we could then examine the number of interactions on that route for each type of interacting vessel and thus determine what type of traffic the ferries on that route encounter as well as the frequency of the encounters.

Average Probability of a Collision Given an Interaction:

This statistic allows us to assess the likelihood of a collision in a specific interaction scenario. For instance, if we examine this probability for each ferry route, we can examine how likely a collision is if an interaction occurs on that route. In the collision risk model, the probability of a collision occurring can vary from one interaction to the next depending upon the situation. Factors such as the types of vessels interacting and the environmental conditions contribute to such variations. In the collision risk model, 10 years of interactions are counted and the probability of a collision in each observed interaction is calculated. The average probability of a collision per interaction is the average of these calculated collision probabilities.

Statistical Expected number of accidents per year:

The statistical expected number of accidents per year is not the number of accidents that are expected to happen in a given year. This term refers to a long-term statistical average number of accidents. For example, suppose were we able to run the system under given operating conditions for 1000 years and count the number of accidents that occurred over this period. If we then divided the number of accidents that occurred by 1000 years, we should find the statistical expected number of accidents per year.

Average return time:

Returning to the hypothetical 1000 years of accident data. If we were to calculate the average of the time between two consecutive accidents, then we would get the average return time. As it turns out, the average return time equals the reciprocal of the statistical expected number of collisions. The actual times between accidents could be highly variable, some of the accidents may not have occurred shortly after each other, while there may also be long periods of time characterized by no occurrence of accidents. Thus we must remember that this quantity gives only the average time between consecutive accidents.

1.3 Scenario 1 – Prior to 1997

Several recent additions to Washington State Ferry fleet have included the Chinook class high-speed, passenger-only ferries and the Jumbo Mark II class car ferries. The inclusion of these vessels into the ferry service operation has lead to a re-assignment of vessels to routes. Such re-assignments change the system dynamics and thus can cause changes to the levels of risk present in the system and thus require separate consideration. Before the introduction of the new vessels, the Washington State Ferry fleet had remained relatively stable for 10 years. This period corresponds to the period for which the study team assimilated and analyzed accident and incident data for the WSF System area. Thus we first examine the collision risk for this period, called Scenario 1. This is followed by a discussion of collision risk after the introduction of the two Jumbo Mark II class ferries and the Chinook, called Scenario 2. Potential collision scenarios are then identified and the conclusions from this analysis are summarized. A detailed route by route analysis of the collision risk model results is given at the end.

Before the introduction of the new vessels, the Washington State Ferry fleet remained relatively stable for 10 years. This period corresponds to the period for which the study team assimilated and analyzed accident and incident data for the WSF System area. As has been mentioned previously, the collision accident probability model is calibrated to this data. This calibration procedure includes the use of the simulation and thus the simulation must be programmed to represent the operation of the Washington State Ferry Service for the period in which the data was collected.

The simulation was programmed to represent the assignments of vessels to routes that existed prior to the introduction of the two new classes of vessels. The ferry schedule used for scenario 1 was taken from the Fall 1997, Spring 1997 and Summer 1997 Sailing Schedules published by the Washington State Ferries.

Figure 1 shows the statistical expected number of collisions per year for each ferry route. Figure 1 allows us to compare the ferry routes and indicates that the highest statistical expected number of collisions is on the Seattle to Bainbridge ferry route. The following dicussion explains the differences in the statistical expected number of collisions per year by ferry route.

To understand the difference in the results by ferry route of the collision risk models, a further understanding of the models used is helpful. There are two main questions that these models must answer. Firstly, how often do various interactions occur and with what types of vessel? Secondly, for a particular interaction, how likely is a collision? The first question is answered by examining the number of interactions per year, information that is supplied by the simulation model. The second question is answered by the average collision probability given an interaction, which is derived from the collision probability model. This model is the combination of a statistical analysis of expert judgment questionnaires and calibration of the expert judgment analysis to accident and incident data for the period 1988-1998.

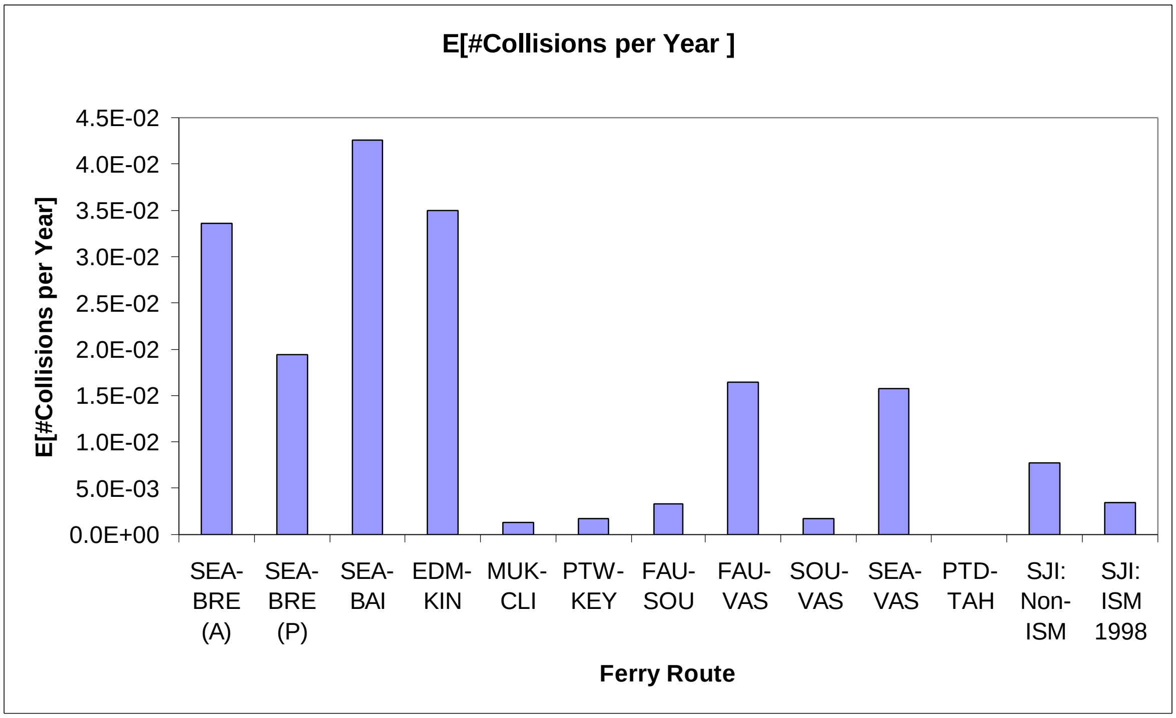


Figure 1. Statistical expected number of collisions per year by ferry route under scenario 1

The results in figures 2 through 4 are given in the form of 3-dimensional graphs. This type of chart is difficult to read and thus the main observations from each chart are discussed in the text. To further the understanding of these results, the results are summarized by ferry route. Table 1 shows the numbered keys used on the 3-dimensional charts. These charts break down the various statistics for each combination of ferry route and type of interacting vessel. Thus there is a numbered key for the ferry routes and a numbered key for the type of interacting vessel. Notice that for the type of interacting vessel key, the numbers from 1 to 12 are non-WSF vessel, while the numbers from 13 to 22 are Washington State ferries.

Table 1. Numbering Keys for Ferry Routes and Ferry Classes

Ferry Route	Route Index
SEA-BRE (A)	1
SEA-BRE (P)	2
SEA-BAI	3
EDM-KIN	4
MUK-CLI	5
PTW-KEY	6
FAU-SOU	7
FAU-VAS	8
SOU-VAS	9
SEA-VAS	10
PTD-TAH	11
ANA-SJI	12
ANA-SID	13

Vessel Type	Vessel Index	Vessel Type	Vessel Index
Passenger	1	Jumbo Mark II	13
Tug/Barge	2	Jumbo	14
Freight Ship	3	Super	15
Container	4	Issaquah	16
Bulk Carrier	5	Evergreen	17
Refr. Cargo	6	Steel Electric	18
Tanker	7	Rhododendron	19
Prod. Tanker	8	Hiyu	20
Other	9	POV	21
Ro-Ro	10	Chinook	22
Naval	11		
Misc.	12		

Figure 2 shows the number of interactions per year by ferry route and interacting vessel type. The higher bars to the right of the chart (keys 13 to 22) shows that the number of interactions is much higher with Washington State ferries. In fact 94% of all interactions experienced by Washington State ferries are with other Washington State ferries.

Figure 3 shows the average collision probability per interaction by ferry route and interacting vessel type. The higher bars to the left of the chart (keys 1 to 12) shows that the interactions with non-WSF vessels are more likely to lead to a collision than interactions with Washington State ferries. Recall from figure 2, however, that these interactions are less frequent.

Figure 4 shows the statistical expected number of collision per year by ferry route and type of interacting vessel. This graph is a combination of the information in figures 2 and 3. There are high bars in the area indicating collisions with non-WSF vessels and the area indicating collisions with other Washington State ferries. The higher statistical expected number of collisions with Washington State ferries is primarily driven by the frequency of interactions.

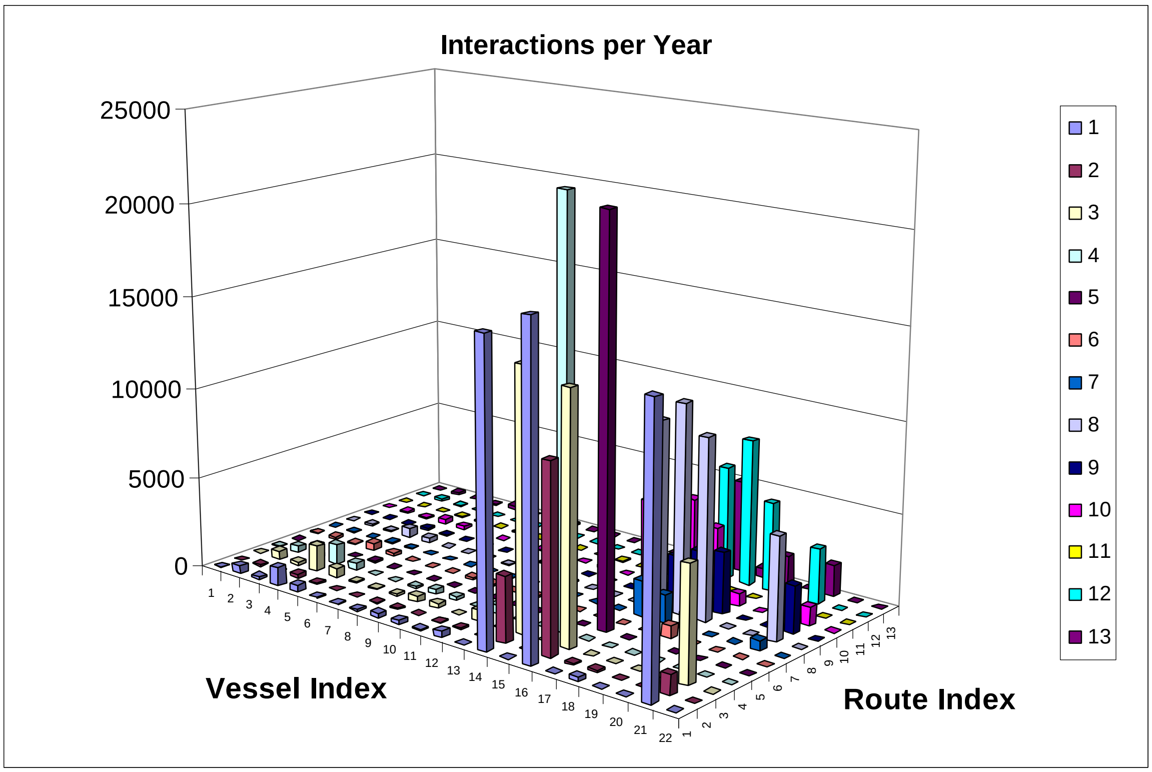


Figure 2. Number of interactions per year by ferry route and ferry class under scenario 1

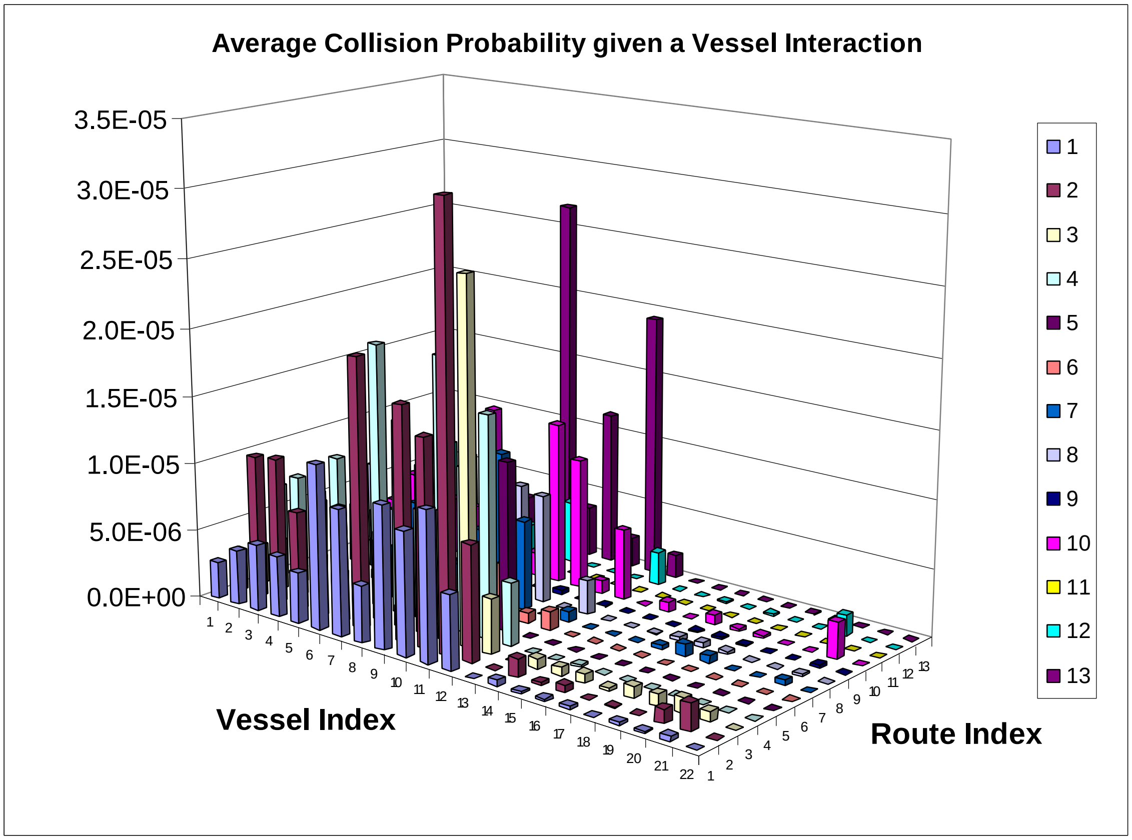


Figure 3. Average collision probability per interaction by ferry route and ferry class under scenario 1

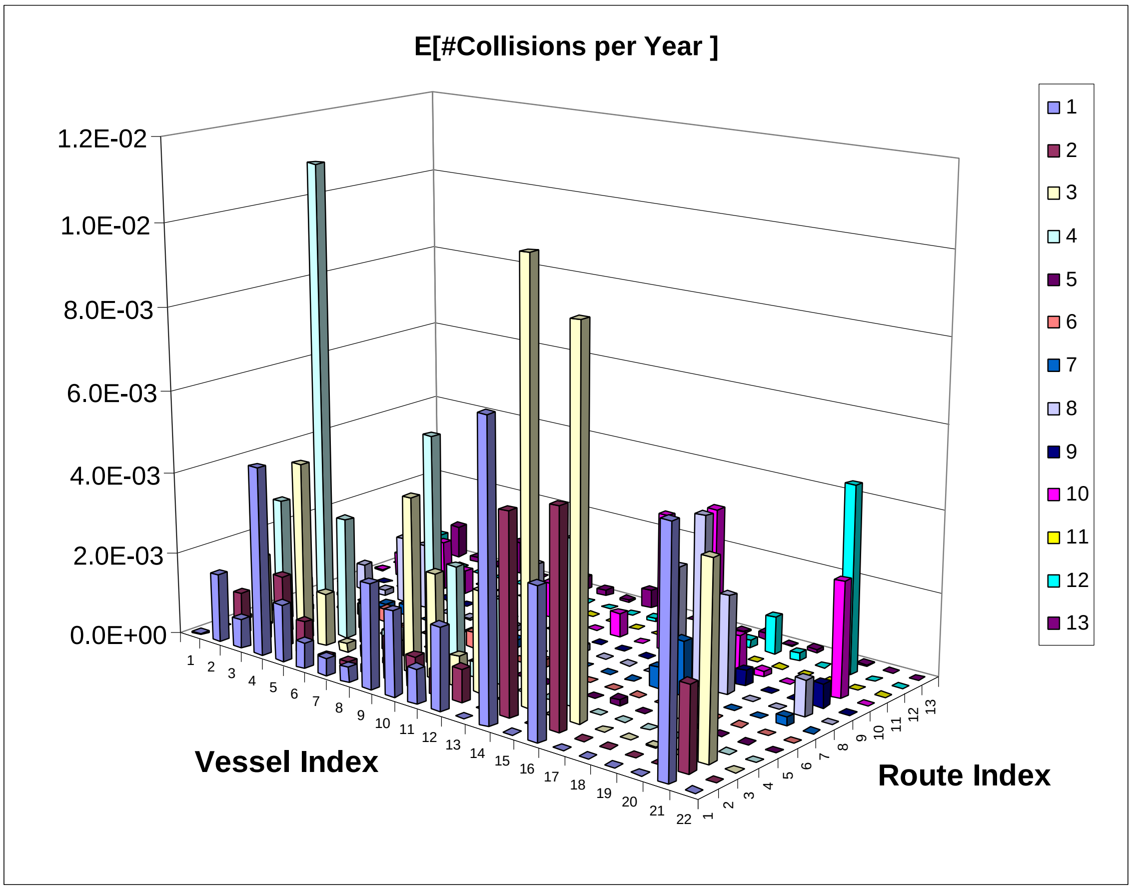


Figure 4. Statistical expected number of collisions per year by ferry route and ferry class under scenario 1

Interactions with the other ferries on the same route and ferries on nearby routes drive the statistical expected number of collisions with Washington State ferries. The higher statistical expected number of collisions with non-WSF vessels is primarily driven by the average collision probability per interaction. The higher bars in this area are collisions with container vessels, ro-ro vessels and bulk carriers.

The final concern in examining collision risk is the safety of the passengers if a collision occurs. Based on damage calculations it may be concluded that collisions with other ferries are not as likely to lead to high consequences as collision with larger, faster vessels such as container vessels. The key factor in the management of consequences from a collision is the response time required for a particular collision. To address the response time issue engineering models of collision impact damage were used to assess the damage to each ferry class in various collision scenarios. Structural plans of the ferries were used to estimate damage to bulkheads. 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 answer the response time question given the potential flooding of multiple compartments, the definition of the 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 model technical appendices.

Three classifications of MRRT are introduced.

- **More than 6 hours**: Allows transportation of the ferry to a safe haven
- **1 - 6 hours**: Orderly evacuation may be possible with onboard emergency equipment + external response.
- **Less than 1 hour**: Requires fast, external response capability

To understand the spread of collision risk across the study area, the statistical expected number of collisions in each of the three MRRT categories are examined. Figures 5 through 7 show 3-dimensional charts of the statistical expected number of collision in each of the three categories broken down by ferry route and type of interacting vessel. The numbering keys from table 1 are again used in these figures. If we were to combine Figures 5 through 7 into one chart, Figure 4 would be the result.

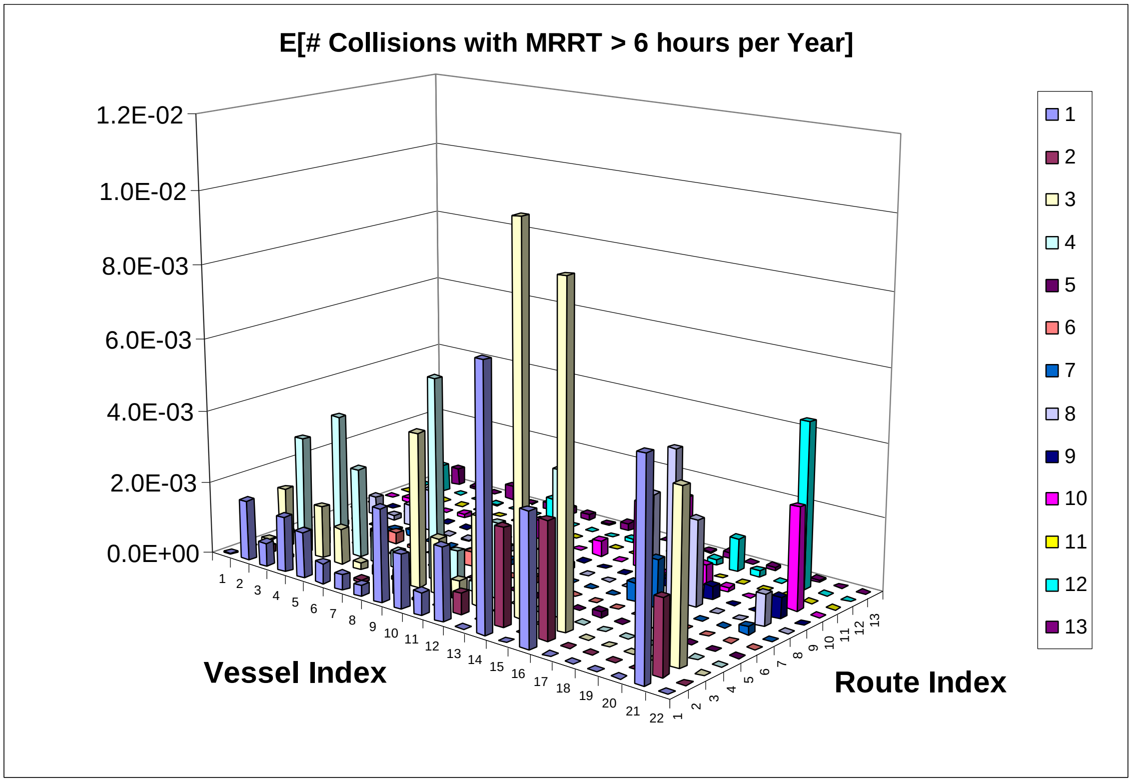


Figure 5. Statistical expected number of collisions per year with a MRRT of more than 6 hours by ferry route and ferry class under scenario 1

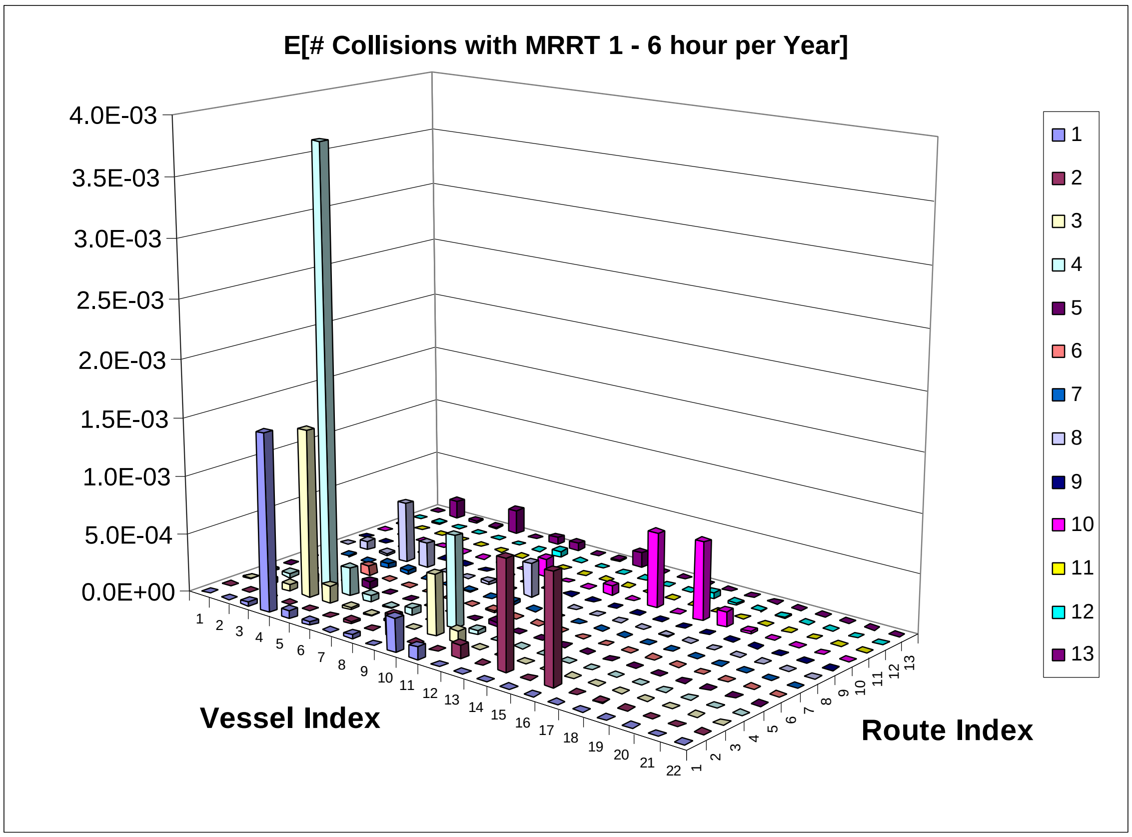


Figure 6. Statistical expected number of collisions per year with a MRRT of 1 to 6 hours by ferry route and ferry class under scenario 1

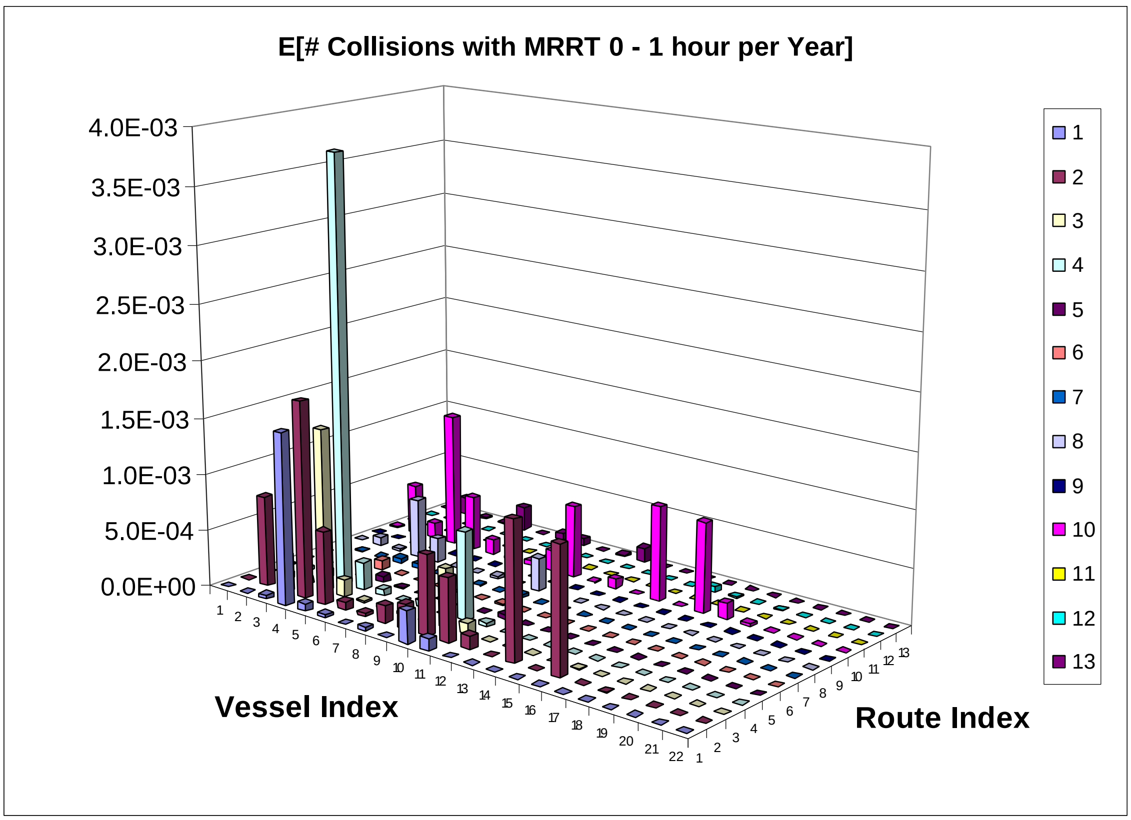


Figure 7. Statistical expected number of collisions per year with a MRRT of less than 1 hour by ferry route and ferry class under scenario 1

The right hand side of figure 5, numbers 13 through 22 on the type of interacting vessel, shows the statistical expected number of collisions with other Washington State ferries with a MRRT of more than 6 hours. This chart looks very similar to the right hand side of figure 4. This is because the damage models showed that collisions between most classes of Washington State ferries would have a MRRT of more than 6 hours.

