A Risk Management Procedure for the Washington State Ferries

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The state of Washington operates the largest passenger vessel ferry system in the United States. In part due to the introduction of high-speed ferries, the state of Washington established an independent blue-ribbon panel to assess the adequacy of requirements for passenger and crew safety aboard the Washington state ferries. On July 9, 1998, the Blue Ribbon Panel on Washington State Ferry Safety engaged a consultant team from The George Washington University and Rensselaer Polytechnic Institute/Le Moyne College to assess the adequacy of passenger and crew safety in the Washington state ferry (WSF) system, to evaluate the level of risk present in the WSF system, and to develop recommendations for prioritized risk reduction measures, which, once implemented, can improve the level of safety in the WSF system. The probability of ferry collisions in the WSF system was assessed using a dynamic simulation methodology that extends the scope of available data with expert judgment. The potential consequences of collisions were modeled in order to determine the requirements for onboard and external emergency response procedures and equipment. The methodology was used to evaluate potential risk reduction measures and to make detailed risk management recommendations to the blue-ribbon panel and the Washington State Transportation Commission.

KEY WORDS: Maritime risk assessment; system simulation; expert judgment

1. INTRODUCTION

The Washington state ferry (henceforth WSF) system is the largest ferry system in the United States. In 1997, total ridership for the ferries serving the central Puget Sound region was nearly 23 million, a 4% increase over 1996 ridership, and more passengers than Amtrak, the U.S. passenger rail carrier, handles in a year. The state of Washington instituted the ferry system in 1951 to connect King and Snohomish Counties with

Kitsap County, saving travelers the long drive around Puget Sound via the Tacoma Narrows Bridge, and to provide mainland access to Vashon Island and Whidbey Island. Prior to 1951 private ferry system(s) offered these services. Figure 1 shows the current ferry routes for the central Puget Sound region. This map illustrates the ferry system's role in linking together the Washington state highway system in the Puget Sound region.[1]

Though to date the Washington state ferries have had an exceptional safety record, the WSF system is facing a number of important changes. First, its regulatory environment, which has been relatively inactive, has changed significantly with the implementation of 46 C.F.R. 199, Subchapter W, of the Code of Federal Regulations, Lifesaving Systems for Certain Inspected Vessels.[2] The WSF system is required by these regulations to address the response to cata-

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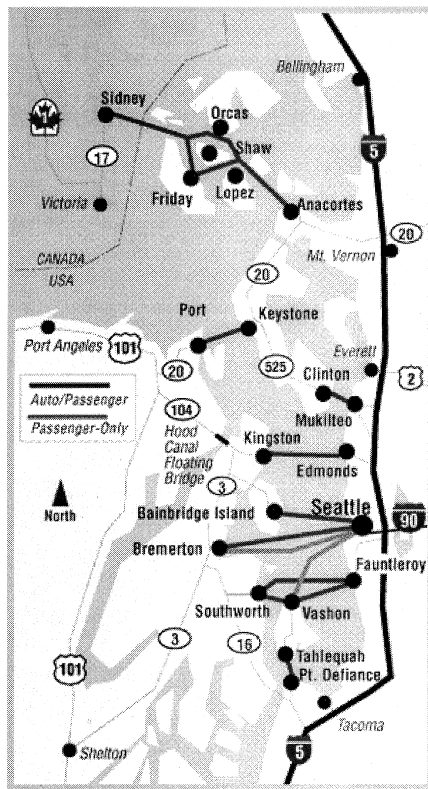
Fig. 1. Washington state ferry system map.

strophic accidents and the requirements for ensuring that passengers could survive such accidents. Specifically, the regulations require the WSF system, within 5 years, either to equip all ferries with adequate survival craft or to provide a safety assessment, a comprehensive shipboard safety management system, and shipboard contingency plans approved by the U.S. Coast Guard (USCG), the U.S. regulatory body for maritime affairs.

A second set of changes in the WSF system stems from pressures to develop a seamless, intermodal transportation system in Washington state in the face of simultaneous increases in the volume and mix of riders on the ferries. Because increasing numbers of Washington state residents are riding the ferries to work, and because connections to other transportation modes (bus, bicycle, car) from the ferries are critical to the success of such an intermodal system, the WSF system is under increased pressure to perform in ways different from those of the past, to measure and report its performance in different ways, and to increase the fluidity with which connections to other transportation modes are made from the ferries.

A third set of changes in the WSF system stems from new technology, for example, high-speed ferries, being introduced into the system to address some pressures for faster transport–passenger-only ferries. These new technologies are being introduced into an aging fleet with some consideration given for how best to mix new and old vessels, new and old technology, new and old operational dynamics, and varying degrees of sophisticated automation. In addition, the International Maritime Organization (IMO) has enacted implementation of the Standards for Training and Certification of Watchkeeping (STCW)[3] for all vessels above 200 gross tons (GT) and has begun the process of developing a high-speed code for vessels. To date the WSF has been exempt from STCW requirements and is in full compliance with all prevention regulations. The focus on high-speed ferries could change this status.

In light of these changes, the state of Washington established the independent Blue Ribbon Panel on Washington State Ferry Safety to assess the adequacy of requirements for passenger and crew safety aboard the Washington state ferries. On July 9, 1998, the panel engaged a consultant team from The George Washington University and Rensselaer Polytechnic Institute/Le Moyne College to assess the adequacy of passenger and crew safety in the WSF system, to evaluate the level of risk present in the WSF system, and to develop recommendations for prioritized risk reduction measures, which, once implemented, can improve the level of safety in the WSF system.

This article provides a discussion of (1) a framework for risk assessment and risk management of maritime transportation systems, (2) an overview of the modeling approach used in the WSF risk assessment, (3) an overview of WSF baseline risk assessment results, (4) WSF risk intervention evaluation results, and (5) recommendations to the panel and the Washington State Transportation Commission.