Figure 6 shows the statistical expected number of collisions with a MRRT of 1 to 6 hours. The higher bars in this graph are on the passenger-only routes, including collisions between the passenger-only ferries and other Washington State ferries, and collision with container vessels, ro-ro vessels and bulk carriers. Figure 7 shows the statistical expected number of collisions with a MRRT of less than 1 hour. The higher bars are similar to those observed in figure 6. The exception is collisions of passenger-only ferries with container vessels, ro-ro vessels and bulk carriers. These are shown to have a MRRT of less than 1 hour.

Drawing by ferry route conclusions from these 3-dimensional charts is difficult. Thus with a greater understanding of the factors that lead to collision risk and a picture of WSF System collision risk, we now turn our attention to a summary of information by ferry route. Figures 8 to 10 show the three key quantities:

- Number of interactions per year,
- Average collision probability given an interaction and
- Statistical expected number of collisions per year

for each ferry route.

Figure 8 shows that the highest statistical expected numbers of collisions are on, in order, the Seattle-Bainbridge ferries, the Edmonds-Kingston ferries, the Seattle-Bremerton car ferries, the Seattle-Bremerton passenger-only ferries and the Fauntleroy-Vashon ferries. Figure 10 shows that these are also the routes with the highest number of interactions per year thereby explaining the high statistical expected number of collisions for these routes.

The highest statistical expected number of collisions with a MRRT of less than 1 hour is on the Seattle-Bremerton passenger-only ferries then the Seattle-Vashon passenger-only ferries. Recall from figure 7 that these collisions can be with both ferries and non-ferries. The other collisions in the non-ferries category are with container vessels, ro-ro vessels and bulk carriers.

Figure 9 shows that the highest average collision probability per interaction is on Edmonds-Kingston route. This is because a large proportion of the interactions is with non-WSF vessels. These interactions have a higher probability of leading to a collision and thus the average collision probability is higher. Other routes with higher average collision probabilities per interaction are the Seattle-Bremerton passenger-only ferries, the Seattle-Bainbridge ferries, the Port Townsend-Keystone ferries and the Seattle-Vashon passenger-only ferries.

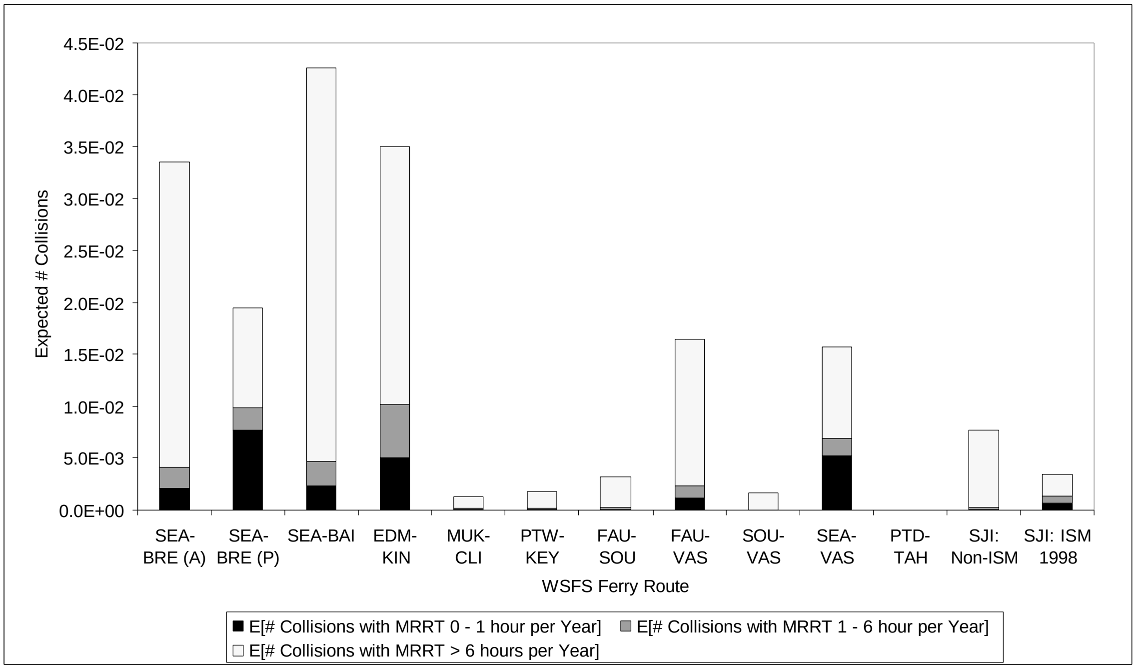


Figure 8. Statistical expected number of collisions per year by ferry route under scenario 1

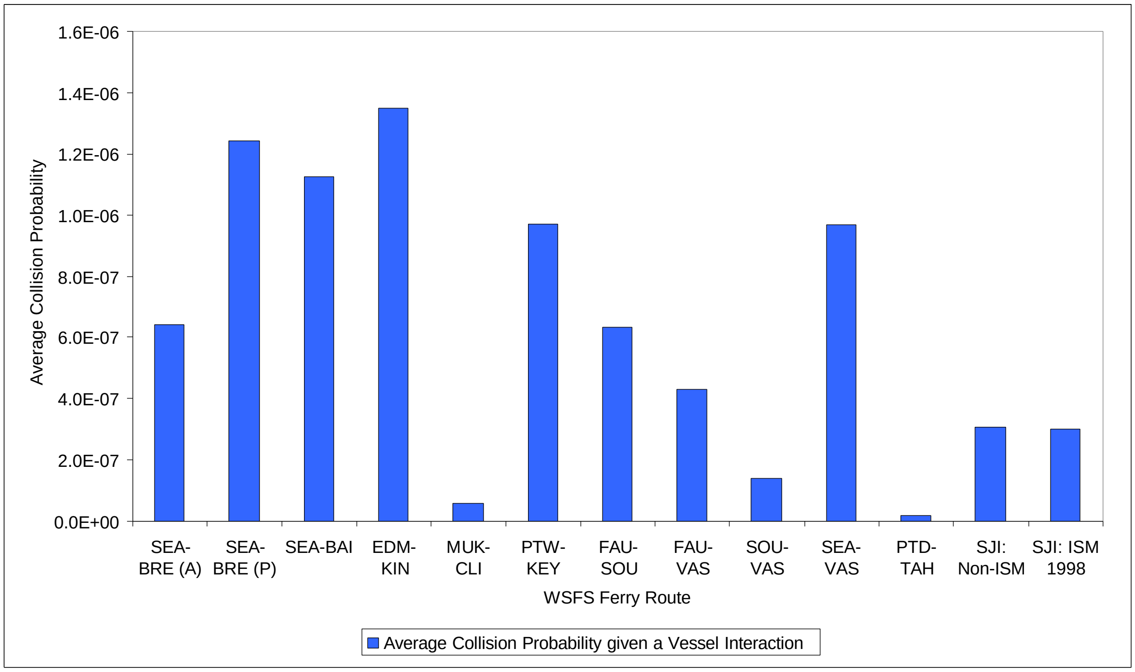


Figure 9. Average collision probability given an interaction by ferry route under scenario 1

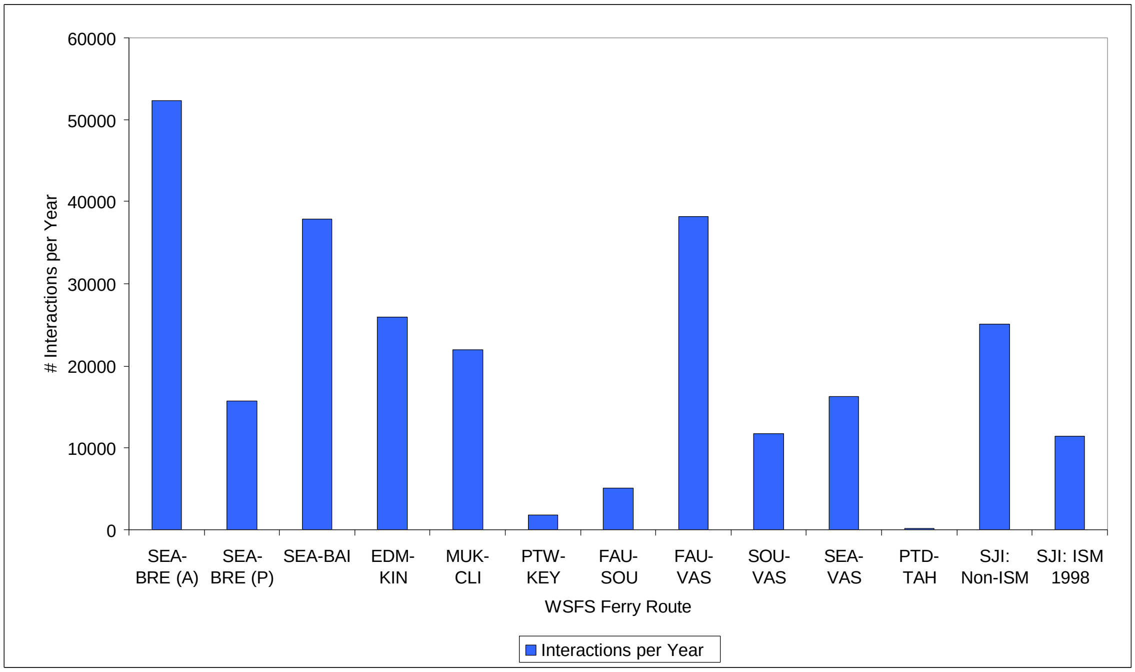


Figure 10. Number of interactions per year by ferry route under scenario 1

1.4 Scenario 2 – 1998

The Washington State Ferry Risk Assessment project started in July 1998. At this time, one Chinook class ferry had been delivered and was operating on the Seattle to Bremerton route. Two Jumbo Mark II class ferries also started service on the Seattle to Bainbridge Island route during 1998. To reflect this change to the system, a simulation scenario was developed with these new vessel assignments.

The simulation was programmed to represent the assignments of vessels to routes used after the introduction of the two new classes of vessels. The ferry schedule used for scenario 2 was taken from the Fall 1998, Spring 1998 and Summer 1998 Sailing Schedules published by the Washington State Ferries.

To understand the change in system risk from Scenario 1 to Scenario 2, we shall use the same format in examining the risk in Scenario 2. Thus Table 2 is a repetition of table 1, defining the numbered keys for the ferry routes and types of interacting vessels in the 3-dimensional charts to follow.

Table 2. Numbering Keys for Ferry Routes and Ferry Classes

Ferry Route	Route Index
SEA-BRE (A)	1
SEA-BRE (P)	2
SEA-BAI	3
EDM-KIN	4
MUK-CLI	5
PTW-KEY	6
FAU-SOU	7
FAU-VAS	8
SOU-VAS	9
SEA-VAS	10
PTD-TAH	11
ANA-SJI	12
ANA-SID	13

Vessel Type	Vessel Index	Vessel Type	Vessel Index
Passenger	1	Jumbo Mark II	13
Tug/Barge	2	Jumbo	14
Freight Ship	3	Super	15
Container	4	Issaquah	16
Bulk Carrier	5	Evergreen	17
Refr. Cargo	6	Steel Electric	18
Tanker	7	Rhododendron	19
Prod. Tanker	8	Hiyu	20
Other	9	POV	21
Ro-Ro	10	Chinook	22
Naval	11		
Misc.	12		

Figure 11 shows the number of interactions per year by ferry route and interacting vessel type. Similar to figure 2 for Scenario 1, the higher bars to the right of the chart (keys 13 to 22) shows that the number of interactions is much higher with Washington State ferries. Notice, however, that there are now bars for vessel index 22, the Chinook, as well as an increase in the heights of the bars for route index 2, the Seattle-Bremerton passenger-only route. The highest bars are on route indices 1 through 3. These are the Seattle-Bremerton routes and the Seattle-Bainbridge route. This indicates the traffic congestion in the area of Elliot Bay.

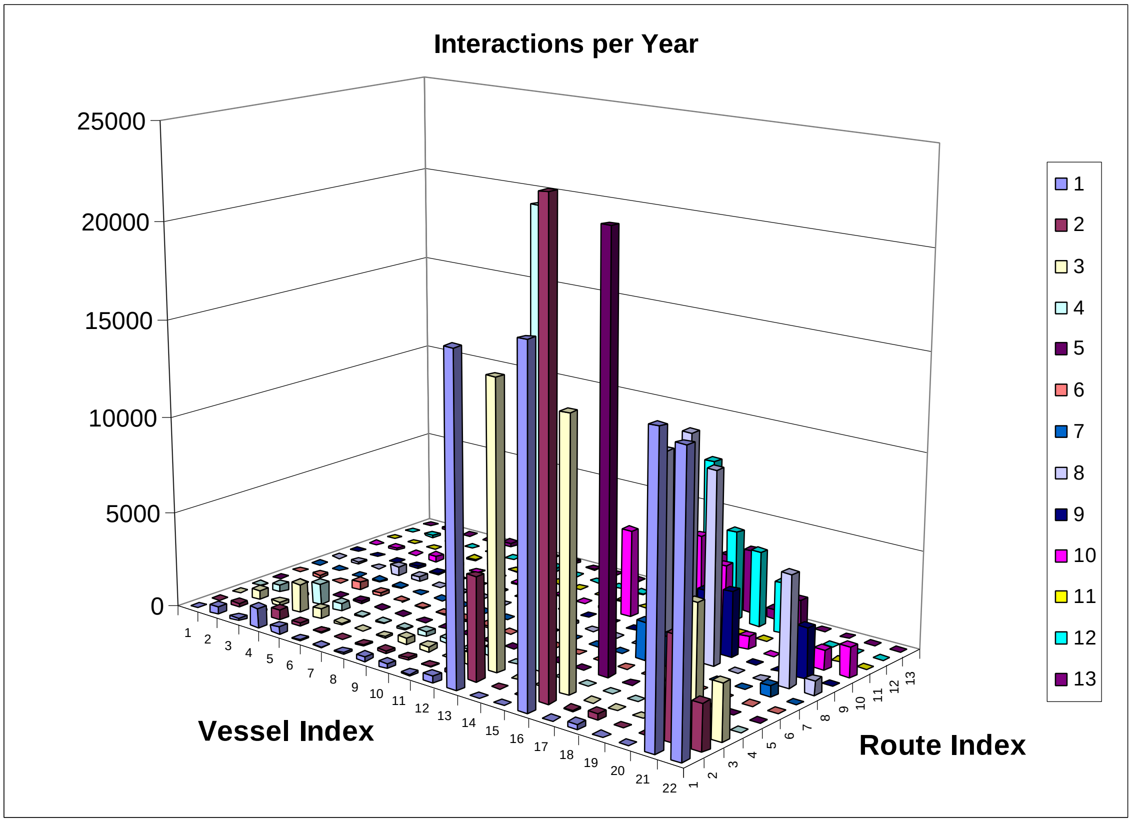


Figure 11. Number of interactions per year by ferry route and ferry class under scenario 2

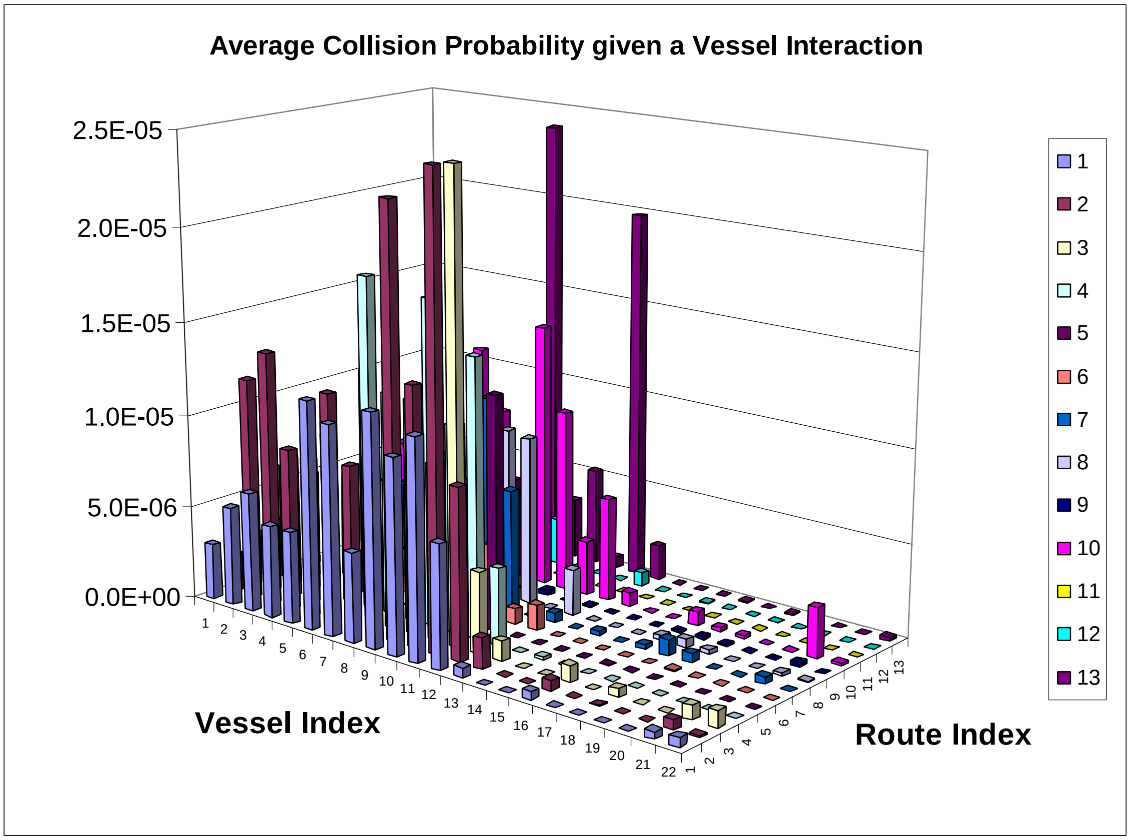


Figure 12. Average collision probability per interaction by ferry route and ferry class under scenario 2

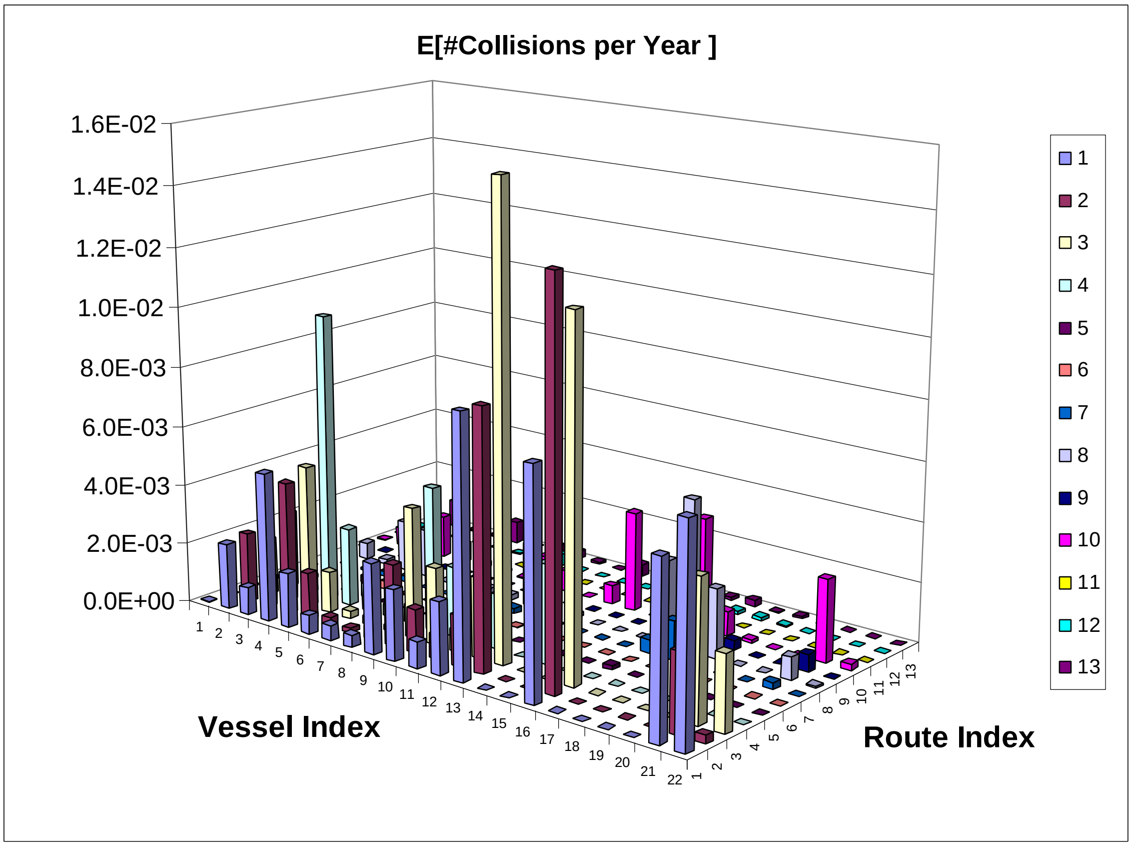


Figure 13. Statistical expected number of collisions per year by ferry route and ferry class under scenario 2

Figure 12 shows the average collision probability per interaction by ferry route and interacting vessel type for Scenario 2 and can be compared to figure 3 for Scenario 1. The higher bars to the left of the chart (keys 1 to 12) shows that the interactions with non-WSF vessels are still more likely to lead to a collision than interactions with Washington State ferries. Figure 12 is similar to figure 3, except that there are now bars for vessel index 22, the Chinook.

Figure 13 shows the statistical expected number of collision per year by ferry route and type of interacting vessel and can be compared to figure 4 for Scenario 1. This graph is a combination of the information in figures 11 and 12. There is a definite increase in the statistical expected number of collisions on the Seattle-Bremerton passenger-only ferries, route index 2 and on the Seattle-Bainbridge ferries, both due to additional interactions with the Chinook. Overall the highest bars are on routes 1 to 3, the Seattle-Bremerton routes and the Seattle-Bainbridge route. Recall that these routes had a high number of interactions due to the congestion in the Elliott Bay area. This leads to a higher statistical expected number of collisions on these routes.

Again, the question of response times must be addressed, thus we repeat the definition:

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

Recall that the three classifications of MRRT are:

- **More than 6 hours**: Allows transportation of the ferry to a safe haven
- **1 - 6 hours**: Orderly evacuation may be possible with onboard emergency equipment + external response.
- **Less than 1 hour**: Requires fast, external response capability

To understand the spread of collision risk across the study area, the statistical expected number of collisions in each of the three MRRT categories are examined. Figures 14 through 16 show 3-dimensional charts of the statistical expected number of collision in each of the three categories. If we were to combine Figures 14 through 16 into one chart, Figure 13 would be the result.

Figure 14 shows the statistical expected number of collisions with a MRRT of more than 6 hours and can be compared to figure 5 for Scenario 1. The only observable difference between figure 5 and figure 14 is the lower heights of the bars for route index 12, the Anacortes-San Juan Islands non-international route. The re-assignment of the Steel Electric class ferry as the inter-island boat replaced the Hiyu and the use of an additional Super class ferry have reduced the statistical expected number of collisions with an MRRT of more than 6 hours.