2. A FRAMEWORK FOR RISK ASSESSMENT AND MANAGEMENT

In order to evaluate proposed risk interventions, one must first define a measure of risk. Risk is often defined by combining the likelihood of an undesirable event and relevant consequences in a single quantitative measure. For example, consequences may include injury, loss of life, or economic losses. It is also possible to define some surrogate measure of risk that indirectly accounts for such attributes. Next, one needs to understand the events and situations that lead to
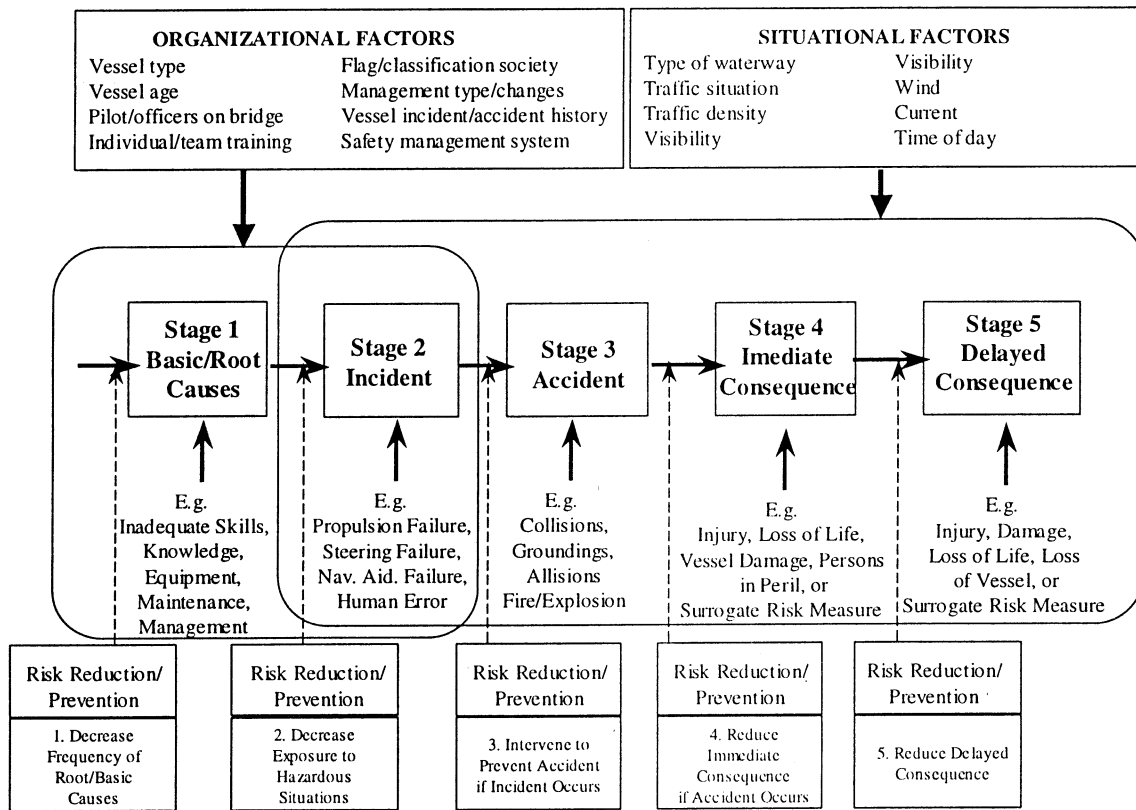
Fig. 2. The maritime accident event chain.

the undesirable event and the impact of proposed risk interventions on these events and situations. Figure 2 shows the maritime risk taxonomy used by the study team and illustrates the importance of organizational and situational factors in both the occurrence and severity of an accident.

In addition, Fig. 2 identifies five categories of risk interventions based on intended impact on the accident event chain. Three categories of impact intend to reduce the likelihood of occurrence of accidents and two categories of impact intend to reduce the consequences of accidents that could occur. Note that a single risk intervention may belong to multiple impact categories.

The objective of risk management is to structure, evaluate, rank, and implement policies and procedures that reduce the threat to life, property, the environment or all of the above posed by hazards. The structuring and evaluation of risk management alternatives/risk interventions herein is based on a multistep process. The first step is to define a quantitative measure of risk. In this study a surrogate consequence measure was defined focusing on response time alternatives as required by Subchapter W while

addressing risk communication concerns of the blue-ribbon panel in terms of providing the results to the public. This surrogate measure will be introduced in Section 3.1. The second step is to identify potential risk interventions and determine their impact on the accident event chain (see, for example, Fig. 2). The third step is to develop a comprehensive quantitative model for comparing the risk interventions in a meaningful manner. The fourth step is to establish a baseline level of risk by defining a baseline scenario and using the developed model to quantify its risk. Additional risk intervention measures may be identified by focusing on high-risk contributors to the baseline level of risk. The fifth step is to model the effect of all the risk interventions in terms of changes to model parameters. The final step is to implement these changes to the model and evaluate the risk interventions relative to the established baseline level of risk.

The ranking and implementation of risk interventions involves assessment of tradeoffs of risk reduction with respect to other measures of interest, such as cost, implementation time, and political acceptability. While this was an important part of the

WSF risk assessment, the ranking and implementation is not a topic discussed further in this article. Rather, the focus is on the assessment of baseline risk and the evaluation of risk interventions.

3. RISK INTERVENTION MODELING IN THE WSF SYSTEM

The six-step process used for structuring and evaluating risk interventions in the WSF risk assessment will be discussed in the sections below.

3.1. Defining Risk for the WSF System

The focus of this study was on passenger safety, including consideration of both the probability of occurrence and the severity of consequence of accidents. Accident types that are a potential threat to the Washington state ferries include collisions (or striking of another vessel), fires or explosions, allisions (or striking of a fixed object), and groundings (or strandings). The potential vulnerability to these accidents is determined by the internal factors previously described 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.

The consequence evaluation focused on defining the appropriate accident response alternatives as required by Subchapter W. Hence, the risk analysis focused solely on WSF passengers. Accidents with vessels not putting WSF passengers in peril were not considered in the study. A measure termed "Maximum required response time" (MRRT) was developed as a surrogate measure for 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 categories of MRRT were deemed appropriate: less than 1 hr, between 1 and 6 hr, and greater than 6 hr. In conjunction with the consulting team, the blue-ribbon panel judged that accidents in the first category primarily require an effective external emergency response, for example, other ferries or vessels, to prevent additional injuries or fatalities since the time would probably not permit in-time launching of survival craft. For accidents in the second category, time is available for evacuation to a safe haven. In order to meet Subchapter W requirements, the WSF system must demonstrate the ability to mobilize evacuation vessels or plan to provide sur-

vival craft adequate for all passengers. For accidents in the third category, adequate response in all cases can be provided without evacuating the passengers from the ferry. Of course, in any accident it is desirable to respond in the shortest amount of time possible. The MRRT measure merely provides an upper bound on the desirable response time.

Historical records for all accident events involving Washington state ferries were collected for an 11-year period and analyzed. Fire and explosions were limited, historically, to stack fires that were contained while under way. Allisions were incidents occurring at the dock and led primarily to property damage and not casualties or injuries as the impact speeds were low. Groundings occurred at shallow areas with small tide fluctuations. In each case, the ferry involved remained a stable, safe platform for the passengers until an orderly evacuation was performed. There were two collisions in an 11-year period of accident data. In each collision, the ferry was able to return to dock and safely disembark the passengers. Summarizing, the Washington state ferries have a commendable safety record in terms of casualties and injuries, with no fatalities.

Potential accident scenarios that could lead to high consequences in injuries and fatalities were, however, developed in conjunction with the Blue Ribbon Panel on Washington State Ferry Safety. Specifically, collisions involving high-speed ferries, collisions between ferries and deep-draft vessels, and acts of intentional fire/explosion were deemed to be events that could possibly fall in the 1–6 hr MRRT and less than 1 hr MRRT categories. Due to the sensitivity of acts of intentional fire/explosion, the panel decided that it was not appropriate to discuss the vulnerability to these acts in the open public forum of the WSF risk assessment. Based on the characteristics of the WSF system, allisions and groundings were judged by the project team, in conjunction with maritime experts, to fall in the more than 6 hr MRRT category. The blue-ribbon panel accepted this assumption. Hence, the main focus was the development of models for collision risk estimating the frequency of collisions and their associated consequences in terms of the three MRRT categories identified.

3.2. Identification and Structuring of Risk Interventions

In the WSF risk assessment, the project team collected a total of 40 risk reduction measures that had been proposed for this system and for other maritime systems, and structured the measures. The

Table I. Summary of Risk Interventions Classes Tested

Risk reduction class	Intervention
1	Adopt international safety management standard fleetwide
2	Implement all mechanical failure reduction measures fleetwide
3	Implement high-speed ferry rules and procedures
4	Implement weather, visibility restrictions
5	Implement traffic separation for high-speed ferries
6	Implement traffic control for deep-draft traffic
7	Increase time available for response

sources of these measures were (1) interviews with ferry system and U.S. Coast Guard personnel, (2) the Revision of the HSC Code, Formal Safety Assessment of High Speed Catamaran (HSC) Ferries Submitted by the United Kingdom,[4] (3) the *Final Report: Prince William Sound Risk Assessment*,[5] (4) Scoping Risk Assessment, Protection against Oil Spills in the Maritime Waters of Northwest Washington State,[6] and (5) alternatives specified in 46 CFR 199, Subchapter W. The 40 risk reduction measures were synthesized to seven classes of risk reduction measures, listed in Table I. The intended impact of these classes on the causal chain of Fig. 2 is displayed in Fig. 3. Note that some classes intervene at multiple points in the accident event chain.

3.3. An Overview of the Modeling Approach for WSF System Collision Risk

The situational and organizational factors, indicated in Fig. 2, that influence the probability of occurrence of events in the causal chain lead to dynamic fluctuations in system collision risk. Identifying how and when these risk spikes occur is a fundamental objective of the use of dynamic system simulation as a risk assessment methodology. As an example of the contribution of situational factors to collision risk, it is clear that a ferry traveling on a clear day with no other traffic nearby is at lower risk than a ferry in foggy conditions with many other vessels nearby. Modeling the contribution of risk factors asks for a quantitative evaluation of collision risk in both situations, that is, how much more risky the first situation is compared to the other. In the WSF risk assessment, a constructive modeling approach combining system simulation, expert judgement, and available data was used to allow for estimation of the contribution of these situational and organizational factors to collision risk.