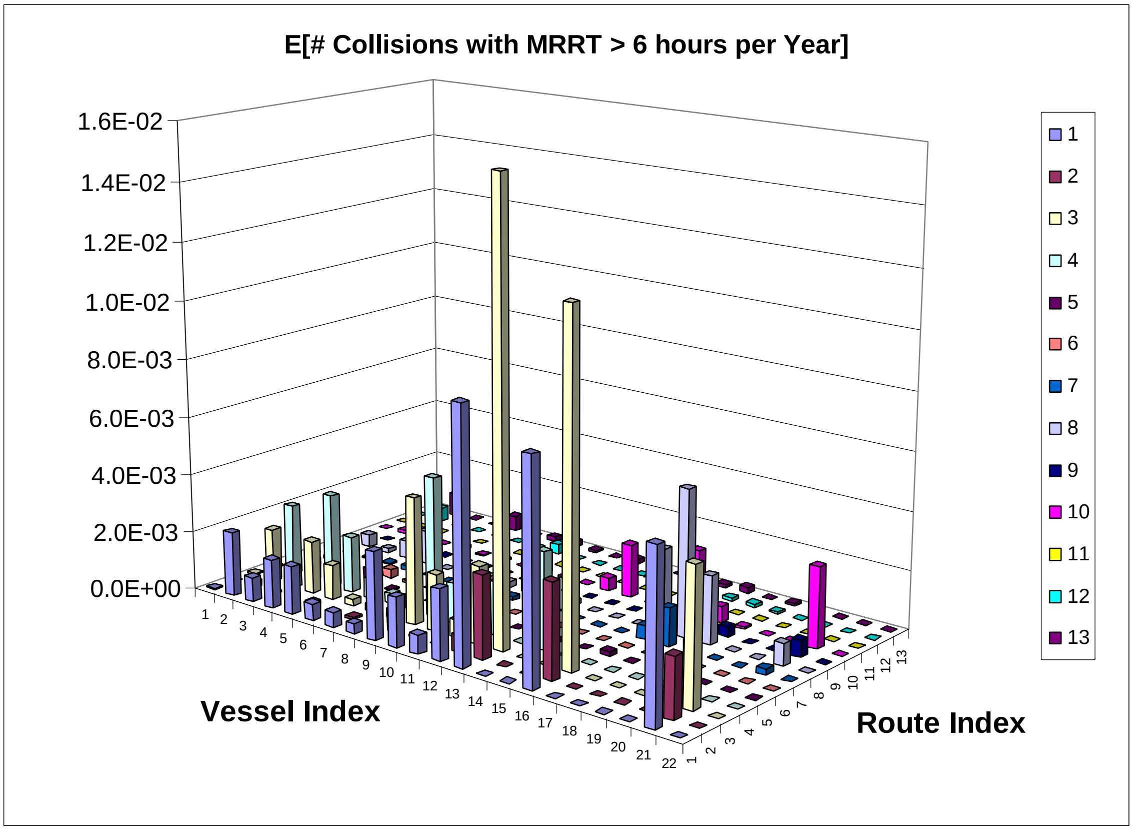


Figure 14. Statistical expected number of collisions per year with a MRRT of more than 6 hours by ferry route and ferry class under scenario 2

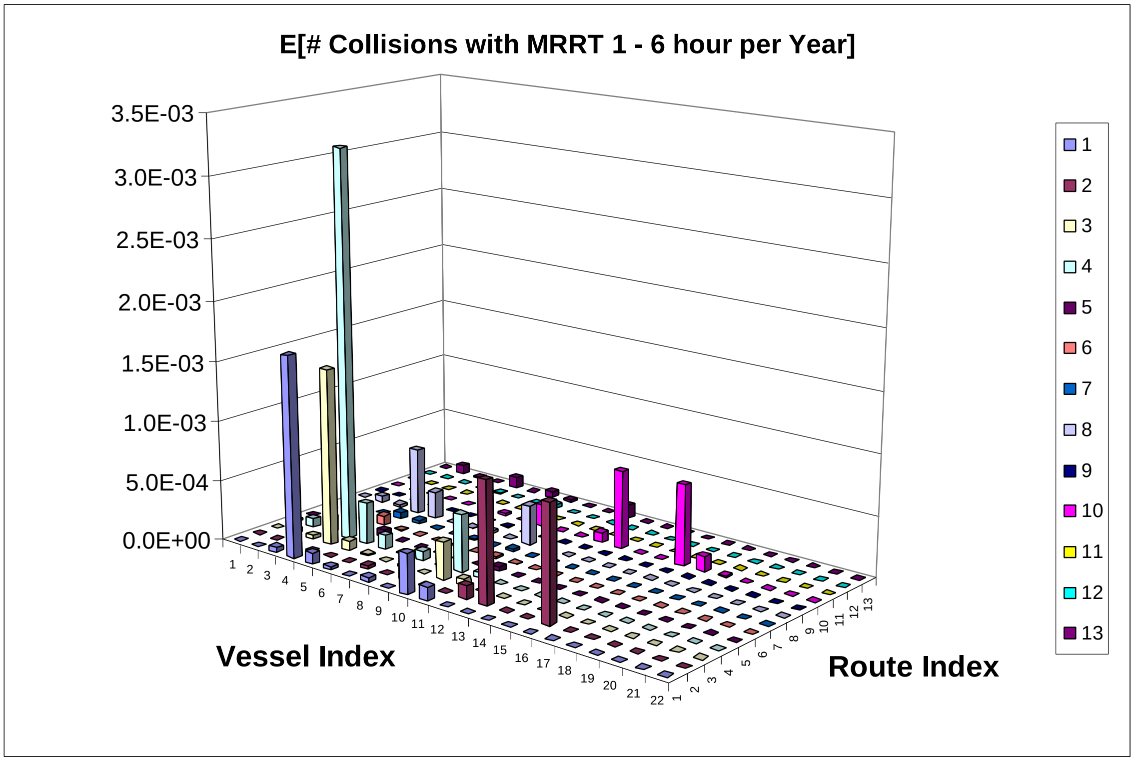


Figure 15. Statistical expected number of collisions per year with a MRRT of 1 to 6 hours by ferry route and ferry class under scenario 2

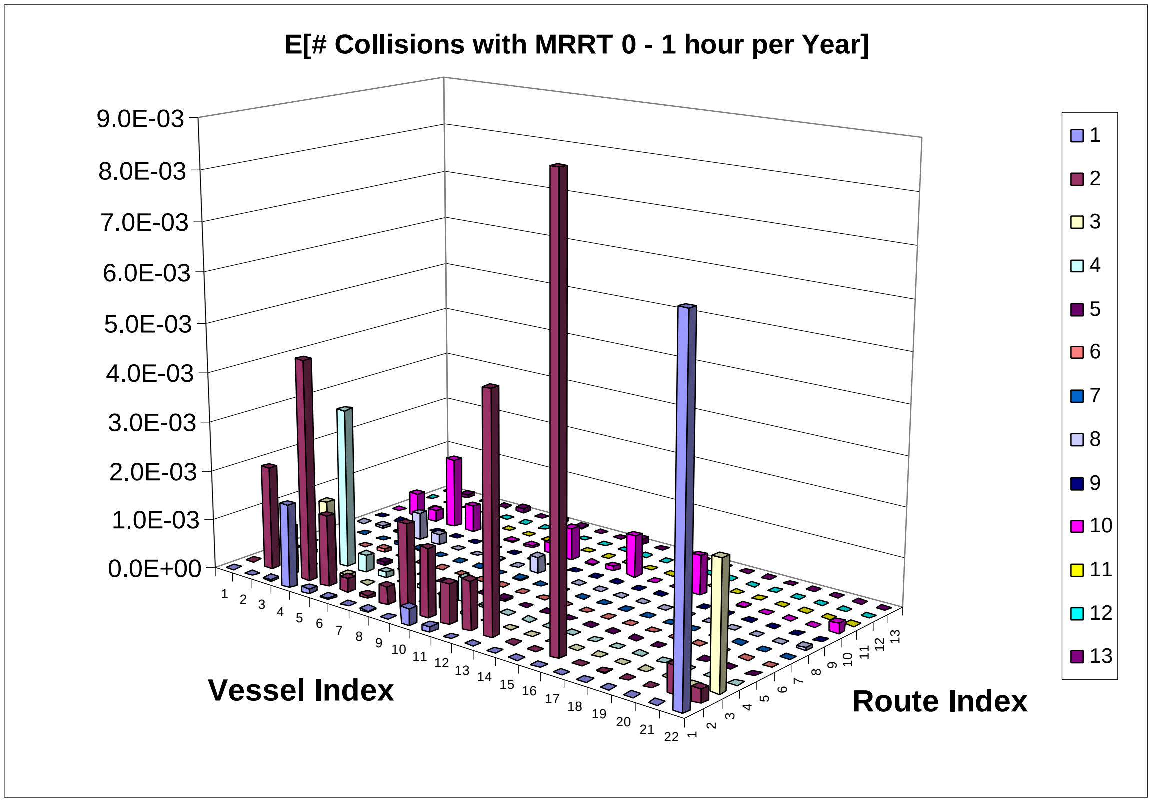


Figure 16. Statistical expected number of collisions per year with a MRRT of less than 1 hour by ferry route and ferry class under scenario 2

Figure 15 shows the statistical expected number of collisions with a MRRT between 1 and 6 hours and is similar to figure 6 for Scenario 2. A major change can be observed by comparing figures 7 and 16, showing the statistical expected number of collisions with a MRRT of less than 1 hour for scenarios 1 and 2 respectively.

Under scenario 2, the Seattle-Bremerton passenger-only route is assigned one of the older passenger-only ferries and a Chinook Class high- passenger-only ferry, as opposed to one of the older passenger-only ferries under Scenario 1. This is the only Chinook class ferry assigned in scenario 2. Collisions involving the Chinook Class high-speed passenger-only ferries are assessed to always require a maximum response time of less than 1 hour. This is primarily due to the high speeds at which the ferry transits. Thus the bars in figure 16 for the Seattle-Bremerton passenger-only route and the vessels that interact with it have a larger statistical expected number of collisions with an MRRT of less than 1 hour. This can primarily be explained due to both the added interactions of the Chinook and the assertion that collisions involving a Chinook fall in the 0 to 1 hour MRRT Category.

To summarize the large amount of information in the 3-dimensional charts, figures 17 to 19 show the three key quantities:

- Number of interactions per year,
- Average collision probability given an interaction and
- Statistical expected number of collisions per year

for each ferry route.

Comparing figure 17, for Scenario 2, with figure 8, for Scenario 1, it can be seen that there is an increase in the proportion of collision with an MRRT of less than 1 hour. The highest statistical expected number of collisions with a MRRT of less than 1 hour is on the Seattle-Bremerton passenger-only ferries. The other collisions in this category are with container vessels, ro-ro vessels and bulk carriers.

Figure 18 shows that the highest average collision probability per interaction is on the Seattle-Bainbridge ferries. This is because a large proportion of the interactions is with non-WSF vessels. These interactions have a higher probability of leading to a collision and thus the average collision probability is higher. Other routes with higher average collision probabilities per interaction are Edmonds-Kingston route, the Seattle-Bremerton passenger-only ferries, the Seattle-Vashon passenger-only ferries and the Port Townsend-Keystone ferries.

Figure 19 shows the number of interactions per year for each ferry route. This figure reinforces the observation that the most congested area is Elliot Bay. The next most congested routes are the Fauntleroy-Vashon route, the Edmonds-Kingston route and the Clinton-Mukilteo route.

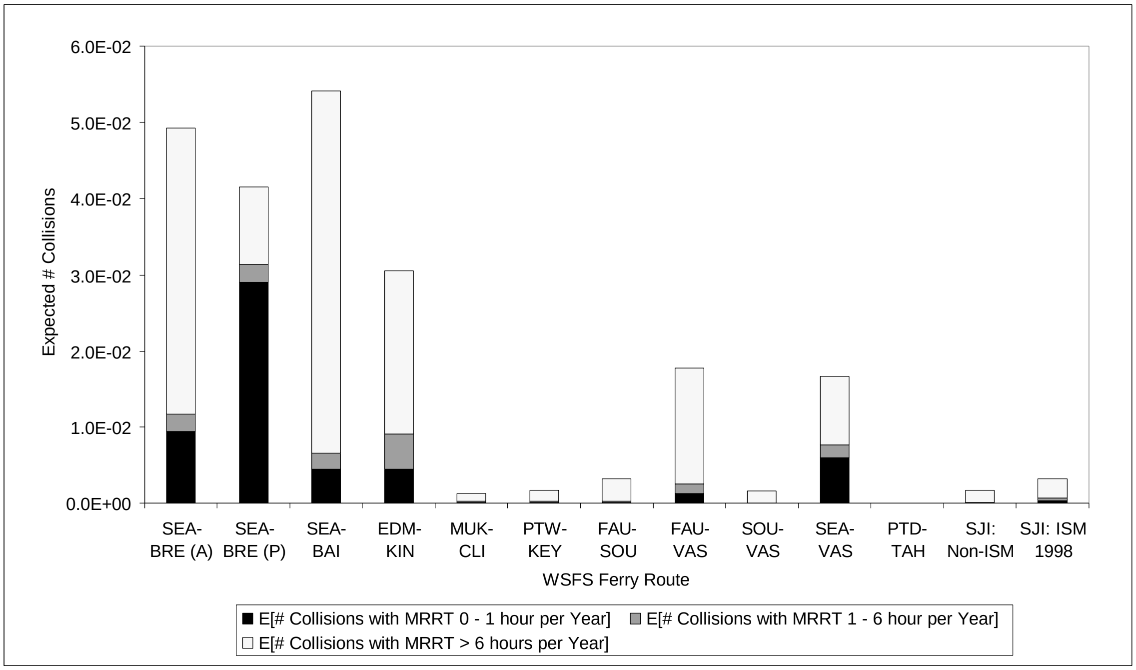


Figure 17. Statistical expected number of collisions per year by ferry route under scenario 2

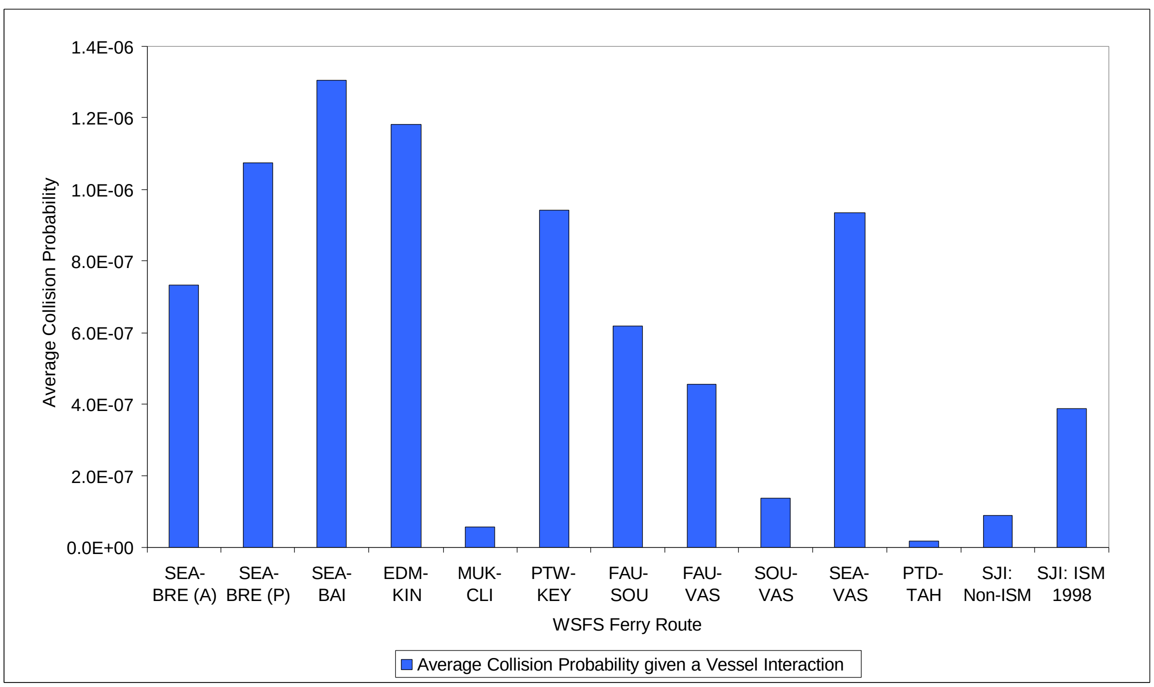


Figure 18. Average collision probability given an interaction by ferry route under scenario 2

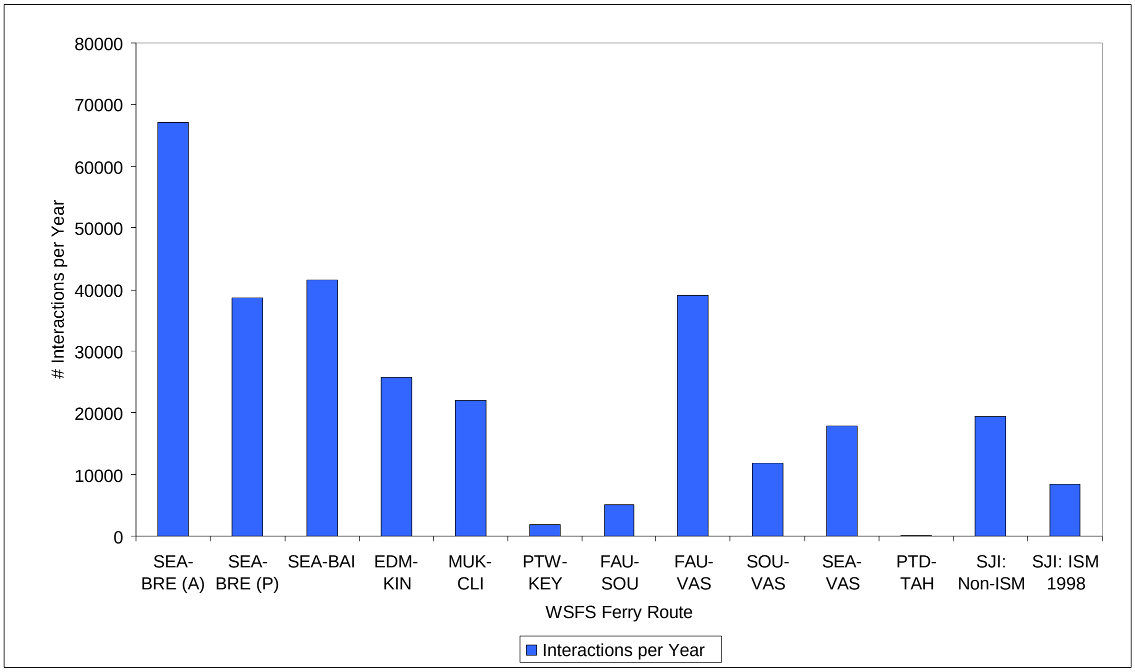


Figure 19. Number of interactions per year by ferry route under scenario 2

We have seen thus far that the introduction of the Chinook in Scenario 2 has lead to an increase in the statistical expected number of collisions with an MRRT of less than1 hour. This can primarily be explained due to both the added interactions of the Chinook and the assertion that collisions involving a Chinook fall in the 0 to 1 hour MRRT Category. However, it is of interest to see if the Chinook is in fact a "dangerous" vessel. Figure 20 shows the average collision probability given an interaction for the different classes of vessel. It can be seen that the average collision probability per interaction for the Chinook is roughly equal to that of the older passenger-only ferries and not the highest by far. Figure 20 indicates that the highest average collision probabilities per interaction are on the Jumbo and Jumbo Mark II class ferries. In Scenario 2, these ferries are assigned to the Edmonds-Kingston route and the Seattle-Bainbridge route respectively and thus interact with a larger proportion of non-WSF vessels.

1.5 Collision Scenario Analysis

A combination of a ferry route and a type of interacting vessel will be defined as a *collision scenario*. The discussion thus far has attempted to indicate the explanations for collision scenarios that exhibit high statistical expected number of collisions. One explanation identified thus far is traffic congestion. When comparing two routes, if the ferries on one route interact more often with other vessels, then the statistical expected number of collisions is likely to be larger. However, if the average probability of a collision is higher then this in turn can also lead to a higher statistical expected number of collisions. With this knowledge we will proceed to further analyze main sources of collisions risks by ordering collision scenarios by their contribution to statistical expected number of collisions per year. The type of interacting vessel also effects the proportion of collisions that require 0 to 1 hour and 1 to 6 hour response times. Therefore, collision scenarios will be ordered with respect to their contribution to statistical expected number of collisions per year in these MRRT categories. The following charts summarize this information categorized by ferry route and the type of the interacting vessel.

Figure 21 shows the statistical expected number of collisions per year for each collision scenario. The ferry route and interacting vessel combinations are ordered from left to right by the percentage contribution to the statistical expected number of collisions per year. The dark part of each bar in figure 21 indicates the percentage contribution to the statistical expected number of collisions for that collision scenario. The total height of the bar indicates the cumulative percentage including all collision scenarios to the left. In other words, figure 21 contains the top collision scenarios that accumulate to 62% of the statistical expected number of collisions per year.

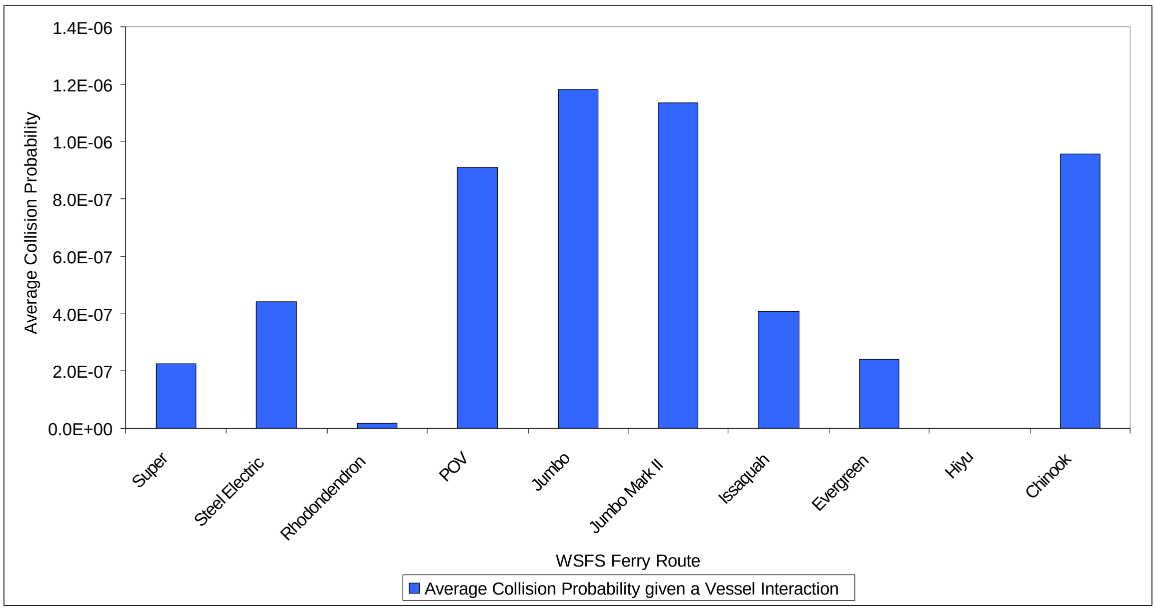


Figure 20. Average collision probability given an interaction by ferry class under scenario 2

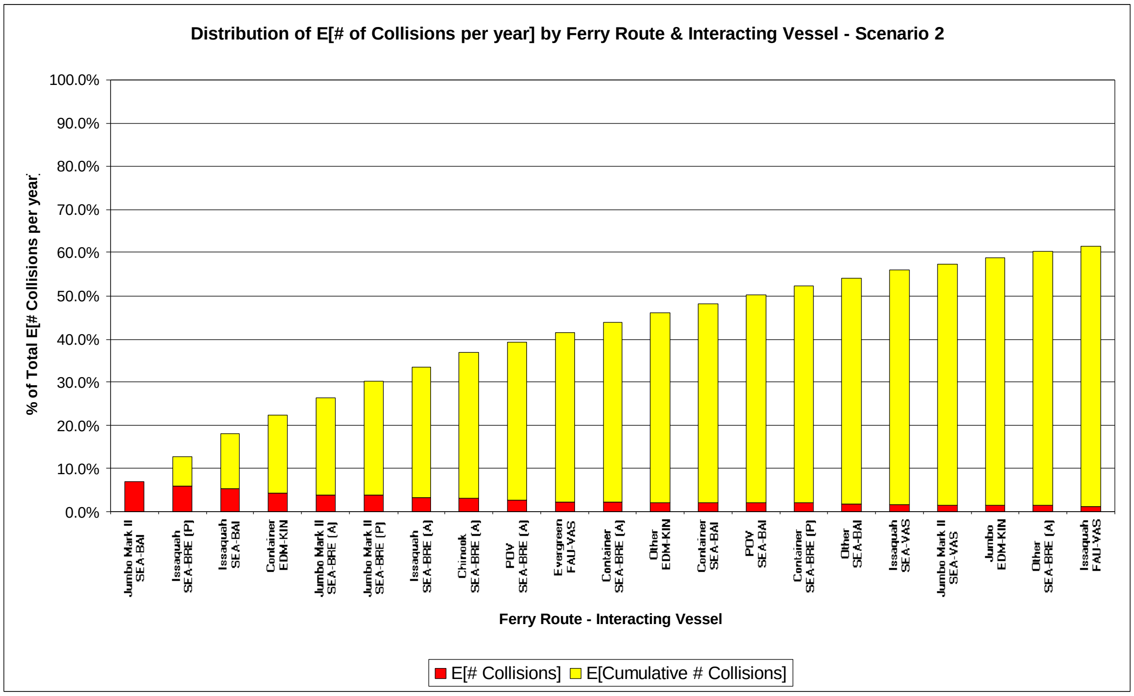


Figure 21. The distribution of the statistical expected number of collision per year by ferry route and interacting vessel type under scenario 2

It can be concluded from figure 21 that the main contributors to the statistical expected number of collisions per are other Washington State Ferries. It should be noted, however, that 94% of all interactions are with other Washington State Ferries. The primary collision risk from non-WSF vessels is a collision scenario involving container vessels. The ferry route/interacting vessel combination that has the highest statistical expected number of collisions per year is the Jumbo Mark II class ferry interacting with the other Seattle-Bainbridge ferry. All the collision scenarios in this figure involve the Seattle-Bremerton ferries, the Seattle-Bainbridge ferries, the Edmonds-Kingston ferries and ferries to Vashon Island. This reinforces the conclusion that the central Puget Sound is a congested area relative to other areas in the WSF system.