A specific combination of situational and organizational factors in a given time point for a specific ferry is an opportunity for incident (OFI). Thus each OFI consists of variables that may be considered contributing risk factors. The risk factors considered in the WSF risk assessment are listed in Table II. Modeling the system in terms of the factors in Table II, re-
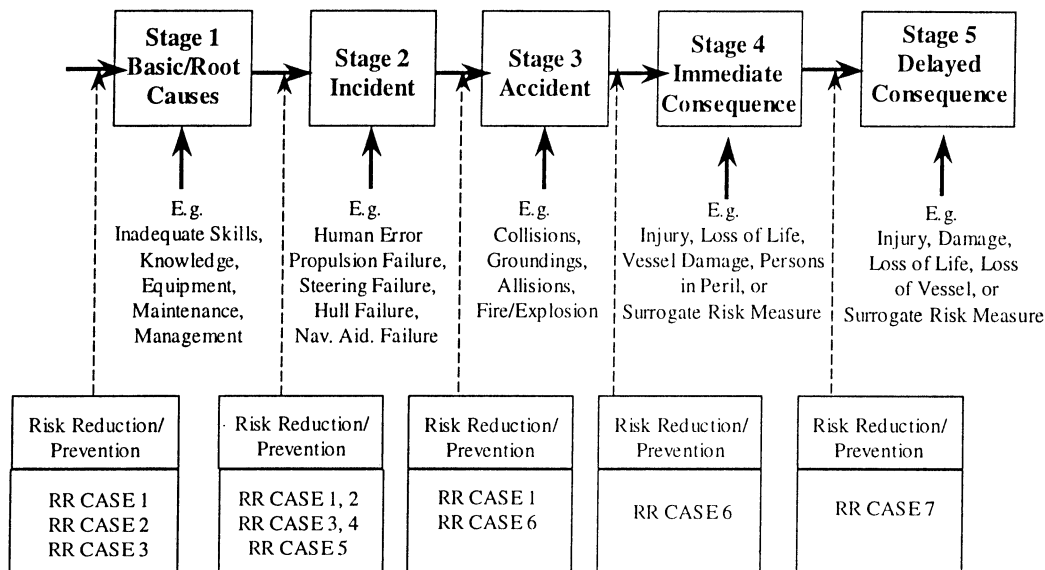

Fig. 3. Impact of risk reduction classes on the causal chain. RR = risk reduction.

Variable name	Possible values
Ferry route	Seattle-Bremerton, Anacortes-Sidney, etc.
Ferry class	Issaquah, Jumbo, Chinook, etc.
Interacting vessel type	Container, bulk carriers, other ferries, etc.
Type of interaction	Crossing, meeting, overtaking
Proximity of interacting vessel	Less than 1 mile, from 1 to 5 miles
Wind speed	0 knots, 10 knots, 20 knots
Wind direction	Perpendicular to ferry, along ferry
Visibility	Less than 0.5 mile, more than 0.5 mile

quires extensive collection of traffic and weather data. Traffic data are available from the USCG logging arrivals of deep-draft vessels to the Puget Sound area. Ferry schedules are published by the Washington State Ferry Service. Weather data was obtained from the National Oceanic and Atmospheric Administration (NOAA) and local airport data. A visibility model was created using a land visibility model developed with local airport data and a sea visibility model using dew point temperature data and water temperature data from NOAA weather buoys.

Traffic data in terms of annual statistics alone cannot be used to infer how often interactions between these vessels occur and in what conditions. Thus, a simulation of the WSF system was built to represent the movement of the Washington state ferries, the movement of other vessels in the area, and the environmental conditions at any given time. Figure 4 gives a screen capture of the WSF system simulation capturing the southern Puget Sound area and central Puget Sound Area. Figure 4 displays (1) ferry routes in central Puget Sound, (2) two wind fans modeling direction and strength in the central Puget Sound and southern Puget Sound regions, (3) bad-visibility conditions (less than 0.5 miles) in southern Puget Sound, and (4) good visibility in central Puget Sound.

Using this simulation, a counting model was developed that observed and recorded snapshots of the study area at regular intervals and counted the occurrences of the various OFIs in terms of the variables displayed in Table II. The simulation is called the OFI generator and the counting model is called the OFI counter. Using the OFI counter, summary statistics on, for example, the number of OFIs involving crossing situations of a high-speed ferry and a container vessel on the Seattle Bremerton route in bad visibility conditions can be analyzed. The next step is

to assess the likelihood of triggering incidents and collisions given the risk factors in Table II.

The preferred method for estimating these probabilities is through data. Accident database information is typically limited, however, to accident and immediate-consequence data, as indicated by Fig. 5. For evaluation of the risk intervention measures impacting early on in the causal chain, the assessment of probabilities in the beginning of the causal chain is required. The assessment of incident probabilities leading to an accident, however, is often not supported by available data in accident and consequence databases. Cooke[7] cites the use of expert judgment in areas as diverse as aerospace programs, military intelligence, nuclear engineering, evaluation of seismic risk, weather forecasting, economic and business forecasting, and policy analysis. Paté-Cornell[8] discusses the necessity of using expert judgment when sufficient data are not available, and Harrald, Mazzuchi, and Stone[9] proposed the use of expert judgment in the analysis of risk in maritime environments.

In the WSF risk assessment, the average likelihood of system events along the maritime accident event chain was estimated using both historical data and expert judgment. A database containing 11 years of incident, accident, and transit data for Puget Sound and the inland waters of the state of Washington was created for this project, reconciling USCG, state of Washington, Marine Exchange, U.S. Army Corps of Engineers, and ferry system databases through rigorous data selection and cross validation. Expert judgment was obtained from WSF captains, USCG personnel, and members of the Puget Sound Pilots Association using elicitation methods based on pairwise comparisons of OFIs. The expert judgment was combined with and calibrated to the accident and incident data available and was used to model the effect of the variables in Table II on the accident and incident probabilities. Figure 6 summarizes the use of the different modeling techniques to establish collision frequencies.

The final step in modeling the maritime accident event chain is consequence modeling. Engineering models of collision impact damage scenarios were used to assess the damage to each ferry class in various collision scenarios. The damage model follows the method of Minorsky.[10] The Minorsky method determines damage size as a function of the collision energy, the colliding-vessel bow angle, and the effective deck thickness of the Washington state ferries. The collision energy is calculated using the masses of both the struck ship (ferry) and the striking ship. The dam-
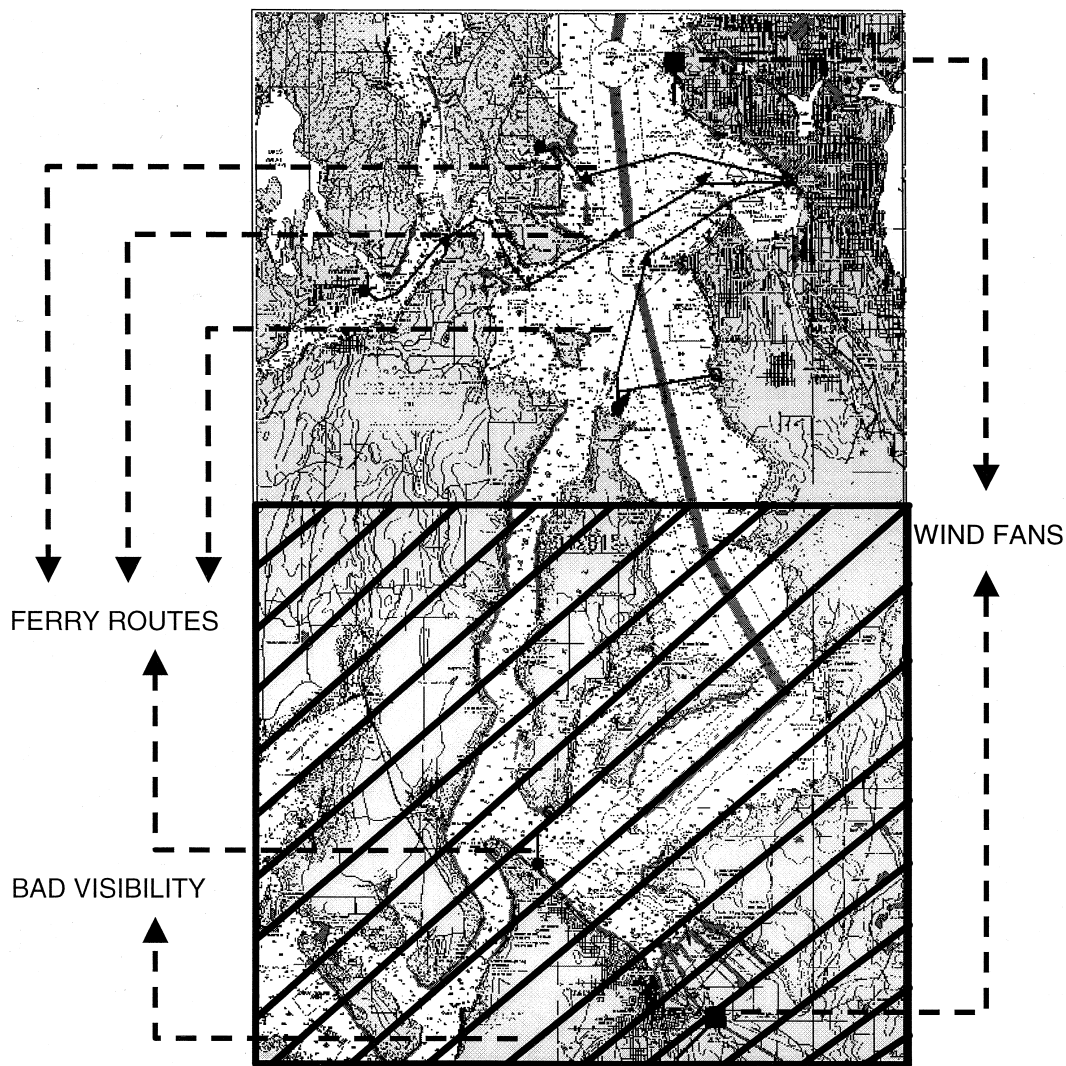
Fig. 4. Screen capture of the Washington state ferry system simulation.

age calculation results in a damage penetration along the waterline (DP_w) and damage width (DW) for every collision scenario. Figure 7 illustrates the importance of location of impact, angle of impact, and horizontal bow angle (α) in these calculations.

To establish the distribution over the three MRRT categories given calculated damage, a response time model was developed. Structural plans of the ferries were used to estimate the damage to bulkheads given calculated damage width and penetration. In case of damage below the waterline of the ferry and damage of enough bulkheads, flooding of multiple compartments of the ferry is possible.

To help address the response time question given the potential flooding of multiple compartments, the concept of MRRT is used. 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. If the possible number of flooded compartments is higher than the design limit, the MRRT may be judged to be short. The analysis was conducted for each possible class of striking vessel and each possible class of ferry in order to determine MRRT categories for each possible collision scenario.

Readers interested in a more in-depth discussion of the modeling approach—for example, the treatment of the expert-judgment elicitation procedure and subsequent analysis—are referred to Technical Appendix III of Harrald, van Dorp, Mazzuchi, Merrick, and Grabowski.[11]
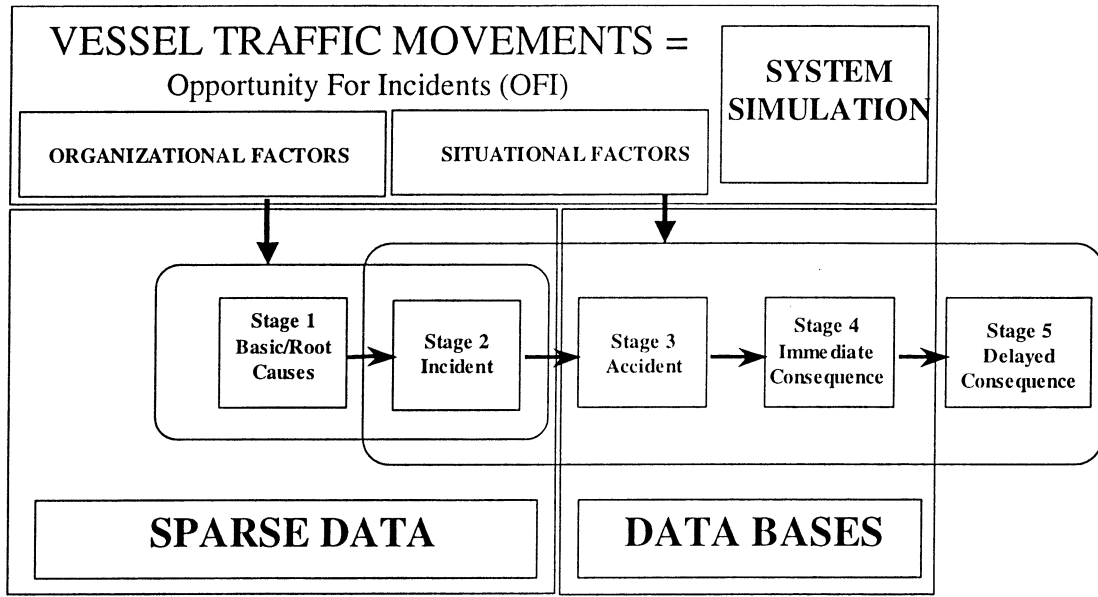
Fig. 5. Typical data availability relative to the maritime accident event chain.