Figure 22 shows the statistical expected number of collisions per year with a 0 to 1 hour MRRT for each ferry route and each type of vessel that interacts with the ferries on that route. The format of figure 22 is the same as described for figure 21 except that the figure portrays the percentage contribution to the statistical expected number of collisions per year with a 0 to 1 hour MRRT. The accident scenario that has the highest statistical expected number of collisions per year with a 0 to 1 hour MRRT is the Issaquah class ferry on the Seattle-Bremerton Auto Run and the Seattle-Bremerton passenger-only ferries. This can be explained through the observation from figure 6 that this combination has the second highest statistical expected number of collisions in total and the assessment that many of these collisions have a 0 to 1 hour MRRT.

It should be noted that for all collision scenarios in figure 22 one of the vessels involve either a passenger-only ferry or a container vessel.

To further analyze this observation, consider figure 23. Figure 23 shows the percentage contribution of ferry class, rather than ferry route, and interacting vessel combinations to the statistical expected number of collisions with a 0 to 1 hour MRRT. Figure 23 shows that 85% of the total statistical expected number of collisions per year with a 0 to 1 hour MRRT one of the vessels involved are either (1) the Chinook, (2) a passenger-only ferry or (3) a container vessel. It must be noted however that the first 85% do include collisions between container vessels and several classes of large ferries. It should also be noted that collisions between the Chinook class ferry and both Washington State ferries and non-ferries are included in this 85%.

Figure 24 shows the statistical expected number of collisions per year with a 1 to 6 hours MMRT for each ferry route and each type of vessel that interacts with the ferries on that route. The format of figure 21 is used for the percentage contribution of collision scenarios to the statistical expected number of collisions per year with a 1 to 6 hour MRRT. The majority of the scenarios to the right of this figure are collisions involving large ferries and container vessels, ro-ro vessels and bulk carriers. Other scenarios are collisions between large ferries and the older passenger-only ferries.

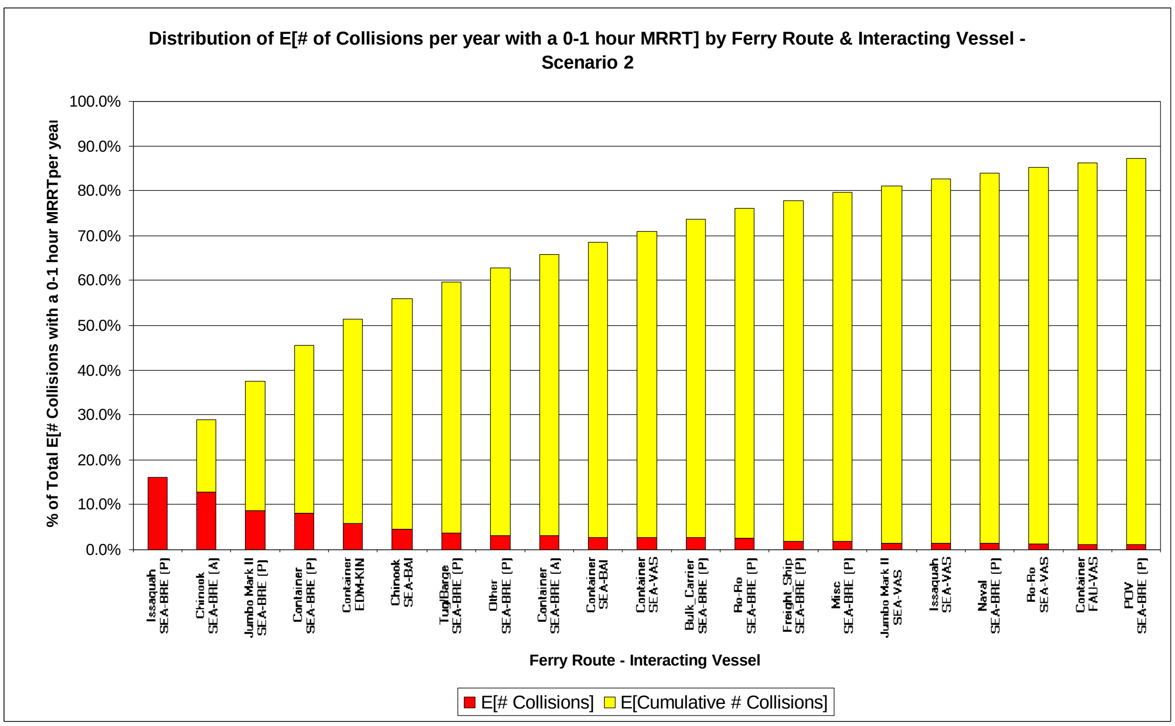


Figure 22. The distribution of the statistical expected number of collision per year with a MRRT of less than 1 hour by ferry route and interacting vessel type under scenario 2

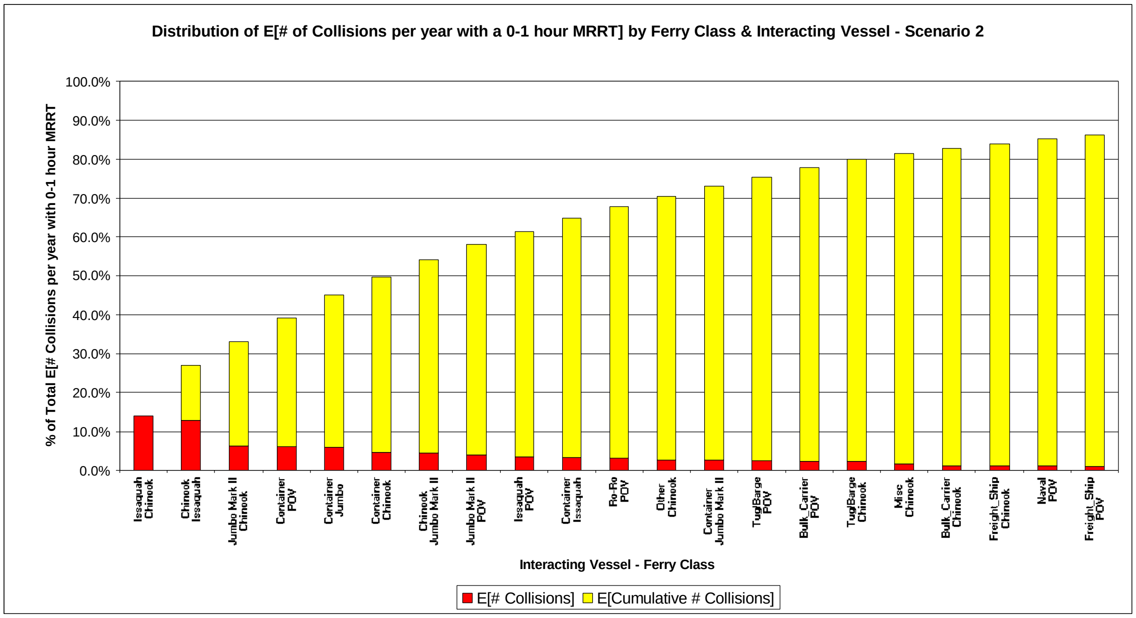


Figure 23. The distribution of the statistical expected number of collision per year with a MRRT of less than 1 hour by ferry class and interacting vessel type under scenario 2

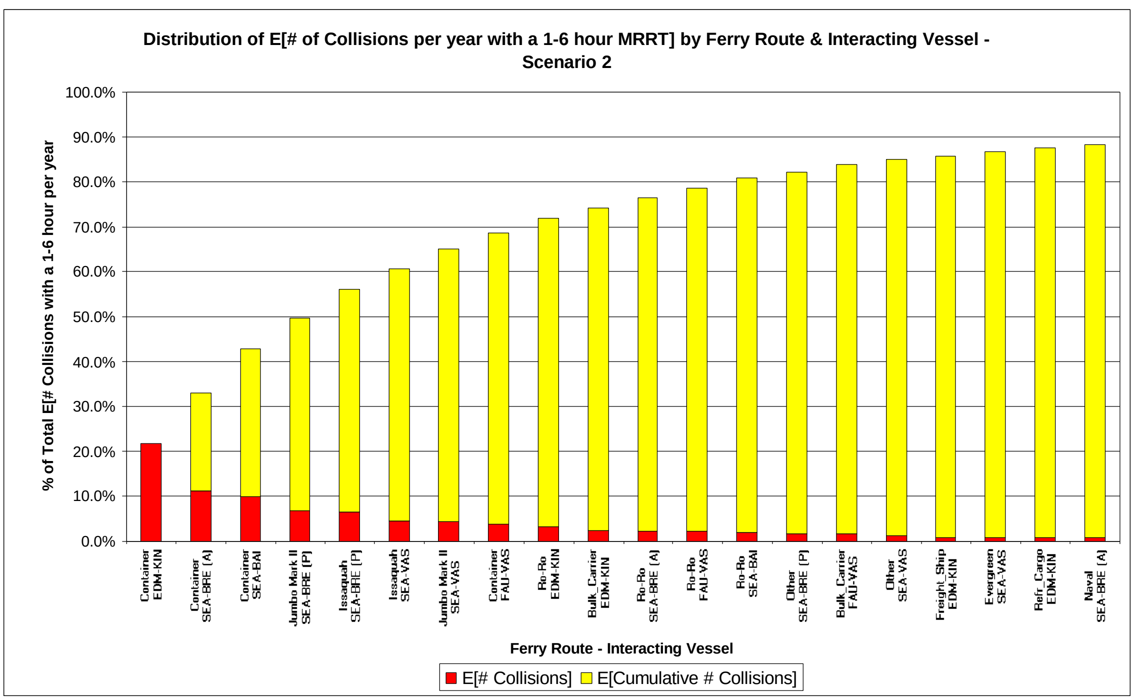


Figure 24. The distribution of the statistical expected number of collision per year with a MRRT of 1 to 6 hours by ferry route and interacting vessel type under scenario 2

1.6 A Detailed Analysis of Each Route

Thus far, we have concentrated on clarifying collision risk for the WSF system, i.e. the aggregate collision risk of all WSF System Ferry Routes together. To further the understanding of collision risk particular to a single ferry route a detailed analysis by ferry route will be presented. It should be noted, however, that while going through the detailed by ferry route analysis descriptions one should be keep in mind the contribution of that route to overall WSF system collision risk as indicated in figure 17.

Seattle-Bremerton Car Ferries

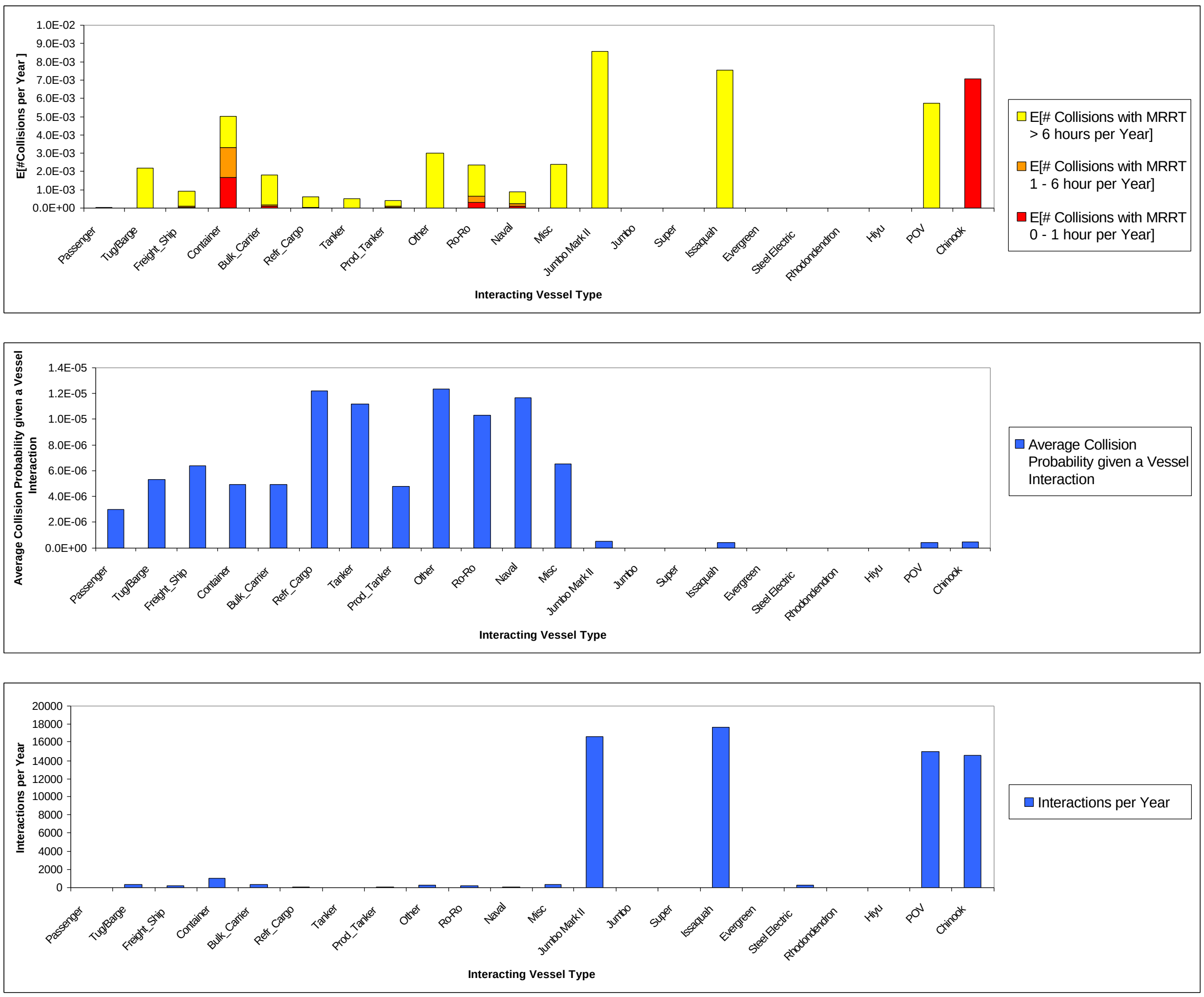


Figure 25. Seattle-Bremerton car ferries under scenario 2

Figure 25 combines the 3 graphs of the statistical expected number of collisions per year, the average collision probability and the number of interactions per year. On the Seattle to Bremerton car ferries, the majority of interactions are with the Jumbo Mark II class ferries on the Seattle to Bainbridge Island route and the other Issaquah route and the passenger only ferries on the Seattle to Bremerton route.

However, the Damage Scenario Model and the Response Time Model showed that collision with the Issaquah class and Jumbo Mark II class ferries fall in the category of a MRRT of more than 6 hours. For the Seattle to Bremerton route, the other collisions that fall in the category of a 0 to 1 hour MRRT or a 1 to 6 hours MRRT are primarily with container and ro-ro vessels. These vessels transit the traffic lanes calling at Seattle, Tacoma and Olympia. The large size and speed of these vessels may result in a potentially dangerous situation for the ferry if a collision occurs as indicated by the less than 6 hour MRRT categories. As can be seen in figure 25, the average collision probability given an interaction with these vessels is higher than for interactions with the other WSF ferries, but the number of interactions is much smaller.

Seattle-Bremerton Passenger Only Ferries

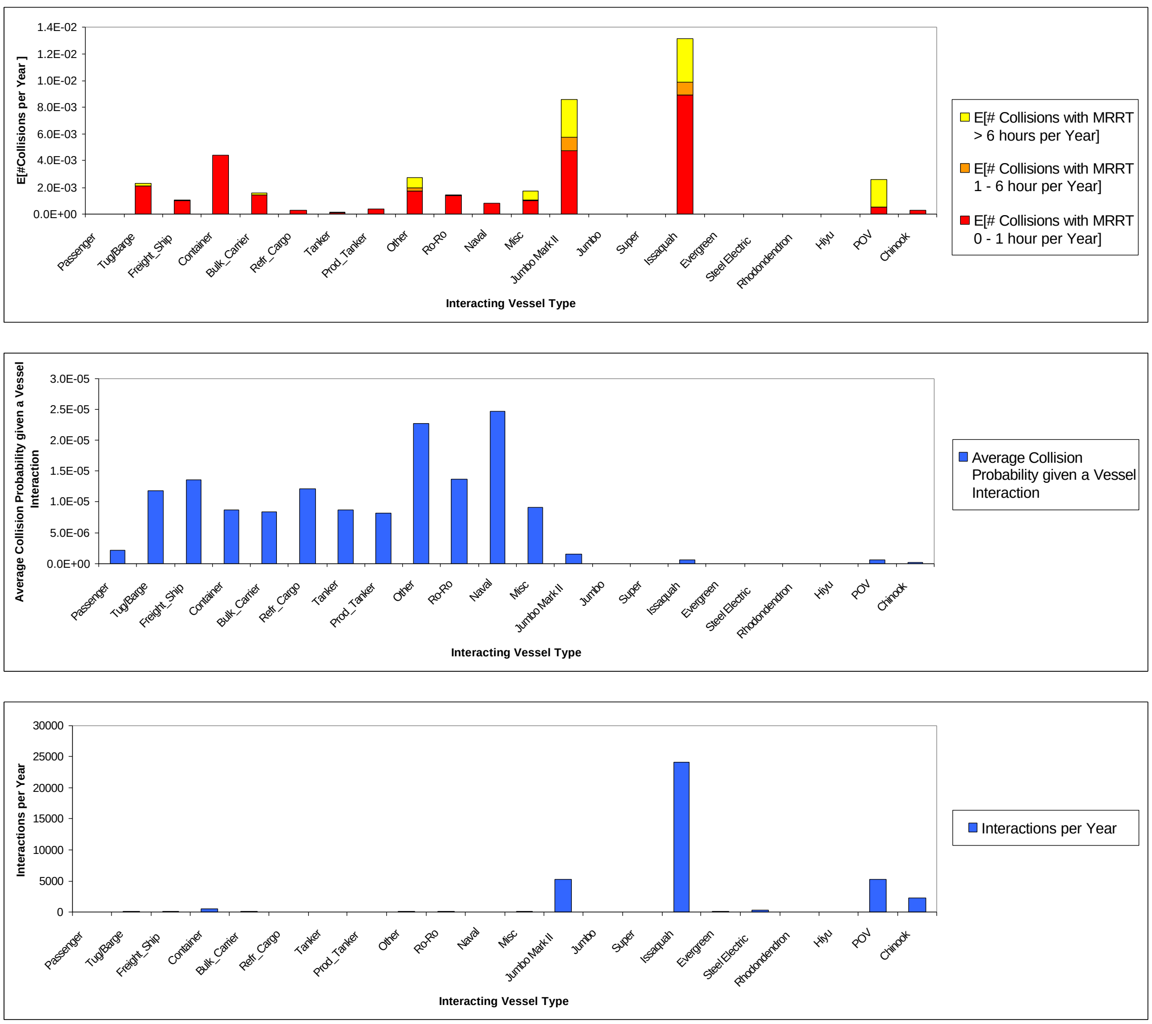


Figure 26. Seattle-Bremerton passenger-only ferries under scenario 2

On the Seattle to Bremerton passenger-only ferries, the majority of interactions are with the Issaquah class ferries on the Seattle to Bremerton car ferry route, the Jumbo Mark II ferries on the Seattle to Bainbridge Island route and the other passenger-only ferry on the Seattle to Bremerton route. The average collision probabilities given an interaction are much higher for interactions with non-WSF vessels than for these WSF vessels.

Examining the statistical expected number of collisions, the major risk lies in collisions with other WSF ferries (higher interaction frequency, lower collision probability) and container and ro-ro vessels (lower interaction frequency, higher collision probability). However, the majority of the collisions with these vessel types are projected to require a MRRT of less than 1 hour. Although, figure 17 shows that this route has the third highest statistical expected number of collisions overall, the high proportion of the statistical expected number of collisions that require a MRRT of less than 1 hour raises concern.

Seattle-Bainbridge Island Ferries

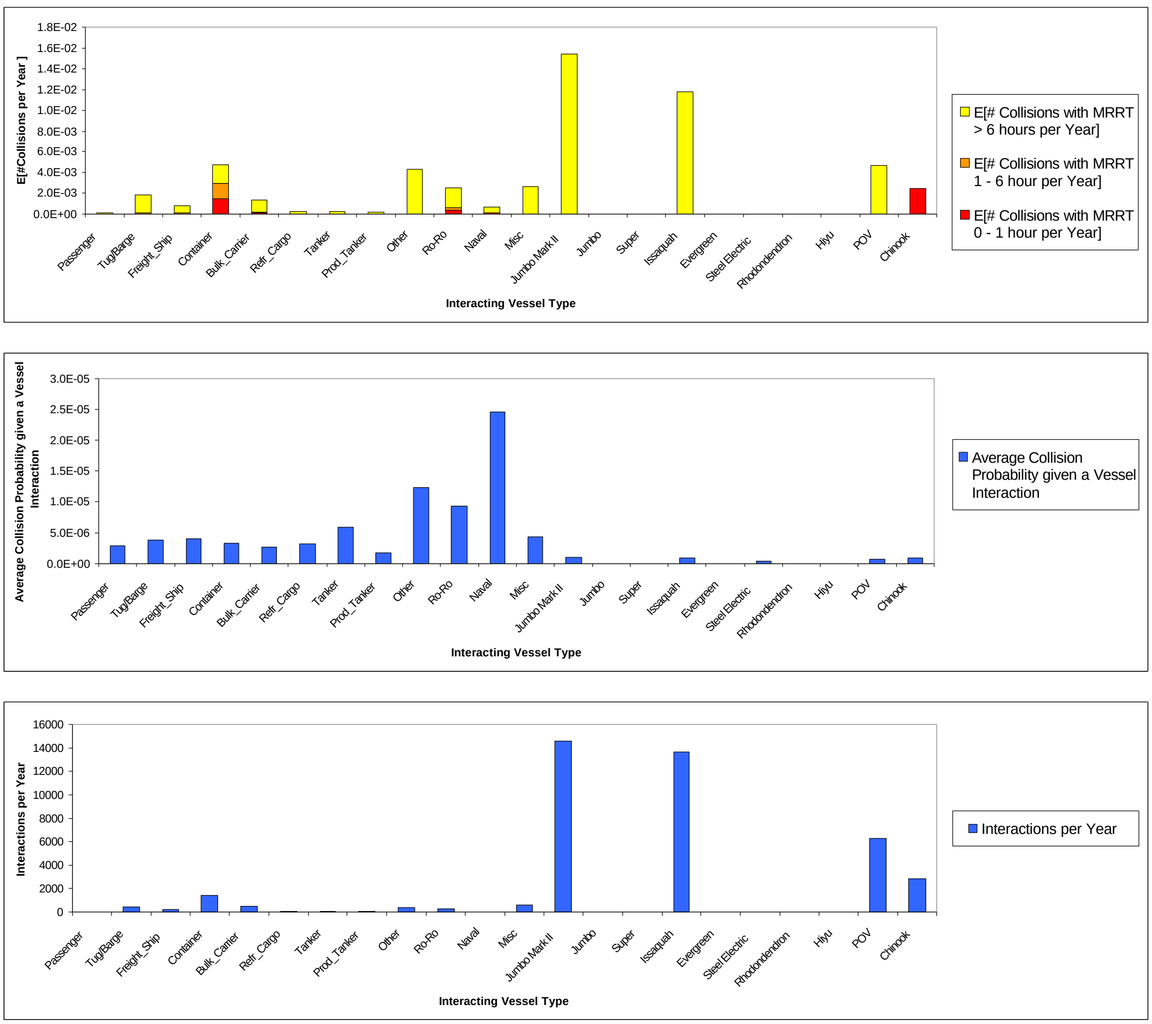


Figure 27. Seattle-Bainbridge Island ferries under scenario 2

On the Seattle to Bainbridge Island ferries, the majority of interactions are with the other Jumbo Mark II class ferry on the same route and the Issaquah class ferries and the passenger-only ferries on the Seattle to Bremerton route. The average collision probabilities are low for these interactions and the MRRT are all more than 6 hours. The exception is the interactions with the Chinook. These interactions can lead to collisions that would require a MRRT of less than 1 hour. This MRRT is due to damage occurring to the Chinook not the Jumbo Mark II.

Due to the higher collision probability given an interaction, the statistical expected numbers of collisions with container and ro-ro vessels have the next highest values. Again, due to the size and speed of these vessels, collisions can lead to shorter MRRT classifications.

Edmonds-Kingston Ferries

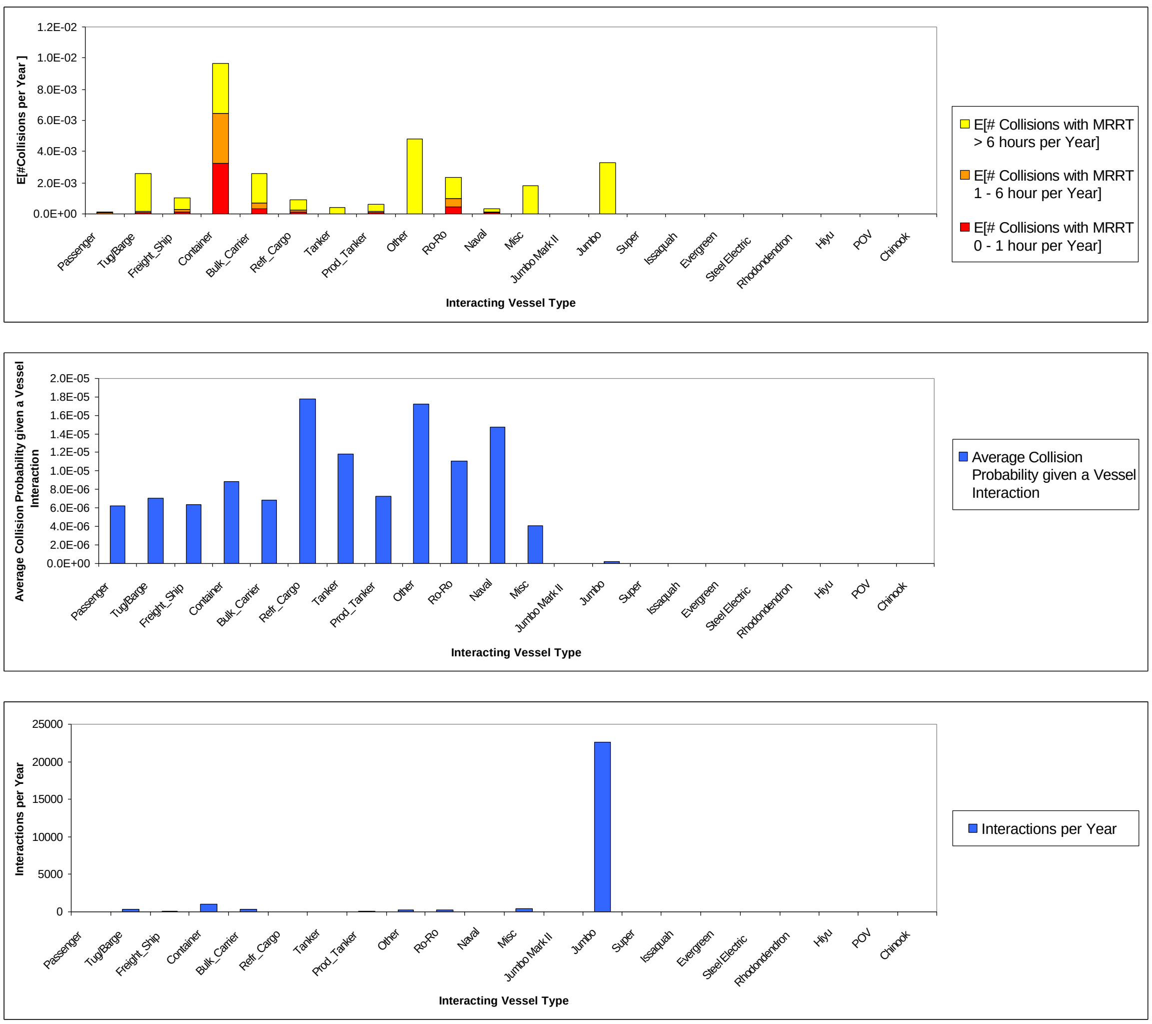


Figure 28. Edmonds-Kingston ferries under scenario 2

The Edmonds to Kingston ferries interacts most often with the other ferry on the same route. The average collision probability of these interactions is low relative to that for interactions with other vessel types. However, the Edmonds-Kingston ferries have the largest number of interactions with container vessels, bulk carriers, ro-ro vessels and other deep-draft traffic in the traffic lanes. These interactions have a higher average collision probability than interactions with WSF ferries, thus the statistical expected number of collisions is significant. Moreover, due to the size and speed of these vessels, collision requiring less than 1 hour and 1 to 6 hour MRRTs are possible. In fact, figure 17 shows that the Edmonds-Kingston ferries have the largest statistical expected number of collisions requiring a MRRT in the 1 to 6 hour range.

Fauntleroy-Vashon-Southworth Ferries

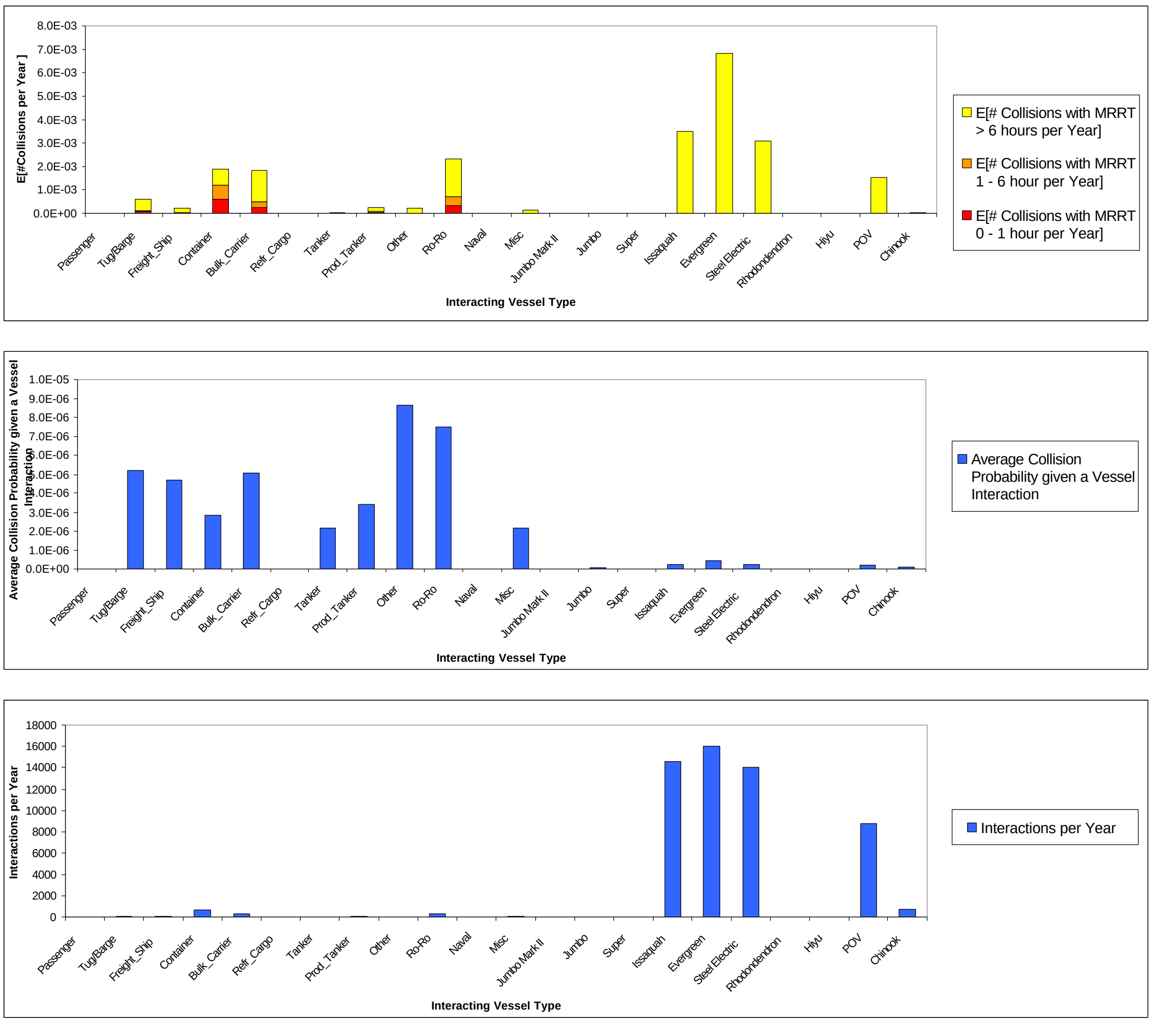


Figure 29. Fauntleroy-Vashon-Southworth ferries under scenario 2

The ferries on the Fauntleroy-Vashon-Southworth routes interact most often with the other ferries on the route, specifically an Issaquah class ferry, an Evergreen State class ferry and a Steel Electric class ferry in scenario 2. In addition, interactions occur with the passenger-only ferry on the Seattle-Vashon route and less frequently with the vessels on the Seattle to Bremerton route, due to the proximity of the routes. Interactions with these WSF vessels have lower average collision probabilities and collisions would only require a MRRT of more than 6 hours. Again the exception is the Chinook class, for which all collisions require a MRRT of less than 1 hour.

The higher average collision probabilities for interaction with non-WSF vessels lead to equally large statistical expected numbers of collisions with container vessels, bulk carriers and ro-ro vessels. Such collisions can also require shorter MRRTs.

Seattle-Vashon Passenger-Only Ferries

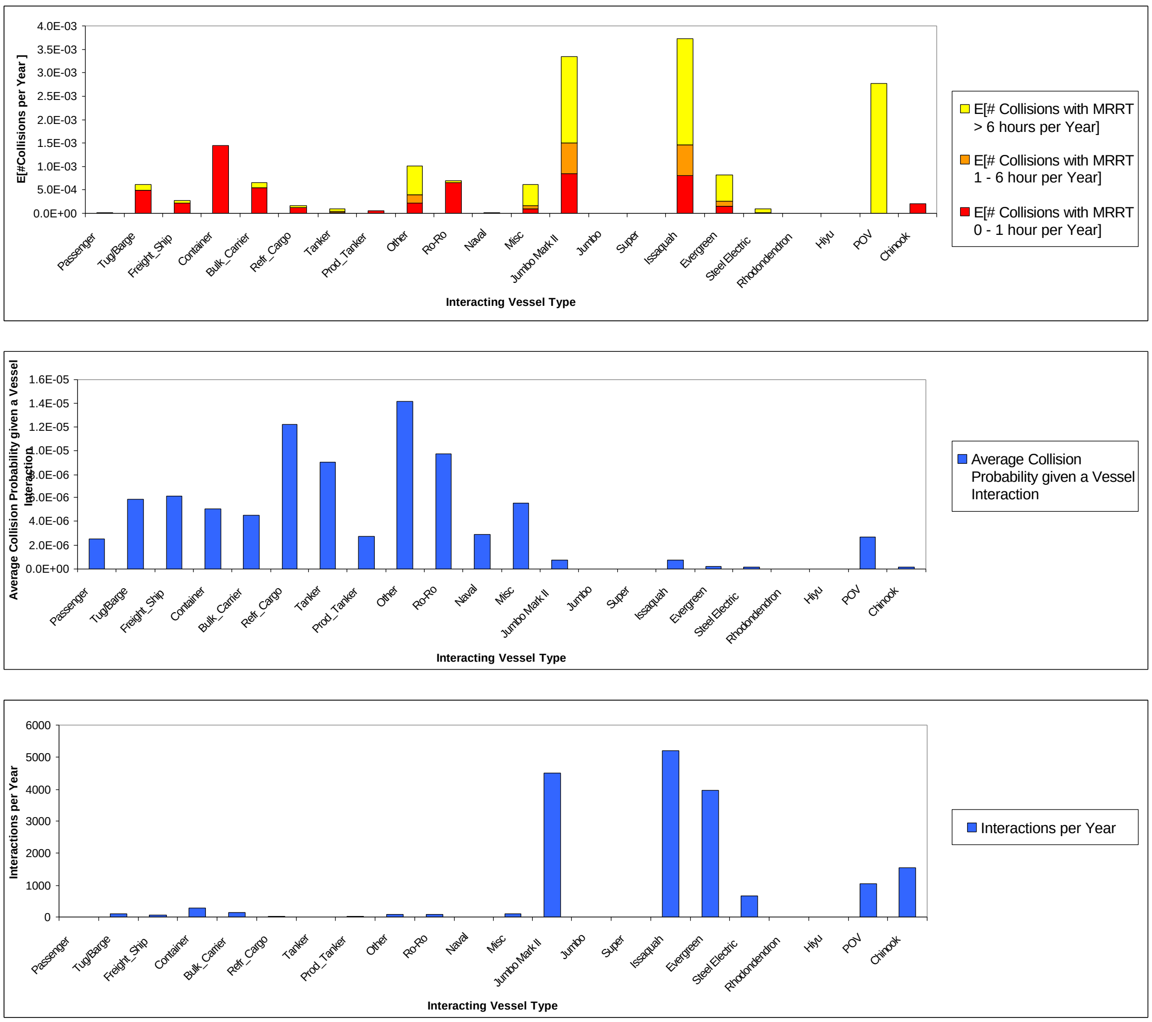


Figure 30. Seattle-Vashon passenger-only ferries under scenario 2

The ferries on the Seattle-Vashon passenger-only route interact most often with Issaquah class ferries on the Seattle-Bremerton car ferry route, the Jumbo Mark II class ferries on the Seattle-Bainbridge Island route and the Evergreen State class ferry and the Steel Electric class ferry on the Fauntleroy-Vashon-Southworth route. In addition, interactions occur with the passenger-only ferry and the Chinook on the Seattle-Bremerton Interactions with these WSF vessels have lower average collision probabilities than for the less frequent interactions with non-WSF vessels. Collisions between the passenger-only vessels on the Seattle-Vashon route and most of these vessel types can lead to situations requiring a MRRT of less than 1 hour or a MRRT of 1 to 6 hours. Collisions with the Chinook class ferry always require a MRRT of less than 1 hour.

Port Townsend-Keystone Ferries

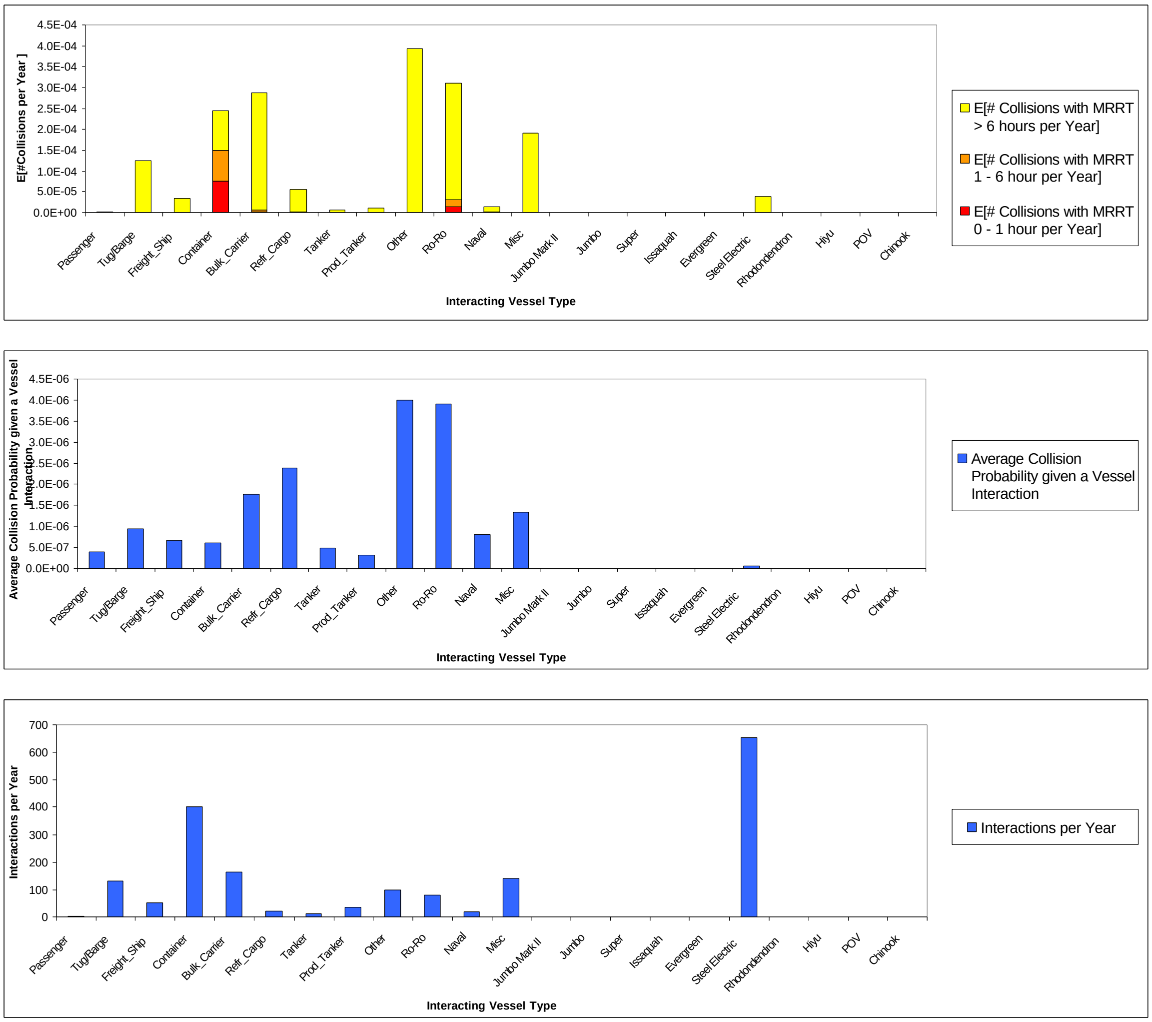


Figure 31. Port Townsend-Keystone ferries under scenario 2

Figure 31 shows that a large proportion of the interactions occur with the other ferry on the same route for the Summer and Spring schedules. However, the traffic lanes entering and leaving the Puget Sound intersect the Port Townsend-Keystone route. Thus interactions occur with all types of non-WSF traffic using these lanes. Of primary concern, are the interactions with container vessels that can cause collisions requiring MRRT in the 1 to 6 hour and the less than 1 hour categories. The isolation of this route would seem to indicate that response plans/evacuation strategies for such collisions should be carefully considered.

San Juan Islands Non-ISM Ferries

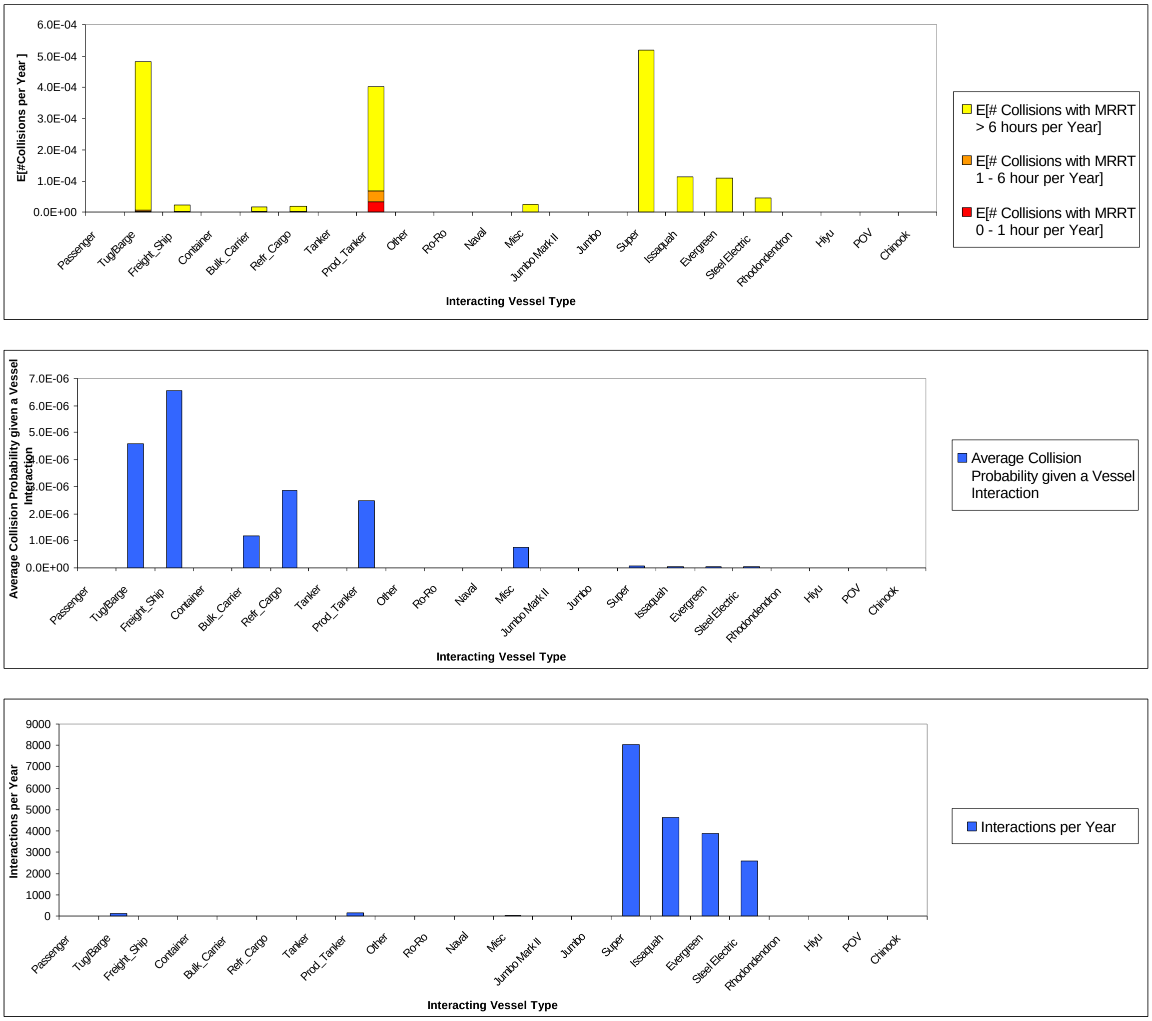


Figure 32. San Juan Islands non-ISM ferries under scenario 2

During 1998, the ferries transiting the San Juan Islands and calling at Sidney, Canada were required to fall under SOLAS regulations and thus the International Safety Management system was implemented on these vessels. The ferries that did not call at Sidney were not required to fall under these regulations. The non-International ferries cross Rosario Strait and call at the various islands. Crossing Rosario Strait the ferries can interact with product tankers, tankers and tug/barge traffic. However, once in the islands, interactions are primarily with other Washington State ferries. Interactions with the large number of pleasure boat and tour boat traffic encountered in this area during the summer months are not modeled due to a lack of data. However, the experts considered such traffic congestion in the expert judgment questionnaires.

San Juan Islands ISM ferries

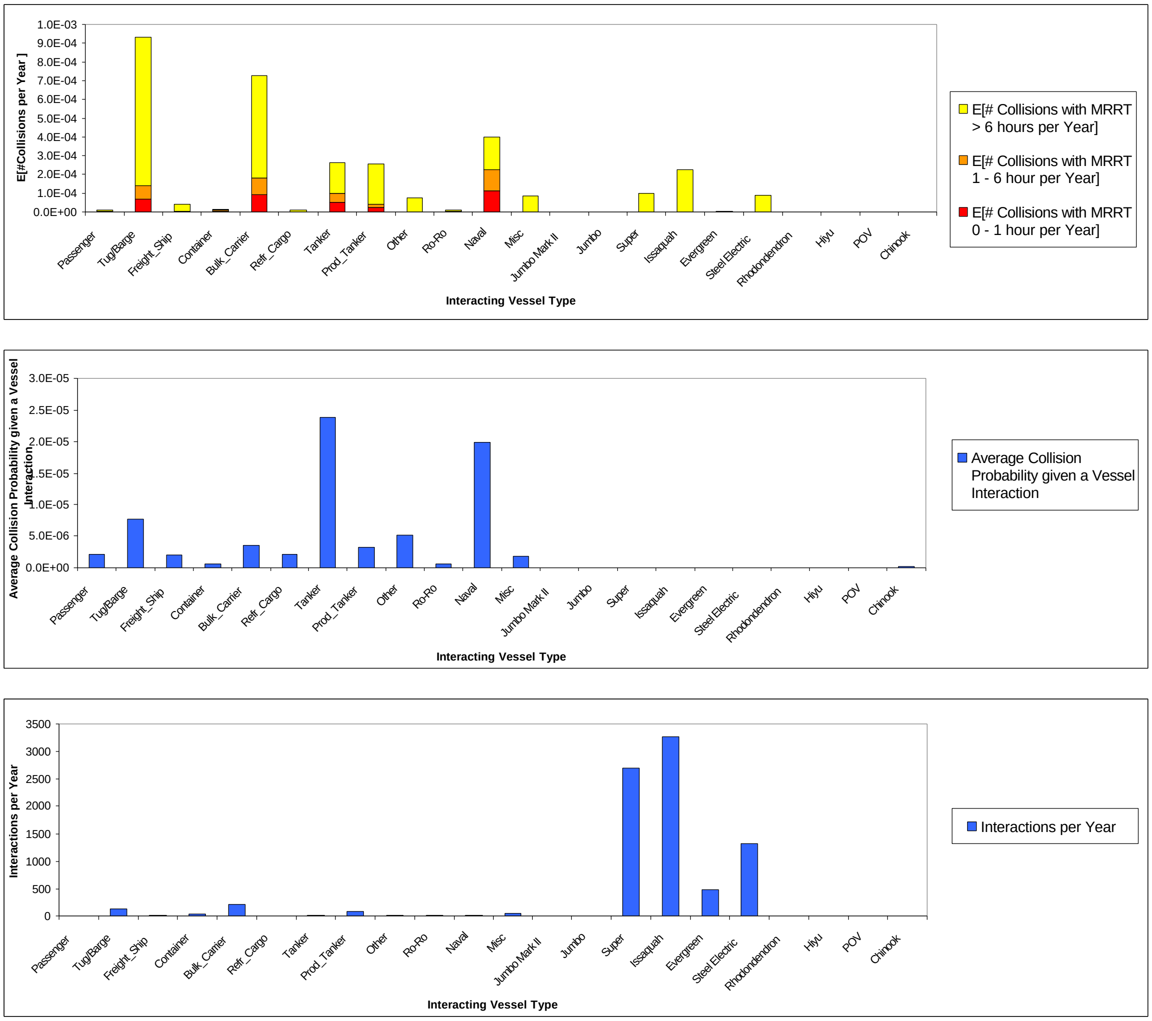


Figure 33. San Juan Islands ISM ferries under scenario 2

The international ferries cross Rosario Strait, call at several of the islands and cross Haro Strait to Sidney. Crossing Rosario Strait the ferries can interact with product tankers, tankers and tug/barge traffic. Once in the islands, interactions are primarily with other Washington State ferries. However, Haro Strait is much busier than Rosario Strait and thus these vessels interact more with non-WSF vessels. Thus collisions are possible with bulk carriers, product tankers, oil carrying tankers, tug/barge traffic and Canadian Navy vessels. These collisions can have a MRRT in the 0 to 1 hour and the 1 to 6 hour categories.