3.4. Defining a Baseline Scenario

A representative simulation scenario was developed for the 11-year period for which historical data were collected. This simulation scenario (referred to as the calibration scenario) was developed for calibration purposes of the accident probability model to the historical data collected. The fall, spring, and summer sailing schedules in the last year (1997) of this 11-year period were used for the calibration scenario. These schedules are published by the WSF and comprise a full year of service. The WSF ferry schedules had remained fairly stable during this 11-year period. The WSF supplied the assignments of ferry classes to routes for the year 1997.

The assignments of ferry classes to routes had remained fairly stable as well over this 11-year period. The blue-ribbon panel and WSF scheduling staff approved the use of the fall 1997, spring 1997, and summer 1997 sailing schedules and 1997 ferry class assignments for the calibration scenario.

To evaluate the risk reduction measures in Table I, a baseline level of risk needed to be established and thus a baseline scenario needed to be defined. The Washington state ferry risk assessment project started in July 1998. At this time, one high-speed ferry, the *Chinook*, had been delivered and was operating on the Seattle to Bremerton route. Two Jumbo Mark II class ferries also had started service or would start service on the Seattle to Bainbridge
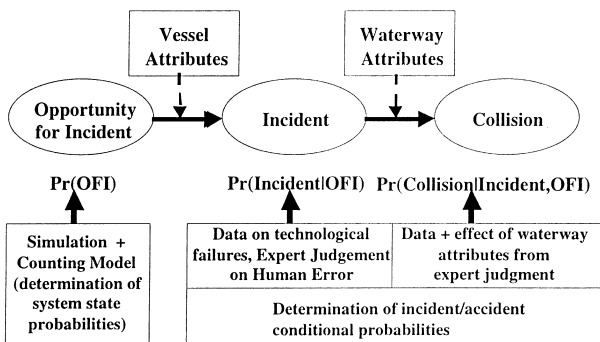

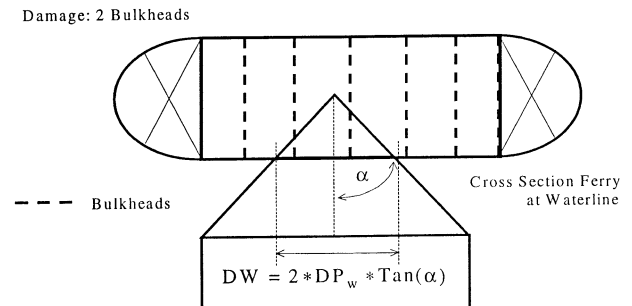**Fig. 6.** Summary of modeling methodologies to establish collision risk.

Fig. 7. Illustration of damage model calculations. DW = damage width, DP_w = damage penetration along the waterline.

Island route during 1998. The WSF schedule after the introduction of these ferries was considered the basis for the baseline scenario. Therefore, the calibration scenario was modified using 1998 schedules to represent a WSF schedule and assignments of ferries to routes after the introduction of these two new ferry classes: one high-speed ferry, the *Chinook*, and two Jumbo Mark II class ferries. The modified calibration scenario was defined as the baseline simulation scenario. The baseline simulation scenario was used to establish the baseline level of risk for risk intervention evaluation.

3.5. Modeling the Effect of Risk Interventions

The seven intervention classes described in Table I reduce accident probabilities, consequences, or both by intervening in the causal chain. The effect of a risk intervention measure may be modeled by changing model parameters from the baseline scenario. As shown in Fig. 3, some measures have an impact early on in the maritime accident event chain. Therefore, to model the effect of these risk interventions in a meaningful way, it is important that the system risk model represents events that far back in the causal chain. Rather than making worst case or best case assumptions concerning the effect of risk interventions on model parameters, the approach of reasonable assumptions following data analysis on human error in other transportation modes and mechanical-failure data of the WSF was taken, followed by sensitivity analysis.[12] The assumptions made to represent the seven intervention classes are listed in Table III. These assumptions were made in cooperation with maritime experts and were presented to and accepted by the Blue-Ribbon Panel on Ferry Safety.

4. BASELINE RISK AND RISK INTERVENTION EVALUATION RESULTS

In this section, a detailed discussion of baseline risk will be given in terms of the distribution of annual collision frequencies per year over the three MRRT categories by (1) ferry route and (2) ferry route and interacting vessel. Following the discussion of baseline risk, the effectiveness of risk intervention measures will be evaluated and presented. Results on the sensitivity analysis will be discussed as well.

4.1. Baseline Risk Results

Table IV presents the evaluated expected annual frequency of collisions per year over the three MRRT categories for the baseline scenario defined in Section 3. The average time between consecutive collisions in Table IV is the reciprocal of the statistical expected number of collisions per year.