Clinton-Mukilteo Ferries

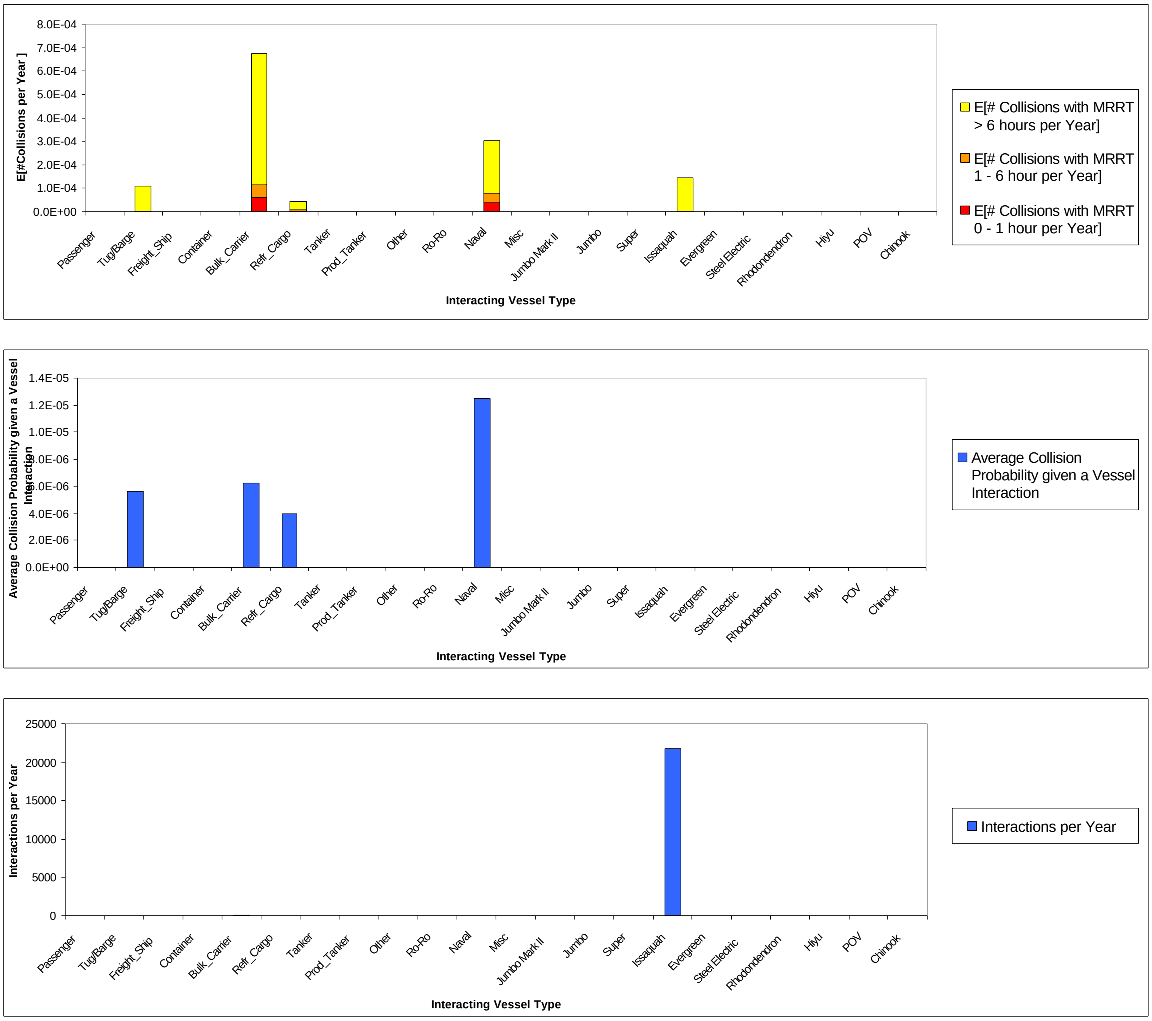


Figure 34. Clinton-Mukilteo ferries under scenario 2

The Clinton-Mukilteo ferries interact primarily with the other ferry on the same route. These interactions can lead to collisions, but would have a MRRT of more than 6. Some interactions also occur with bulk carriers, refrigerated cargo vessels, tug/barge traffic and US Navy vessels from Everett. Collisions with these non-WSF vessels can lead to more serious accidents in the 1 to 6 hour and less than 1 hour MRRT categories.

Point Defiance-Tahlequah Ferries

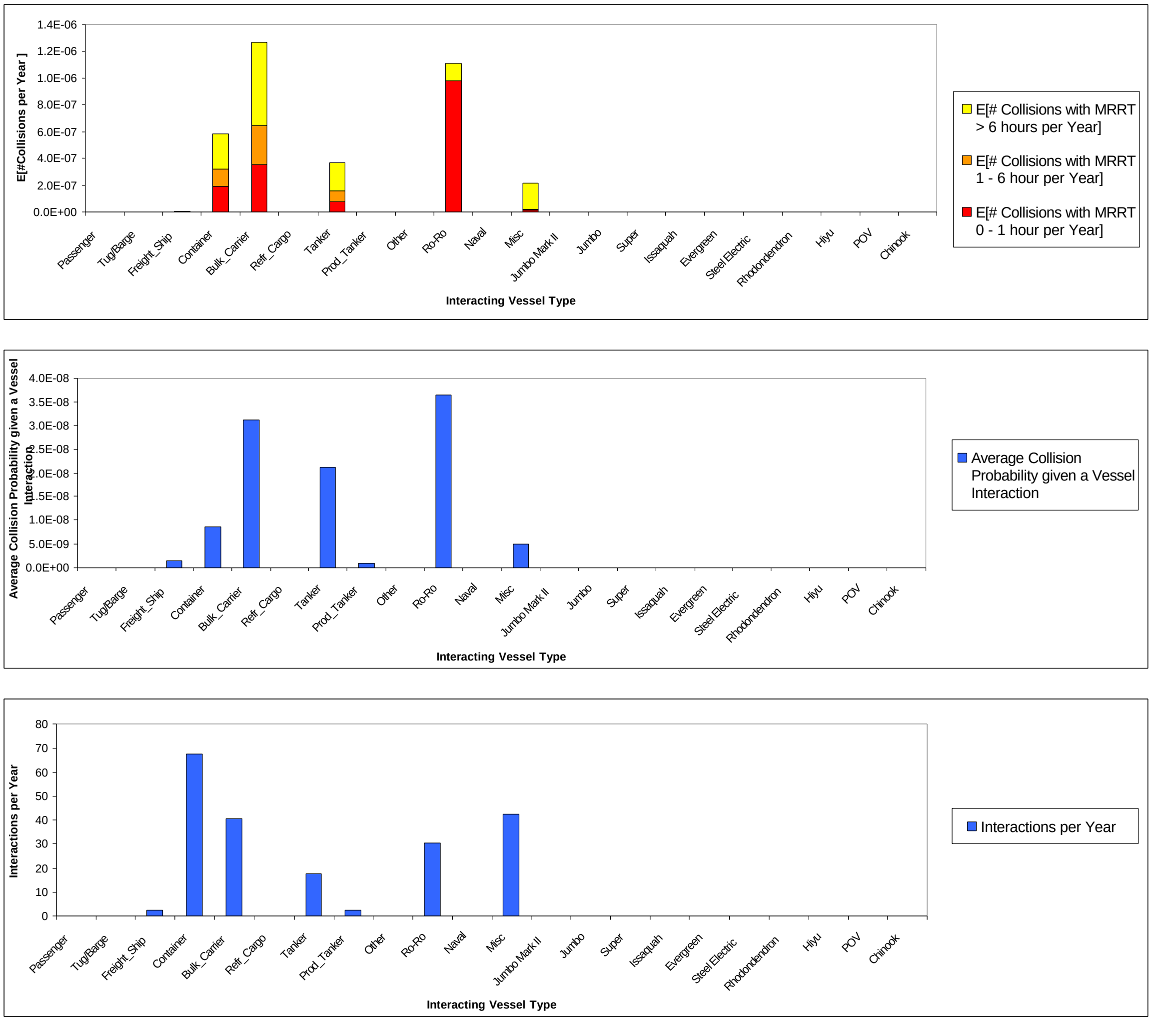


Figure 35. Point Defiance-Tahlequah ferries under scenario 2

The Point Defiance-Tahlequah ferry is the only ferry that does not interact with other Washington State ferries since it is isolated from the other routes and there is only a single ferry on the route. Thus interactions occur with container vessels, bulk carriers, tankers, ro-ro vessels, small fishing vessels and yachts. A large proportion of the statistical expected number of collisions with container vessels, bulk carriers and ro-ro vessels have a MRRT in the 0 to 1 hour and 1 to 6 hour categories. However, it may be concluded from figure 17 that, the total statistical expected number of collisions per year attributed to the Point Definance-Tahlequah run is hardly noticable compared to other ferry routes.

Section 2: The Effect of Ongoing Changes to the WSF and the Implementation of ISM

2.1 Specific Findings from the Analysis in this Section

The following are specific findings from the Final Report that are justified by the results discussed in this section. The numbering of the findings is the same as that used in the final report to ensure tracability between the two documents.

The risk models demonstrate that potential accidents have serious consequences and identify the dominant potential accident scenarios.

15. The addition of the high speed (Chinook) class ferry to the schedule and the subsequent additional interactions in a high ferry to ferry interaction area has resulted in an increased statistical expected number of collisions. However, the average collision probability per interaction for the Chinook is less than that for the older passenger-only ferries. Since all collisions involving high-speed class vessels were assumed to require an immediate response, the introduction of the high-speed class ferries increases the statistical frequency of collisions requiring a MRRT of less than 1 hour by over 50%.

Risk reduction interventions are required to maintain the current low likelihood of accidents and to reduce the potential consequences of accidents that could occur by increasing the effectiveness of emergency response.

23. The single most effective risk management intervention is the fleet wide implementation of the International Safety Management System (ISM). It is estimated that fleet wide implementation of ISM will reduce the potential rate of accidents by approximately 15%, offsetting the potential increase in risk due to the introduction of new ferries and routes. Funds for fleet wide implementation have been approved by the Washington State Legislature. ISM will reduce both the probability of accidents and the consequences if accidents do occur.

2.2 Changes to the WSF

Several recent additions to Washington State Ferry fleet have included the Chinook class high-speed, passenger-only ferries and the Jumbo Mark II class car ferries. The inclusion of these vessels into the ferry service operation has lead to a re-assignment of vessels to routes. Such re-assignments change the system dynamics and thus can cause changes to the levels of risk present in the system and thus require separate consideration.

During 1998, the ferries transiting the San Juan Islands and calling at Sidney, Canada were required to fall under SOLAS regulations and thus the International Safety Management (ISM) system was implemented on these vessels. The ferry service has developed its own Safety Management System to meet the requirements of an external ISM audit by Det Norske Veritas, a major shipping classification company. Washington State Ferries have received approval from the Washington State Legislature and the Washington State Transportation Commission for the fleet-wide implementation of the Safety Management System, thus study team was asked to assess the impact of ISM on the collision risk.

To reflect the changes listed above, 4 simulation scenarios were considered.

Scenario 1 – Prior to 1997
Before the introduction of the new vessels, the Washington State Ferry fleet had remained unchanged for 10 years. This period corresponds to the period for which the study team assimilated and analyzed accident and incident data for the Puget Sound area. As has been mentioned previously, the accident probability model is calibrated to this collected data. This calibration procedure includes the use of the simulation and thus the simulation must be programmed to represent the operation of the Washington State Ferry Service for the period in which the data was collected.

The simulation was programmed to represent the assignments of vessels to routes that existed prior to the introduction of the two new classes of vessels. The ferry schedule used for scenario 1 was taken from the Fall 1997, Spring 1997 and Summer 1997 Sailing Schedules published by the Washington State Ferries.

Scenario 2 – 1998
The Washington State Ferry Risk Assessment project started in July 1998. At this time, one Chinook class ferry had been delivered and was operating on the Seattle to Bremerton route. Two Jumbo Mark II class ferries also started service on the Seattle to Bainbridge Island route during 1998. To reflect this change to the system, a simulation scenario was developed with these new vessel assignments.

The simulation was programmed to represent the assignments of vessels to routes used after the introduction of the two new classes of vessels. The addition of the two Jumbo Mark II class ferries lead to a shuffling of the larger ferries, while the Chinook added additional service on the Seattle-Bremerton passenger-only route. The ferry schedule used for scenario 2 was taken from the Fall 1998, Spring 1998 and Summer 1998 Sailing Schedules published by the Washington State Ferries.

Scenario 3 – 2 Chinook Class High-speed Ferries
On Monday, June 8 1998, Washington State Ferries exercised their option to purchase a second Chinook Class high-speed, passenger-only vessel from Dakota Creek Shipyard in Anacortes, Washington. The second Chinook is projected to replace the passenger-only ferry currently operating on the Seattle to Bremerton route. This will mean that 2 Chinook Class vessels will be operating this route. The schedule used and the assignments of the other ferry classes were the same as specified in scenario 2.

Scenario 4 – 2 Chinook Class High-speed Ferries plus ISM
Scenario 4 is intended to model the system risk after the implementation of ISM. Thus scenario 3 is taken as a basis for the simulation, but the frequencies of human error related incidents are reduced to reflect the training and organizational improvements inherent in the implementation of ISM. At this point some discussion of the effect of ISM is required.

2.3 The Effect of ISM

The International Safety Management Code establishes safety-management objectives and involves the establishment of a safety management system (SMS). The operator is then required to establish and implement a policy for achieving these objectives. This includes providing the necessary resources and shore-based support.

One effect of such training is a reduction in the occurrence of human error incidents. However, a better understanding of such incidents must be reached to assess the impact on the system risk. 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. 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 70% of the errors committed during accidents were related to human and organizational error.

Reason (1997) introduced a cognitive framework of human error that is illustrated in Figure 36. In this taxonomy, unsafe acts result from two types of activities: errors, which are unintended actions; and violations, which are intended actions. Errors can be of three types: decision errors, encompassing both rule-based and knowledge-based errors; skill-based, and perceptual errors. Violations can be either of two types: routine, which are common place abrogation of policies, rules and/or procedures that are condoned by management, or exceptional violations, which are not condoned by management.

A comparative analysis of aviation accidents investigated by the National Transportation Safety Board (NTSB) between 1978 and 1990 was completed in 1994 (NTSB, 1994). 37 major accidents were reviewed, during which primary and secondary errors that occurred during a major accident were identified. Those errors were then allocated to the Reason human error taxonomy, in the same way that 51 errors identified during the 46 Washington State Ferry accidents were allocated. The distribution of errors in the 1994 NTSB report is shown in figure 36.

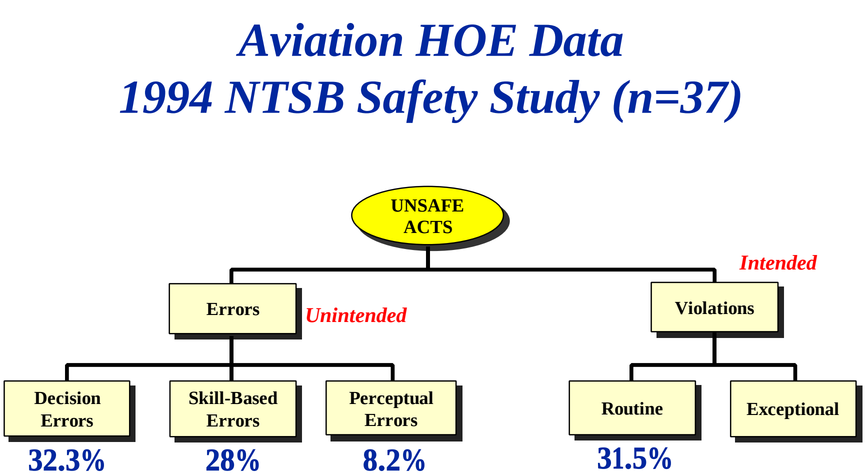


Figure 36. Taxonomy of Human Errors

Based on NTSB data it may be assumed that approximately 60% of these errors are theoretically addressable by the improved selection, training, and qualifications associated with ISM (30% are assumed to be decision errors, 30% are assumed to be skill based errors). In addition, 7.4% of all mechanical failures were directly attributed to human error. All of these errors are assumed to be skill and knowledge errors addressable by training. Thus to represent the implementation of ISM fleet-wide in the collision risk models, the frequency of human error incidents was reduced by 30% (a 50% reduction of the 60% of human errors that are addressable by training) and mechanical failures were reduced by 3.7% (a 50% reduction of the 7.4% of mechanical failures that are addressable by training).

These assumptions made in modeling the effect of ISM are conservative. It can be argued that the implementation of ISM and the SMS would lead to a reduction in routine violations due to a "safety culture" and a reduction in perceptual errors, due to tougher crew screening procedures. However, the aim of this modeling is to give a reasonable estimate of the effect, thus only the obvious reductions are included.

2.4 A Comparison of the 4 Scenarios

In the previous discussion we have seen that the Chinook class high-speed, passenger-only ferries are of concern due to the severity of a possible collision. One of the main differences between the 4 scenarios stems from the Chinook class ferry. In Scenario 1, there are no Chinook class ferries operating. In scenario 2, there is one Chinook class ferry, while in scenario 3, there are two Chinook class ferries operating. The other major difference between scenarios is the Jumbo Mark II ferries introduced in scenarios 2 and 3 and absent from scenario 1. Scenario 4 is based on scenario 3 but includes an estimate of the effect of implementing the Safety Management System fleet wide. Thus a comparison of the 4 scenarios is necessary to understand the change in the systemic risk caused by the introduction of the new ferry classes.

Table 3 shows the statistical expected number of collisions for the 4 scenarios in total and in each MRRT category.

Table 3. A comparison of the 4 scenarios by statistical expected number of collisions

	Statistical Expected Number of Collisions per Year				
	Scenario Desciption	MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
Scenario 1	No Chinook, No Jumbo Mark II	0.025	0.016	0.141	**0.182**
Scenario 2	1 Chinook, 2 Jumbo Mark II	0.055	0.015	0.152	**0.223**
Scenario 3	2 Chinook, 2 Jumbo Mark II	0.075	0.013	0.133	**0.221**
Scenario 4	2 Chinook, 2 Jumbo Mark II + Fleetwide ISM	0.063	0.011	0.113	**0.187**

Scenario 2 represents the operational characteristics of the Washington State Ferries during the study and has been discussed in detail previously. Thus scenario 2 is considered the base case with which to compare the other scenarios. Table 4 shows the % reductions from Scenario 2. Logically scenario 2 shows no change from itself. However, the change in the other cases is of interest.

The results in table 3 show that the introduction of the additional service by the first Chinook increased the total statistical expected number of collisions (from 0.18 per year to 0.22 per year), with the largest increase in collision with an MRRT of less than 1 hour (from 0.025 per year to 0.055 per year).

Table 4. A comparison of the 4 scenarios by % reduction from Scenario 2

		Percent Change from Scenario 2			
	Scenario Desciption	MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
Scenario 1	No Chinook, No Jumbo Mark II	-14%	0%	-5%	**-18%**
Scenario 2	1 Chinook, 2 Jumbo Mark II	0%	0%	0%	**0%**
Scenario 3	2 Chinook, 2 Jumbo Mark II	9%	-1%	-9%	**-1%**
Scenario 4	2 Chinook, 2 Jumbo Mark II + Fleetwide ISM	3%	-2%	-18%	**-16%**

Examining table 4, we can see that the replacement of the older passenger-only vessel with a Chinook (Scenario 2 to Scenario 3) has a minimal effect on the total statistical expected number of collisions. However, there is an increase in the statistical expected number of collisions with an MRRT of less than 1 hour, with an associated decrease in the statistical expected number of collision in the other 2 MRRT categories. Thus, although the replacement does not cause any more collisions to be predicted, the collisions that may occur will require faster response times.

The implementation of ISM fleet-wide is predicted to decrease the statistical expected number of collisions by almost 16% from Scenario 2, despite the additional service of the second Chinook. It can be seen, however, that these reductions are realized for collisions with an MRRT of more than 1 hour, not in the less than 1 hour category.

Table 5 shows the average time between collisions predicted for each scenario. It should be noted that despite the concern with the high-speed ferries highlighted in this analysis, the average time between collisions with an MRRT of less than 1 hour is predicted to be 16 years in scenario 4. However, it becomes apparent that more stringent training and procedural requirements are necessary to minimize the risk contribution of the high-speed ferries.

Table 5. A comparison of the 4 scenarios by average return time

		Average Time between Collisions (in Years)			
	Scenario Desciption	MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
Scenario 1	No Chinook, No Jumbo Mark II	41	64	7.1	**5.5**
Scenario 2	1 Chinook, 2 Jumbo Mark II	18	67	6.6	**4.5**
Scenario 3	2 Chinook, 2 Jumbo Mark II	13	79	7.5	**4.5**
Scenario 4	2 Chinook, 2 Jumbo Mark II + Fleetwide ISM	16	88	8.8	**5.3**

Section 3: Historical Rates for Allisions, Groundings and Fires / Explosions

3.1 Specific Findings from the Analysis in this Section

The following are specific findings from the Final Report that are justified by the results discussed in this section. The numbering of the findings is the same as that used in the final report to ensure tracability between the two documents.

The risk models demonstrate that potential accidents have serious consequences and identify the dominant potential accident scenarios.

18. Fires on board ferries have historically been limited to engine spaces, the car deck, and galley and all of these spaces have adequate fire control systems. However, a fire on the car deck could lead to an explosion that could produce catastrophic results– particularly if there was an illegal hazardous cargo in a truck or vehicle near the source of the fire, or if the explosion is the result of a deliberate act.. The Edmonds-Kingston route is the route with the highest historical rate of minor fires.

19. There is no evidence of a serious threat of sabotage or attack against the Washington State Ferries. However, the relatively open boarding procedures, lack of security systems, and minimal capability for checking vehicle contents make it highly unlikely that an attempt, were it to occur, would be detected and thwarted.

20. Allisions are serious property damage and service interruption issues, but not significant threats to passengers. Allisions are the most common accident in the WSF system and must be avoided to minimize property and service losses due to accidents. The highest historical allision rates observed were in the San Juan Islands: Issaquah class ferries at the Orcas Island terminal, Steel Electric class ferries at the Lopez Island terminal, and Super class ferries at the Anacortes terminal.

21. There were six groundings of Washington State Ferries during the period 1988-1998. There are only certain geographical areas where groundings are possible. The area of greatest risk for grounding is Keystone Harbor. Groundings are not an immediate threat to passengers and the MRRT for groundings is assumed to be 6 hours or greater in all cases.

22. Flooding and foundering are insignificant threats to passenger safety, no serious structural incidents have been reported in the last eleven years.

3.2 Introduction

Accident types that are a potential threat to the WS ferries include *collisions, allisions, groundings* and *fires/explosion*s. The term allision is specific to the maritime area. Specifically, an allision is a collision with a fixed object, while the term collision is restricted to the striking of two vessels while underway. Collision have been discussed in detail in section 2. A grounding is a contact with the shore or bottom. The potential vulnerability to these accidents is determined by the internal factors described above and by factors external to the system, such as high levels of traffic congestion, the emergency coordination and response capabilities of external organizations, and the intentional or unintentional presence of hazardous materials on board.

An allision may occur on any docking of a ferry at a ferry terminal. In the following, a discussion is made of the historical occurrence of allisions examining the ferry classes and ferry terminals involved.

Since Washington State ferries operate in the deepest waters in the United States, grounding is not a major hazard on most routes. However, the likelihood of grounding is a concern in Rich Passage (Seattle/Bremerton route), at the Keystone Harbor entrance (Port Townsend/Keystone route), and on the San Juan Island routes.

The Washington State ferries meet all federal fire prevention and fire control standards. These standards are adequate to ensure a high probability of controlling a "routine" engine room, car deck, or galley fire. However, the ferries are vulnerable to an intentional (e.g. terrorist) or unintentional (e.g. illegal cargo) explosion on the car deck, or to a fire following a collision.

3.3 Allision Analysis Results

In the accident data for the period 1988-1998, there were 26 allisions of Washington State ferries. In two cases, the ferry terminal at which the allision occurred could not be determined. Figure 37 shows the occurrence of allisions over the period categorized by the class of ferry involved and the ferry terminal at which it occurred.

However, concluding from figure 37 that the ferry terminal/ferry class combinations for which allisions occurred are risky, is misleading. If a particular ferry class docks at a particular ferry terminal a large number of times then the number of allisions will be higher than for smaller numbers of dockings. Thus we must normalize this allision data by dividing by the number of dockings made in this period. The number of dockings was counted in the simulation.

Figure 38 shows the accidents per docking statistic for each ferry terminal and ferry class. It can be seen in figure 38 that the highest allision per docking rate are in order

- Issaquah class ferries at Orcas terminal
- Steel Electric class ferries at Lopez terminal
- Super class ferries at Anacortes terminal
- Passenger-only ferries at Vashon terminal
- Passenger-only ferries at Seattle terminal
- Issaquah class ferries at Bremerton terminal
- Steel Electric class ferries at Keystone terminal

It should be noted that the overall allision per docking is in the order of 1 in every 90,000 dockings and the highest rate for Issaquah class ferries at Orcas terminal is in the order of 1 in every 2500 dockings.

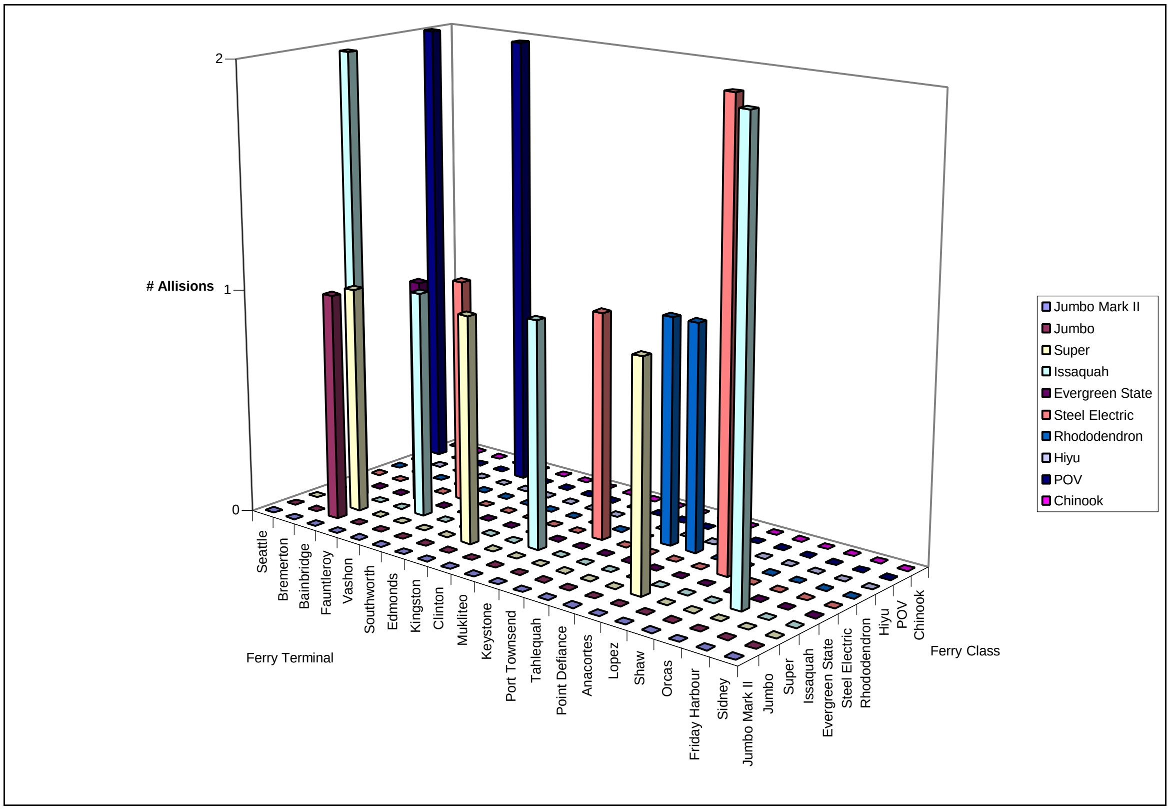


Figure 37. Allisions by ferry terminal and ferry class

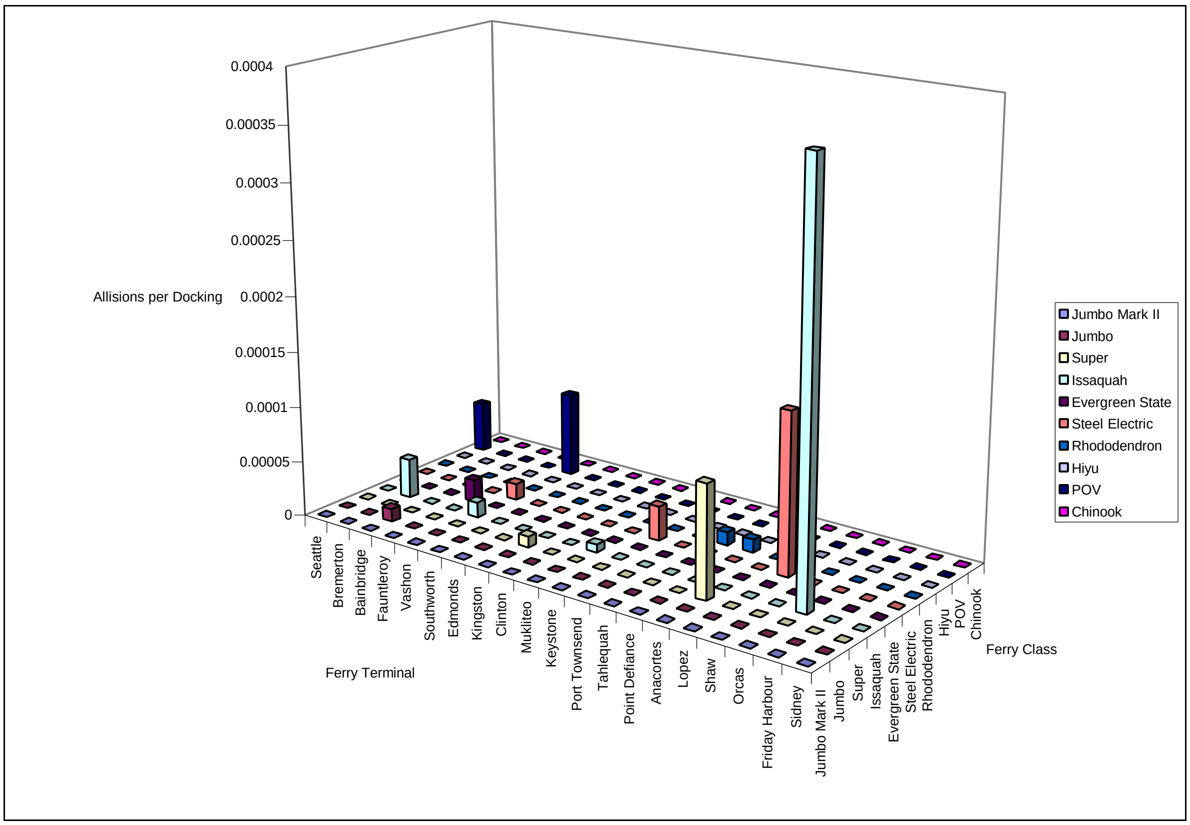


Figure 38. Allisions per docking by ferry terminal and ferry class

3.4 Grounding Analysis Results

In the accident data for the period 1988-1998, there were 6 groundings of Washington State ferries. 2 groundings occurred in the San Juan Islands (specifically Elwha Rock and Cattle Pass), 2 groundings occurred at Keystone Harbor, 1 grounding occurred in Rich Passage and 1 occurred at Vashon Island.

There are only certain geographical areas in the study area in which grounding accidents may occur. Groundings have occurred in each of these areas, referred to henceforth as grounding zones. However, we must, once again, be careful to normalize the grounding accidents. There will be more grounding accidents in a particular grounding zone if the ferries transit that area more frequently. Thus the time spent in each grounding zone was counted in the simulation and the grounding rate per hour calculated. Figure 39 shows the grounding rate per hour spent in each of the grounding zones.

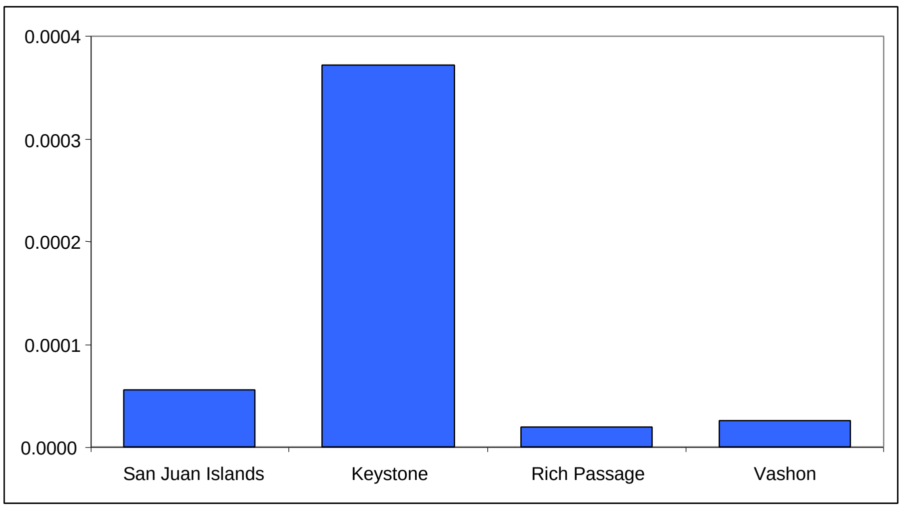


Figure 39. Grounding accidents per hour spent in grounding zone.

The total rate of groundings per operational hour spent in these grounding zones is 1 in every 22,000 operational hours. It is apparent that the entry into the terminal at Keystone leads to the highest grounding risk. The strong currents in Admiralty Bay make this approach difficult, leading to the high grounding rate. The strong tidal forces were listed as the primary cause for the two grounding accidents that occurred in the period 1988-1998. Washington State Ferries are aware of this problem and efforts are underway to improve the design of the terminal and improve operating procedures.

3.5 Fire / Explosion Analysis Results

In the accident data for the period 1988-1998, there were 9 fires / explosions on the Washington State ferries. Of these 9, 2 occurred on Evergreen State class ferries and 3 on the Issaquah class ferries. The other 4 occurred, one each, on the Hiyu, Jumbo, Steel Electric and Super class ferries. It should be noted that the single fire on the Super class ferry was actually on a motor home on board the ferry.

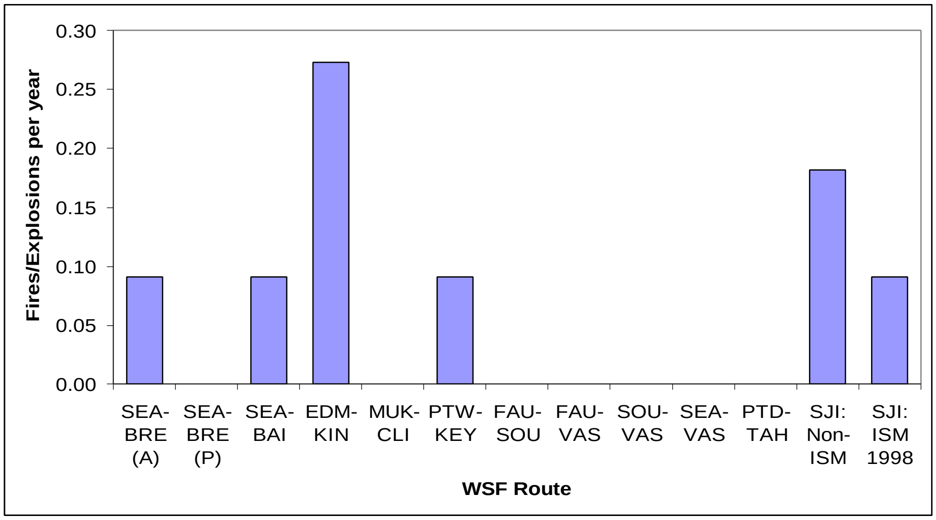


Figure 40. Fires / Explosions accidents per year by ferry route.

Of interest is the distribution of the occurrence of fires and explosions across the ferry routes. Figure 40 shows the historical rate of fires / explosions per year by ferry route. It can be seen that the most fires / explosions have occurred on the Edmonds-Kingston route and then the San Juan Islands routes.

The occurrence of fires / explosions can also be analyzed by ferry class and is exposure driven. Figure 41 shows the historical rate of occurrence normalized by the transit hours traveled over the period in which the data was collected.

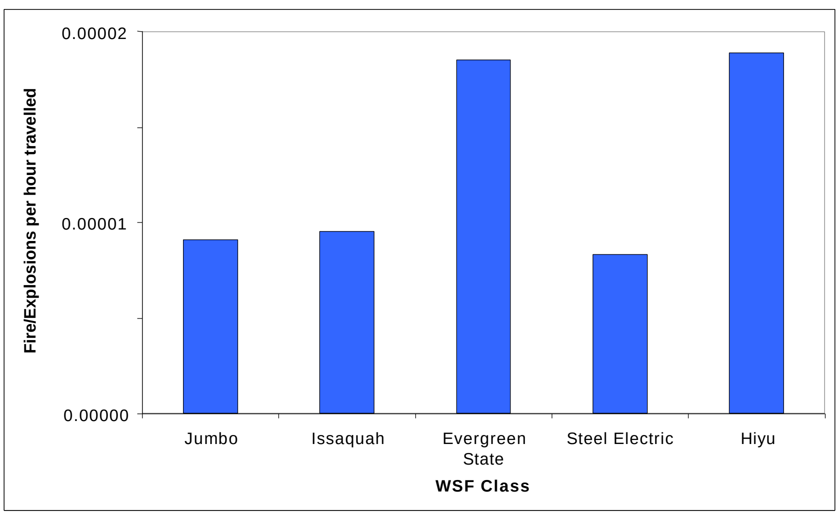


Figure 41. Fires / Explosions accidents per hour traveled.

The higher rates are observed on the Evergreen State class and the Hiyu. The two occurrences on the Evergreen State class were crank case explosions, while the single occurrence on the Hiyu was an electrical fire. Although the highest number of events was on the Issaquah class ferries, this is also the most highly used class.

Section 4: The Effect of Risk Reduction Interventions

4.1 Specific Findings from the Analysis in this Section

The following are specific findings from the Final Report that are justified by the results discussed in this section. The numbering of the findings is the same as that used in the final report to ensure tracability between the two documents.

Risk reduction interventions are required to maintain the current low likelihood of accidents and to reduce the potential consequences of accidents that could occur by increasing the effectiveness of emergency response.

23. The single most effective risk management intervention is the fleet wide implementation of the International Safety Management System (ISM). It is estimated that fleet wide implementation of ISM will reduce the potential rate of accidents by approximately 15%, offsetting the potential increase in risk due to the introduction of new ferries and routes. Funds for fleet wide implementation have been approved by the Washington State Legislature. ISM will reduce both the probability of accidents and the consequences if accidents do occur.

24. Reducing the occurrence of mechanical failures through appropriate improvements to the Washington State Ferries' maintenance policies, rules and procedures can lead to a proportional reduction in the number of accidents triggered by these incidents.

25. Due to the potential risk of an accident with an MRRT of less than 1 hour, the Washington State Ferries and the Coast Guard must be prepared to respond to a potentially catastrophic event requiring an immediate, coordinated response. Example scenarios are a collision of a high-speed ferry, a collision of an automobile ferry with a large, high-speed container vessel or an explosion. The planning, preparation, exercises and drills required to develop and maintain such a capability have been initiated and these efforts should be fully supported and expanded. ISM provides for enhanced crew training and qualifications for emergency procedures.

26. Policies and procedures that reduce nearby vessel interactions during periods of low visibility and high speed ferry operating procedures that reduce the number of nearby interactions with other vessels would be effective risk reduction interventions. The operational feasibility and cost of such procedures is difficult to evaluate since their impact is on service, not capital or operational budgets.

27. Although the statistical expected number of collision with an MRRT of less than 1 hour on the Port Townsend-Keystone and Haro Strait transits are low relative to other routes, the isolation of these routes from other Washington State ferries and US Coast Guard response equipment is a cause of concern. Vessels making the Haro Strait transit are subject to international conventions and currently carry survival craft adequate for all passengers. Ferries on the Pt. Townsend– Keystone run are not required by current Coast Guard regulations to carry 100% survival craft.

4.2 Risk Reduction Interventions

A maritime accident is not a single event, but the culmination of a series of events. The assessment framework used in this study differentiates between these triggering events (i.e. incident) and causal events (either basic or root causes). Triggering events were separated into mechanical failures and human errors. Thus there are multiple points at which interventions can be implemented to stop a possible precipitation of events along the accident chain. Figure 42 shows a taxonomy of risk interventions based upon the stage of the accident event chain at which the intervention takes effect.

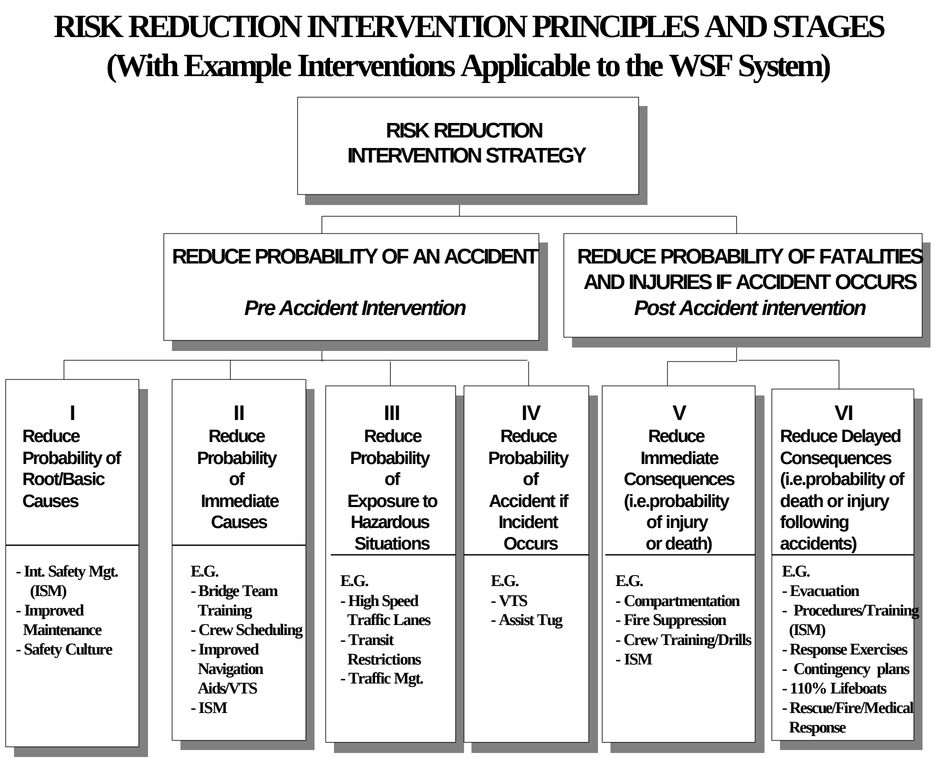


Figure 42. Intervening at different stages of the accident event chain

It is for this reason that the accident probability models used in this study reflect the accident event chain. The effect of risk interventions may be realistically modeled by reducing the frequency of events at various points in the model. Table 6 lists the risk interventions tested using the collision risk models. The descriptions of the changes inherent in each risk intervention are given along with the changes made in the models to estimate the reduction in risk.

Case 1 reflects the implementation of the Safety Management System (developed for the ISM requirements) fleet-wide. The effects of this risk reduction measure on the occurrence of human error and mechanical failure are discussed in section 2. It should be noted that Washington State Ferries have received approval and funding from the Washington State Legislature and the Washington State Transportation Commission for the fleet-wide implementation of the Safety Management System.

Table 6. Summary of Interventions Tested

	Scenario Desciption	Modification
Scenario 2	1 Chinook, 2 Jumbo Mark II	N/A
Risk Reduction Case 1	ISM Fleet Wide	Reduce Human Error by 30%, Reduce Mechanical Failure by 3.7%, Reduce Consequences by 10%
Risk Reduction Case 2	Implement all Human Error Reduction Measures Fleet Wide	Reduce Human Error Incidents by 30%, Reduce Mechanical Failure Incidents by 3.7%
Risk Reduction Case 3	Implement all Mechanical Failure Reduction Measures	Reduce Mechanical Failure Incidents by 50%
Risk Reduction Case 4	Implement High Speed Ferry Rules and Procedures	Reduce Human Error Incidents on High Speed Ferries by 30%, Reduce Mechanical Failure Incidents on High Speed Ferries by 3.7%
Risk Reduction Case 5	Impliment Visibility Restrictions	Reduce nearby vessel interactions in bad visibility conditions by 10%
Risk Reduction Case 6	Implement Traffic Separation for High Speed Ferries	Reduce Interactions with High Speed Ferries within one mile by 50%
Risk Reduction Case 7	Implement Traffic Control for Deep Draft Traffic	Set Maximum Allowable Traveling Speed in Admiral Inlet, Norther Puget Sound, Central Puget Sound, South Puget Sound at 15 knots.
Risk Reduction Case 8	Increase time available for Response	Allocate 50% of the Collisions in the MRRT 1-6 hour Category to the MRRT > 6 hour Category

Case 2 is a subset of case 1 reflecting only the reduction in human error related incidents. Case 4 is a combination of measures aimed at reducing the effect of mechanical failures. A variety of measures aimed reducing the risk introduced by the high-speed ferries are grouped as case 4. Case 5 models the effect of reducing interactions with commercial vessels in poor visibility conditions. Traffic separation procedures are implemented in case 6 for the high-speed ferries. In case 7, the speed of all commercial traffic in the Puget Sound is reduced to minimize the effect of collisions. Case 8 reflects the implementation of procedures to evacuate passengers to a safe haven in the event of collision with an MRRT of 1 to 6 hours.

The modifications in table 6 were programmed in to the collision risk models. Figure 43 shows the percentage reductions from Scenario 2 predicted by the collision risk models. The risk intervention cases are ordered from the most effective to the least effective in reducing the total statistical expected number of collisions. Also indicated in figure 43 is the % reduction in each MRRT category.

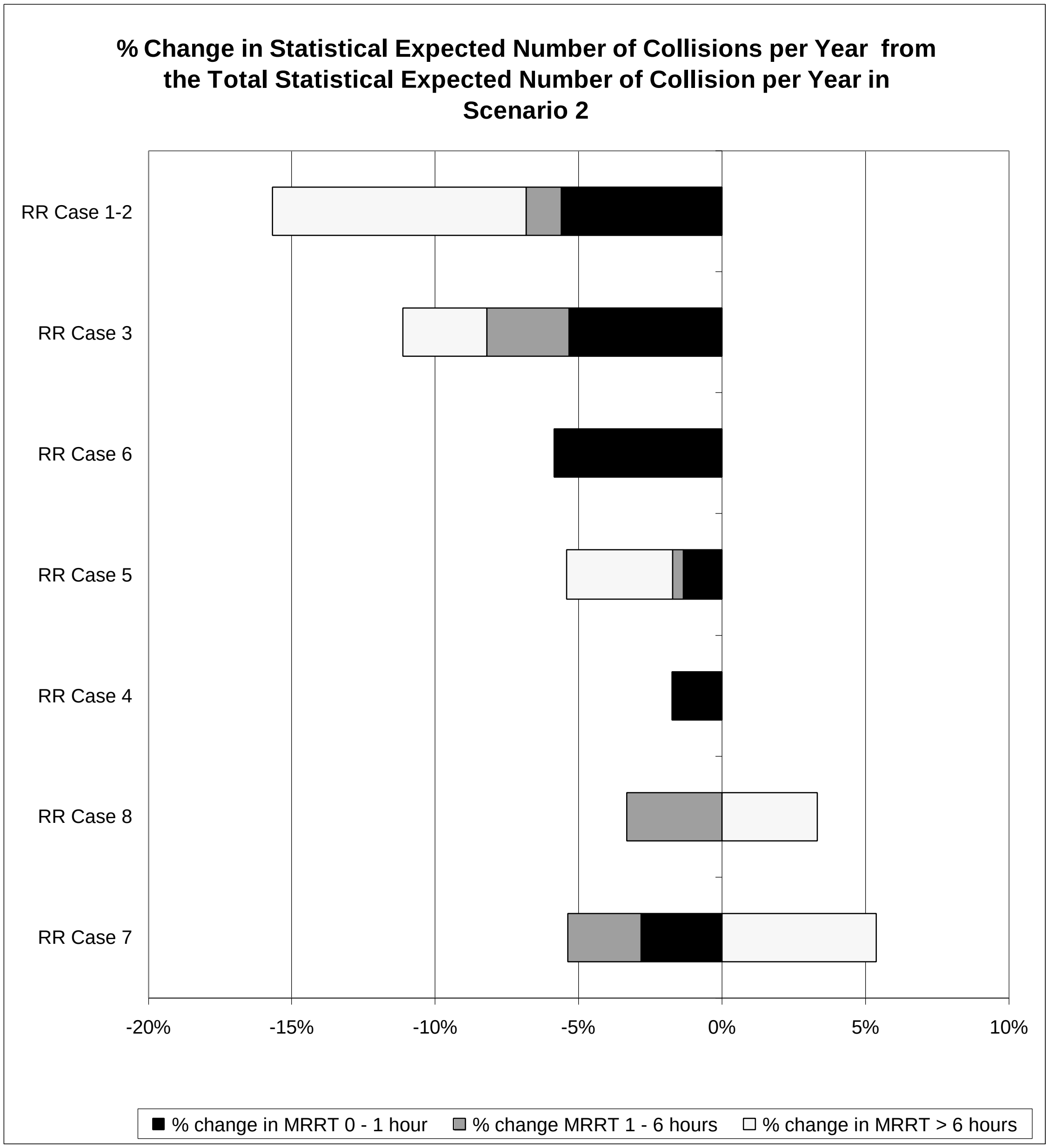


Figure 43. The Estimated Risk Reduction for the 8 Cases Tested.

Cases 1 and 2 have the largest risk reduction at 16%. These results reflect the implementation of ISM across the fleet. The only difference between the 2 cases is in the reduction of the consequences in case 1, an effect that is not shown in this result. There is a large reduction for both the less than 1 hour and the more than 6 hours MRRT categories.

Case 3, the implementation of mechanical failure reducing measures, is the next most effective at 11%. It can be seen that there is a large reduction in each MRRT category. Of note is the large reduction predicted for collisions with a MRRT of 1 to 6 hours.

The implementation of traffic separation rules for the high-speed ferries, case 6, causes a 6% reduction in the total statistical expected number of collisions. However, as this reduces the statistical expected number of collisions involving high-speed ferries, all this reduction is for collisions with an MRRT of less than 1 hour.

A 5% reduction in the total statistical expected number of collisions is predicted for the implementation of visibility restrictions, case 5. There is a 5% reduction in the statistical expected number of collisions in each MRRT category.

The implementation of high-speed ferry rules, case 4, decreases the total statistical expected number of collisions by 2%, with all the reduction being for collisions with an MRRT of less than 1 hour.

Case 8 is aimed at reducing the consequences if a collision occurs, not the probability of occurrence. This case reflects the implementation of procedures to evacuate passengers to a safe haven in the event of collision with an MRRT of 1 to 6 hours. This allows the external response to have an MRRT of more than 6 hours 50% of the time. The statistical expected number of collisions with an MRRT of 1 to 6 hours decreases by 3.3% compared to the total frequency of collisions under scenario 2. Of course this means that the statistical expected number of collisions with an MRRT of more than 6 hours increases by the same amount, so the total statistical expected number of collision does not change.

Reducing the speed of commercial vessels in the Puget Sound, case 7, also does not reduce the total statistical expected number of collision. However, the statistical expected numbers of collisions with a MRRT of less than 1 hour and a MRRT of 1 to 6 hours are both reduced, while the statistical expected number of collisions with an MRRT of more than 6 hours increases by the same amount.

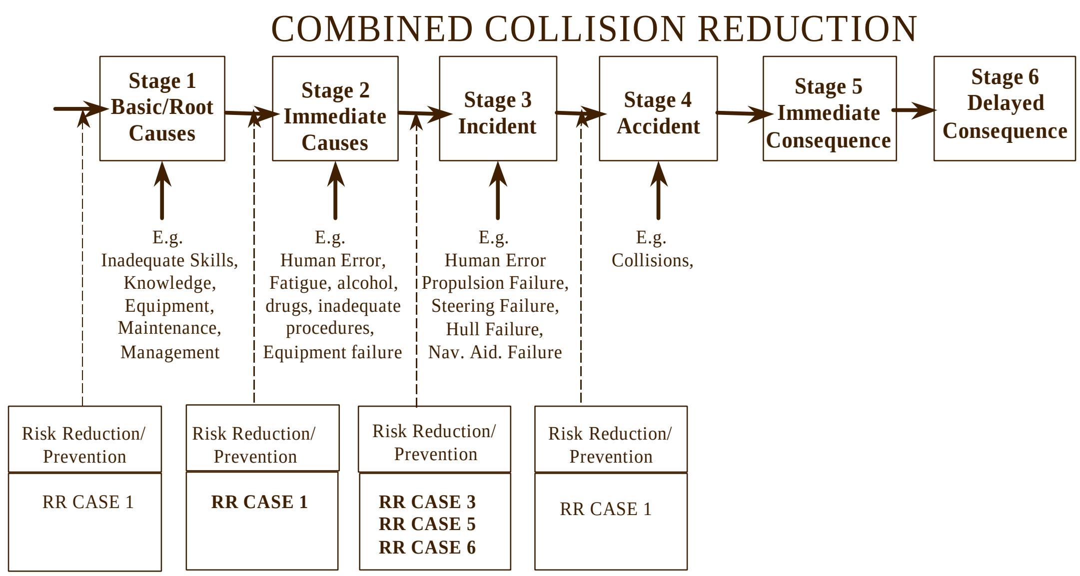
Table 7 summarizes the risk reduction results and gives the values for figure 43.