Table IV summarizes the level of collision risk in the WSF system as a whole. The baseline statistical frequency of collisions per year, calculated using the baseline simulation, is 0.223 per year. The calibration statistical frequency of collisions per year, calculated using the calibration simulation, is 0.182 per year (equals two collisions over an 11-year period). Further analysis showed that this 22.7% increase in statistical frequency of collisions was mainly a result of replacing one of the older, slower passenger-only ferries on the Seattle–Bremerton route by the high-speed passenger-only ferry, the *Chinook*. It should be noted that the increase in statistical frequency of collisions is primarily of the 0–1 hr MRRT category due to the impact resulting from a high-speed collision with another vessel.

Table IV does not provide insight into which ferry route contributes most to the baseline level of

Table III. Summary of Modeling Effect of Risk Interventions Classes Tested

Class	Intervention	Assumed impact
1	Adopt ISM (International Safety Management) standard fleetwide	Reduce human error incidents by 30%, reduce mechanical failures by 3.7%, reduce consequences by 10%
2	Implement all mechanical-failure reduction measures fleetwide	Reduce mechanical-failure incidents by 50%
3	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%
4	Implement weather, visibility restrictions	Reduce the interactions with other vessels in bad visibility conditions by 10%
5	Implement traffic separation for high-speed ferries	Reduce interactions with high-speed ferries within 1 mile by 50%
6	Implement traffic control for deep-draft traffic	Set maximum allowable traveling speed in Admiral Inlet, north Puget Sound, central Puget Sound, and south Puget Sound at 15 knots
7	Increase time available for response	Improve response time in the 1–6 hr MRRT category by 50%

Note: MRRT = maximum required response time.

Table IV. Baseline Risk

Category	Statistical expected number of collisions per year per category	Average time between consecutive collisions per category (years)
0–1 hr MRRT	0.055	18.1
1–6 hr MRRT	0.015	67.5
>6 hr MRRT	0.152	6.6
Total	0.223	4.5

Note: MRRT = maximum required response time.

system collision risk. To further the understanding of the baseline collision risk levels, Fig. 8 shows the contribution to collision risk by ferry route. Table V gives the abbreviations used for the 13 different ferry routes displayed in Fig. 8.

In Fig. 8, the annual frequency of collisions for each route is further broken down into the three MRRT categories. Figure 8 shows that the six routes that contribute most to the level of system collision risk are (1) the Seattle to Bremerton car ferries, (2) the Seattle to Bremerton passenger ferries, (3) the Seattle to Bainbridge Island ferries, (4) the Edmonds to Kingston ferries, (5) the Fauntlerory to Vashon Island ferries, and (6) the Seattle to Vashon ferries. These routes are geographically centered around the main Seattle metropolitan area.

It cannot be concluded from the information in Fig. 8 whether the risk levels for the ferry routes are driven by (1) high numbers of interactions with other vessels, that is, traffic congestion relative to the other ferry route, (2) high collision risk per interaction, or (3) both. Hence, the next step in understanding baseline risk is to further decompose the collision risk levels by the type of vessels that the ferries interact with on a particular ferry route. The type of interacting vessel contributes both to the collision probability for each interaction and the MRRT categorization of each interaction.

The results will be presented in three-dimensional graphs displaying the collision risk levels by ferry route and interacting vessel type. The keys for these graphs are given in Table V and Table VI. Figure 9 shows the number of interactions per year by ferry route and by interacting vessel type. The higher bars to the right of the Vessel Class Index axis shows that the number of interactions is much higher with Washington state ferries (Keys 13 to 22 in Table VI) than with non-WSF vessels (Keys 1 to 12). For the Ferry Route Index axis, the highest bars are on Route indices 1 through 3. These are the Seattle to Bremerton routes and the Seattle to Bainbridge route.

Figure 10 shows the average collision probability per interaction by ferry route and interacting vessel type. The higher bars to the left of the Vessel Class Index axis (Keys 1 to 12) show that the interactions with
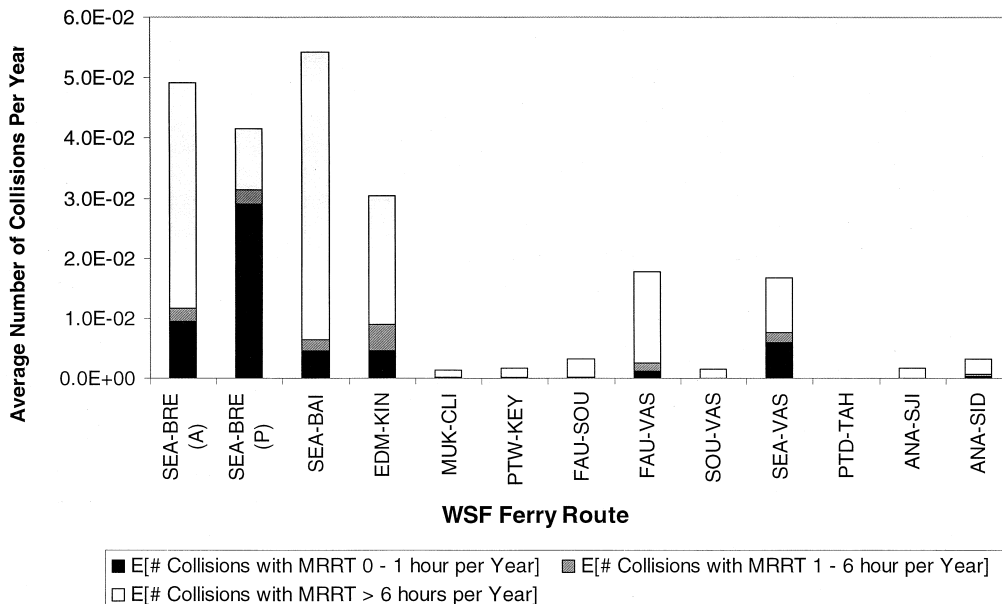

Fig. 8. Statistical expected number of collisions per year by ferry route. See Table V for abbreviations. WSF = Washington state ferries. MRRT = maximum required response time.