Figure 44 and Figure 45 contain analysis result in terms of risk reduction when intervening at different locations in the maritime causal chain. Figure 44 combines the risk reduction cases from table 6 that focus on accident prevention. Figure 45 combines the risk reduction cases from table 6 that focus on consequence reduction. From figure 44 follows that the total risk reduction in terms of total statistical frequency of collisions per year for the combined cases in figure 44 is 38% of which 16 % is a reduction of the statistical frequency of collisions in the less than one hour MRRT category. From figure 45 follows that the combined cases for risk reduction in figure 45 do not result in an overall risk reduction in terms of the total statistical frequency of collisions, but result in a re-distribution of this statistical frequency over the three MRRT categories. The re-distribution in figure 45 results in a 3% risk reduction in terms of the statistical frequency of collisions per year in the less than one hour MRRT category.

Table 7. Summary of % risk reductions

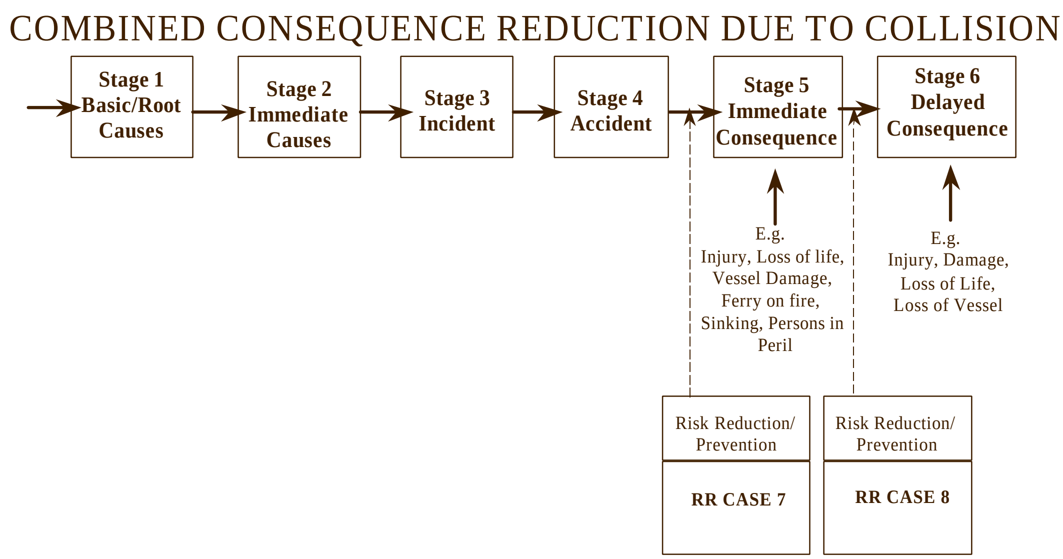
	Statistical Expected Number of Collisions per Year			
	MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
Scenario 2	0.055	0.015	0.152	0.223
Case 1-2	0.043	0.012	0.133	0.188
Case 3	0.043	0.008	0.146	0.198
Case 4	0.051	0.015	0.152	0.219
Case 5	0.052	0.014	0.144	0.211
Case 6	0.042	0.015	0.152	0.210
Case 7	0.049	0.009	0.164	0.223
Case 8	0.055	0.007	0.160	0.223

	Percent Change of Total Statistical Expected Collision per Year in Scenario 2			
	MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
Case 1-2	-6%	-1%	-9%	**-16%**
Case 3	-5%	-3%	-3%	**-11%**
Case 4	-2%	0%	0%	**-2%**
Case 5	-1%	0%	-4%	**-5%**
Case 6	-6%	0%	0%	**-6%**
Case 7	-3%	-3%	5%	**0%**
Case 8	0%	-3%	3%	**0%**



Percent Change of Total Statistical Expected Collision per Year in Scenario 2			
MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
-16%	-2%	-21%	-38%

Figure 44. Combined Risk Reduction for cases in Table 6 that focus on accident prevention.



Percent Change of Total Statistical Expected Collision per Year in Scenario 2			
MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
-3%	-5%	7%	0%

Figure 45. Combined risk reduction for cases in Table 6 that focus on consequence reduction.

Section 5: Uncertainty in Risk Assessment and Sensitivity Analysis

The rigorous analysis of the WSF Risk Assessment provides the basis both for determining that the system is currently operated in a safe manner, as compared to other transportation modes, and for identifying how the risk in the system could be reduced to even lower levels. The findings of a quantitative study must be interpreted with care, however, as uncertainty is introduced at various level of the analysis. Sources of this uncertainty include incomplete and/or inaccurate data, biased or uninformed expert judgment, modeling error and computational error. Testing for the level of uncertainty in an analysis requires accounting for both parameter uncertainty and model uncertainty and their impact on the results and conclusions. This is referred to as an uncertainty analysis.

While the use of proper procedures, such as rigorous data selection and cross validation, structured and proven elicitation methods for expert judgment and use of accepted models, can reduce uncertainty and bias in an analysis, it can never be fully eliminated. The reader should recognize that the value of an analysis is not only in the precision of the results, but is also in the understanding of the system. Of great value is the identification of peaks, patterns, unusual circumstances and trends in system risk and changes in system risk through risk mitigation measure implementation.

The methodology in this study has been reviewed for rigor and tested in operational settings. The methodology thus provides many safeguards to remove bias and to detect error. The general approach towards modeling assumptions in the WSF risk assessment was that of reasonableness rather than pursuing one worst case assumption after the other. The latter approach has been shown in multiple risk assessments to lead to highly unlikely and therefore less useful results. The approach of using reasonable assumptions rather than worst case assumptions is supported by leading scientists in the field of Risk Analysis (See for example, Dale Hattis and Elizabeth L. Anderson, *What should be the implications of uncertainty, variability, and inherent "biases"/"conservatism" for risk management decision making*, Journal of Risk Analysis, Vol. 19, No.1 1999, pp. 95-107).

Although a formal uncertainty analysis has not been presented within these results, sensitivity of the results to some of the more contentious modeling assumptions has been tested. Specifically, 9 sensitivity cases were analyzed and are summarized in table 8. All cases in table 8 are deviations from the 1998 case or scenario 2. The assumptions tested/challenged through the sensitivity cases in Table 8 are:

1. All collisions involving a high-speed ferry fall in the category of collision with a MRRT of 0-1 hour.
2. The vertical bow angle reduces the damage penetration below the waterline.
3. The horizontal bow angle for vessels in the WSF System is on average 66 degrees.
4. The collision speed for non-WSF vessels is 80% of the travelling speed and the collision speed WSF vessels is 50% of the travelling speed.
5. The Relative Depth Penetration (RDP =percentage damage penetration relative to the beam of the WSF-Ferry) threshold beyond which the RDP determines the distribution of collision over the three MRRT categories is 50%.

6. The Steel Electric Vessel has parts that satisfy one-compartment vessel characteristics and two compartment vessel characteristics.

Table 8. Sensitivity Cases Tested

Sensitivity Analysis Case	Modified Model/ Assumption	New Assumption
Sensitivity Case 1	Response Time Model – Case 1	50% MRRT 0-1, 50% MRRT 1-6 for Chinook
Sensitivity Case 2	Response Time Model – Case 2	33.33% for all MRRT Cases for Chinook
Sensitivity Case 3	Damage Model – Case 1	90 Degree Vertical Bow Angle for all Vessels
Sensitivity Case 4	Damage Model – Case 2	+ 10 Degrees Horizontal Bow Angle for all Vessels
Sensitivity Case 5	Damage Model – Case 3	- 10 Degrees Horizontal Bow Angle for all Vessels
Sensitivity Case 6	Damage Model – Case 4	Collision Speed = Traveling Speed
Sensitivity Case 7	Damage Model – Case 5	RDP Threshold = 40%
Sensitivity Case 8	Damage Model – Case 6	RDP Threshold = 60%
Sensitivity Case 9	Damage Model – Case 7	Steel Electric as a One Compartment Vessel

Assumption 1 was modified in Sensitivity Case 1 and in Sensitivity Case 2. In sensitivity Case 1 it is assumed that 50% of the collisions involving a Chinook fall in the less than one-hour MRRT category and 50% fall in the 1 to 6 hour MRRT category. In Sensitivity Case 2, assumption 1 has been modified such that all three MRRT categories are equally likely in case of a collision involving the Chinook. Both Sensitivity cases are more optimistic than assumption 1 as can be concluded from figure 46. Note that, the statistical frequency of collisions in the less than 1 hour MRRT category reduces by 9% in Sensitivity Case 2 and 7% in Sensitivity Case 1. Also note that combined percentage increase in statistical frequency of collisions in the 1 to 6 hour MRRT Category and more than 6 hour MRRT category equals the percentage reduction in the less than one hour MRRT category. In other words, the effect of the modified assumption is a redistribution of the total statistical frequency of collisions over the three different MRRT categories. The same observation can be made for all the other sensitivity cases as well.

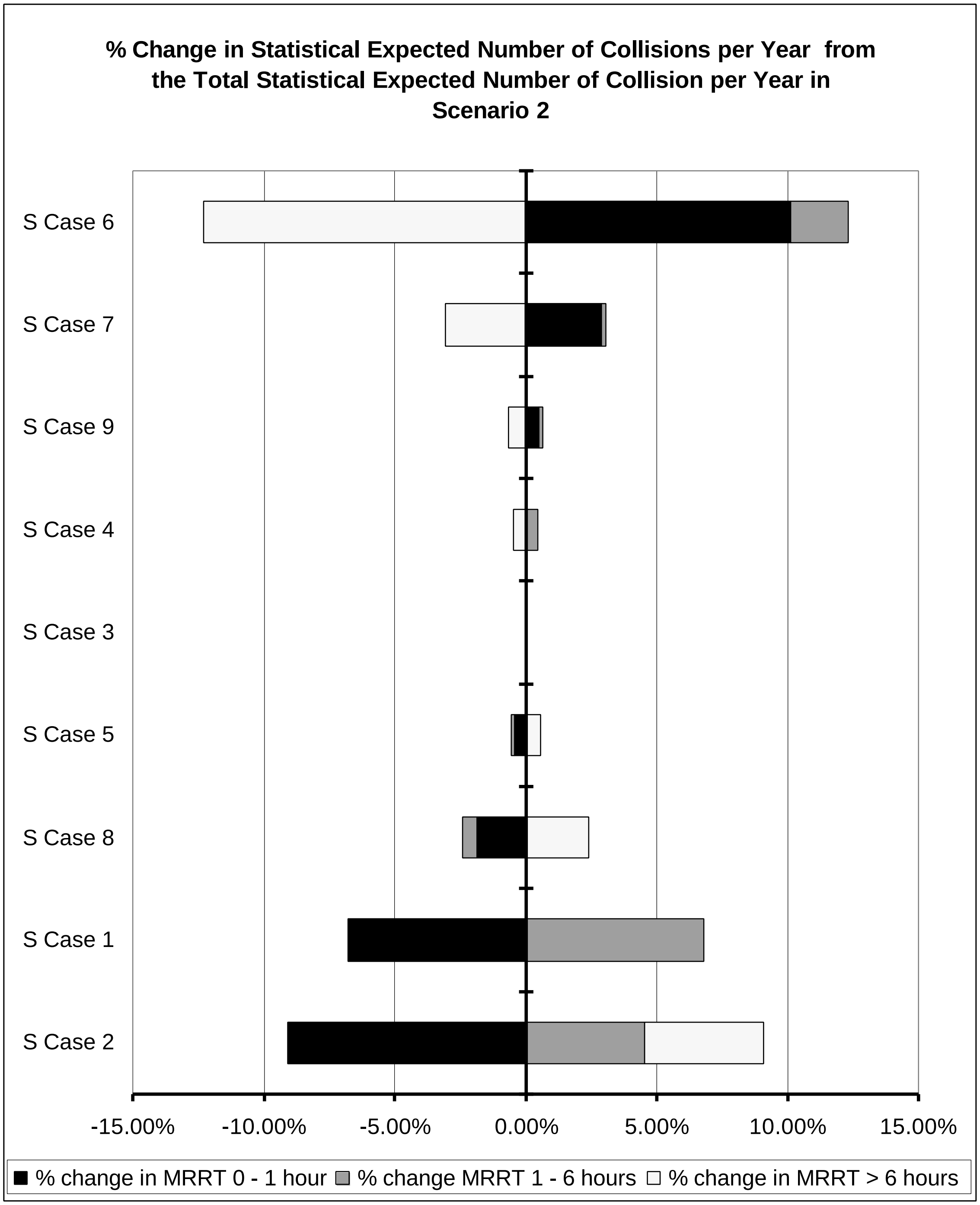


Figure 46. Sensitivity Analysis Results

Assumptions 2-5 and the associated sensitivity cases 2-9 are all sensitivity analyses on the damage model. Sensitivity Case 3 stands out, as the modified assumption does not have a noticeable effect on the distribution of the statistical frequency of collision over the three MRRT Categories. The explanation is that the calculated damage penetrations are large enough to cause damage below the waterline under scenario 2, such that the more conservative assumption of a 90 degree vertical bow angle does not have an noticeable effect.

Speed of the colliding vessel of the colliding vessel is a determining factor in the damage penetration model. Sensitivity Case 6 confirms that assertion by being the most sensitive of the cases tested in terms of percentage increase of the statistical frequency of collisions in the less than one hour MRRT Category. The assumption under scenario 2 was that for non-WSF vessels the collision speed equals 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 equals 50% of the traveling speed under scenario 2. 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. Again, the approach here was to use a reasonable assumption rather than a worst case assumption. The sensitivity analysis performed by Sensitivity Case 6 is to change the assumption concerning collision speed under scenario 2 to the worst case assumption, i.e. the collision speed of the colliding vessel equals the travelling speed both for WSF and non-WSF vessel.

Sensitivity Case 7 and Sensitivity Case 8 concern the assumption on the threshold of the Relative Depth Penetration (RDP = damage penetration/beam of the ferry) at which the distribution of the statistical frequency of collisions over the three MRRT categories is determined by the RDP rather than the number of bulkheads damaged below the waterline. Under Scenario 2, this threshold was set at 50%, which coincides with a penetration of half the beam of the ferry. Under Scenario 7, this threshold was set at 40% and resulted in an increase of the statistical frequency of collisions in the less than one-hour MRRT category of 3%. Under Scenario 8, this threshold was set at 60% and resulted in a decrease of the statistical frequency of collisions in the less than one-hour MRRT category of 2%.

Sensitivity Case 4, 5 result in a percent change in the statistical frequency of the collisions in the less than hour MRRT category of less than 1%. Sensitivity Case 4 and Sensitivity Case 5 increase, respectively decrease, the horizontal bow angle of a typical vessels in the WSF system by 10 degrees. The horizontal bow angle determines the damage width along the ferry given a particular damage penetration. The damage width in turn determines the number of bulkheads damaged below the waterline.

In Sensitivity Case 9, the steel electric vessel is treated as a one compartment vessel as opposed to being treated as a special case under scenario 2. In scenario 2, some parts of the steel electric vessel satisfy one compartment vessel characteristics and other parts satisfy two compartment vessel characteristics, as discussed in the modeling appendix. Even though the classification of the steel electric is an issue of debate between naval architect, it follows from the sensitivity analyses that the change in the distribution of the statistical frequency of collision over the three MRRT categories is relatively stable compared to Sensitivity Case 1, Sensitivity Case 2, Sensitivity Case 6, Sensitivity Case 7 and Sensitivity Case 8. The change in the statistical frequency of collisions in the less than 1-hour MRRT category is less than 1%.

For completeness, Table 9 contains the statistical frequency of collisions in the three MRRT categories for all sensitivity cases. Table 10 contains the statistical average return time between collisions in the three MRRT categories for all sensitivity cases.

Table 9. Statistical frequency of collisions for the sensitivity cases tested.

	Scenario Desciption	Modification	Statistical Frequency of Collisions per Year MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
Scenario 2	1 Chinook, 2 Jumbo Mark II	N/A	0.055	0.015	0.152	**0.223**
Sensitivity Case 1	Reponse Time Model Case 1	50% MRRT 0-1, 50% MRRT 1-6 for Chinook	0.040	0.030	0.152	**0.223**
Sensitivity Case 2	Reponse Time Model Case 2	33.33% for all MRRT Cases for Chinook	0.035	0.025	0.163	**0.223**
Sensitivity Case 3	Damage Model Sensitivity - Case 1	90 Degree Vertical Bow Angle for all Vessels	0.055	0.015	0.152	**0.223**
Sensitivity Case 4	Damage Model Sensitivity - Case 2	+ 10 Degrees Horizontal Bow Angle for all Vessels	0.056	0.016	0.151	**0.223**
Sensitivity Case 5	Damage Model Sensitivity - Case 3	- 10 Degrees Horizontal Bow Angle for all Vessels	0.054	0.015	0.154	**0.223**
Sensitivity Case 6	Damage Model Sensitivity - Case 4	Collision Speed = Traveling Speed	0.078	0.020	0.125	**0.223**
Sensitivity Case 7	Damage Model Sensitivity - Case 5	RDP Threshold = 40%	0.062	0.015	0.146	**0.223**
Sensitivity Case 8	Damage Model Sensitivity - Case 6	RDP Threshold = 60%	0.051	0.014	0.158	**0.223**
Sensitivity Case 9	Damage Model Sensitivity - Case 7	Steel Electric as a one compartment vessel	0.057	0.015	0.151	**0.223**
		Min Change	**0.078**	**0.030**	**0.163**	**0.223**
		Max Change	**0.035**	**0.014**	**0.125**	**0.223**

Table 10. Average return times between collision for the sensitivity cases tested.

	Scenario Desciption		Average Time between Collissions (in Years) MRRT 0-1	MRRT 1-6	MRRT>6	TOTAL
Scenario 2	1 Chinook, 2 Jumbo Mark II	N/A	18.1	67.5	6.6	**-100.0%**
Sensitivity Case 1	Reponse Time Model Case 1	50% MRRT 0-1, 50% MRRT 1-6 for Chinook	24.9	33.3	6.6	**4.5**
Sensitivity Case 2	Reponse Time Model Case 2	33.33% for all MRRT Cases for Chinook	28.5	40.1	6.2	**4.5**
Sensitivity Case 3	Damage Model Sensitivity - Case 1	90 Degree Vertical Bow Angle for all Vessels	18.1	67.5	6.6	**4.5**
Sensitivity Case 4	Damage Model Sensitivity - Case 2	+ 10 Degrees Horizontal Bow Angle for all Vessels	18.0	63.5	6.6	**4.5**
Sensitivity Case 5	Damage Model Sensitivity - Case 3	- 10 Degrees Horizontal Bow Angle for all Vessels	18.4	68.8	6.5	**4.5**
Sensitivity Case 6	Damage Model Sensitivity - Case 4	Collision Speed = Traveling Speed	12.8	50.7	8.0	**4.5**
Sensitivity Case 7	Damage Model Sensitivity - Case 5	RDP Threshold = 40%	16.2	65.7	6.9	**4.5**
Sensitivity Case 8	Damage Model Sensitivity - Case 6	RDP Threshold = 60%	19.5	73.3	6.3	**4.5**
Sensitivity Case 9	Damage Model Sensitivity - Case 7	Steel Electric as a one compartment vessel	17.7	66.1	6.6	**4.5**
		Min Change	**28.5**	**73.3**	**8.0**	**4.5**
		Max Change	**12.8**	**33.3**	**6.2**	**4.5**

It can be concluded from Table 9 and Table 10 that the results for all sensitivity cases remain within the same order of magnitude and may considered to be robust relative to the changes in the modeling assumptions in the 9 sensitivity cases.

Figure 47, Figure 48 and Figure 49 summarize the collision analysis by ferry route for Scenario 2 and the most extreme cases in terms of sensitivity, i.e. Sensitivity Case 2 and Sensitivity Case 6. Comparing Figure 47 and Figure 48, it can be observed that the statistical frequency of collisions in the less than hour MRRT category has primarily reduced on the Seattle Bremerton Passenger Ferries, Seattle Bremerton Car Ferries, The Seattle Bainbridge ferries. However, the predominant WSF Ferry Routes in terms of the statistical frequency of collisions in the less than one hour MRRT category are the same under scenario 2 and sensitivity case 2. Comparing Figure 47 and Figure 49, it can be observed that the statistical frequency of collisions in the less than hour MRRT category has increased most noticeably on the on the Seattle Bremerton Passenger Ferries, Seattle Vashon Ferries. However, the predominant WSF Ferry Routes in terms of the statistical frequency of collisions in the less than one hour MRRT category are the same under scenario 2 and sensitivity case 9. Similar conclusions can be drawn when analyzing these results for the other sensitivity cases as well.

The conclusions and recommendations in the final report are driven by the distribution of the statistical frequency of collisions in total and over the three MRRT categories. Based on the results of the sensitivity analysis described in this section, it is concluded that the conclusions and recommendations are robust relative to the modifed assumptions tested in the 9 sensitivity cases.

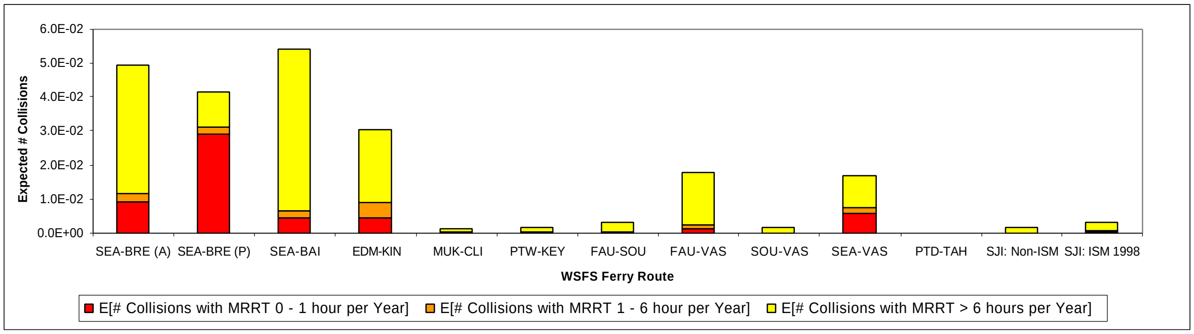


Figure 47. Distribution of Statistical Frequency of Collisions over the three MRRT Categories by Ferry Route – Scenario 2

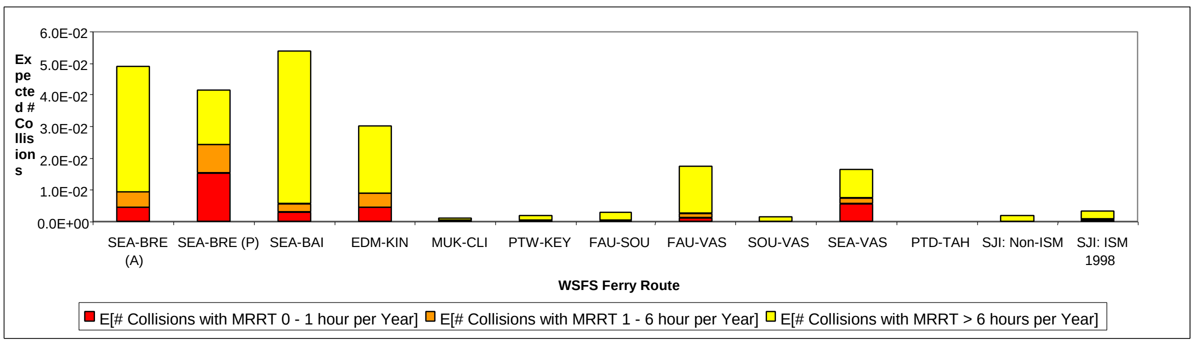


Figure 48. Distribution of Statistical Frequency of Collisions over the three MRRT Categories by Ferry Route – Sensitivity Case 2

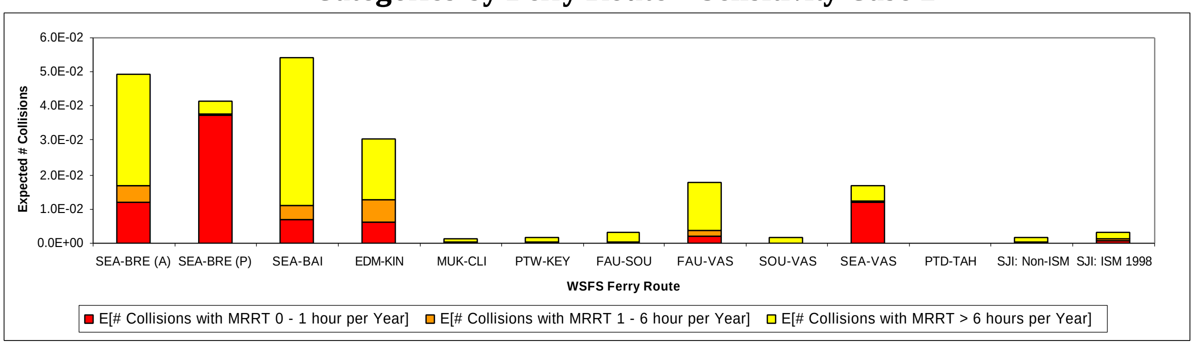


Figure 49. Distribution of Statistical Frequency of Collisions over the three MRRT Categories by Ferry Route – Sensitivity Case 6

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