Table V. Numbering Keys and Abbreviations for Ferry Routes

Route index	Ferry route	Abbreviation
1	Seattle–Bremerton car ferries	SEA-BRE (A)
2	Seattle–Bremerton passenger ferries	SEA-BRE (P)
3	Seattle–Bainbridge	SEA-BAI
4	Edmonds–Kingston	EDM-KIN
5	Mukilteo–Clinton	MUK-CLI
6	Port Townsend–Keystone	PTW-KEY
7	Fauntleroy–Southworth	FAU-SOU
8	Fauntleroy–Vashon	FAU-VAS
9	Southworth–Vashon	SOU-VAS
10	Seattle–Vashon	SEA-VAS
11	Port Defiance–Tahlequah	PTD-TAH
12	Anacortes–San Juan Islands	ANA-SJI
13	Anacortes–Sidney	ANA-SID

non-WSF vessels are more likely to lead to a collision than interactions with Washington state ferries (Keys 13 to 22). Figure 11 shows the annual collision frequency by ferry route and type of interacting vessel and is a combination of the information in Figs. 9 and 10. The highest bars are on Routes 1 to 3, the Seattle–Bremerton routes and the Seattle–Bainbridge route. Overall, there are relatively high bars for the annual collision frequency for interactions with both other WSF ferries and non-WSF vessels on these routes.

From Fig. 10 it can be observed that the annual frequency of collisions with non-WSF vessels is driven by the collision probability for each interaction. From Fig. 9 it can be observed that the annual frequency of collisions with WSF ferries are driven by the number of interactions per year.

In terms of emergency response, accidents that fall in the less than 1 hr MRRT category are of particular concern. Using the damage model and the re-

sponse time model, the annual collision frequencies in Fig. 11 can be filtered to include only those in the less than 1 hr MRRT category. The results are shown in Fig. 12. It can be concluded from Figs. 11 and 12 that the Seattle–Bremerton passenger-only route (Ferry Route Index Key 2) and the vessels that interact with it have a larger statistical expected number of collisions with an MRRT of less than 1 hr. The Seattle to Vashon passenger-only route (ferry Route Index Key 10) also has a relatively high annual frequency of collisions in the less than 1 hr MRRT category. The new high-speed passenger-only ferry is solely assigned to the Seattle–Bremerton passenger-only route. Collisions involving the high-speed passenger-only ferries are always assessed to require a maximum response time of less than 1 hr. The older passenger-only ferries are used for both the Seattle to Bremerton and the Seattle to Vashon passenger-only routes and interact with both large car ferries and deep-draft non-WSF vessels, as shown in Fig. 9. A proportion of the collisions of the older passenger-only ferries with large car ferries and deep-draft non-WSF vessel fall in the less than 1 hr MRRT category.

The information in Fig. 12 may be summarized in the form of a ranked cumulative risk contribution chart, as presented in Fig. 13. 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 Fig. 14 indicates the percentage contribution to the statistical expected number of collisions in the less than 1 hr MRRT category for that collision scenario. The total height of the bar indicates the cumulative percentage including all colli-

Table VI. Numbering Keys for Interacting Vessels

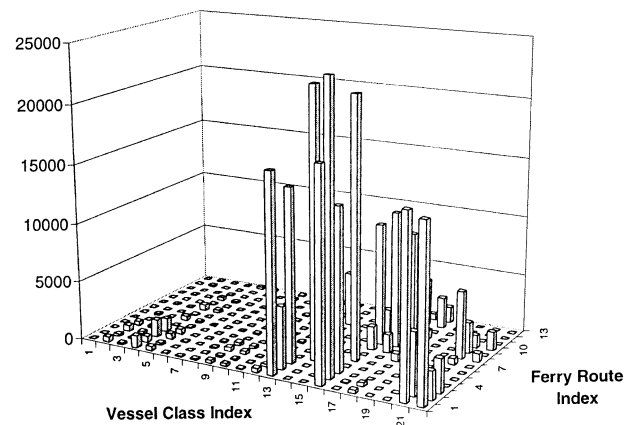| Vessel index	Vessel class	Vessel index	Vessel class
1	Passenger	12	Misc.
2	Tug/barge	13	Jumbo Mark II
3	Freight ship	14	Jumbo
4	Container	15	Super
5	Bulk carrier	16	Issaquah
6	Refrigerated cargo	17	Evergreen
7	Tanker	18	Steel electric
8	Product tanker	19	Rhododendron
9	Other	20	Hiyu
10	Roll-on, roll-off	21	Passenger-only vessel
11	Naval	22	Chinook

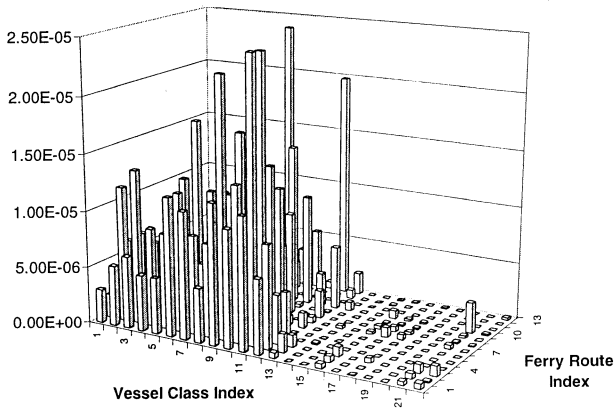**Fig. 9.** Number of interactions per year by ferry route and vessel class.

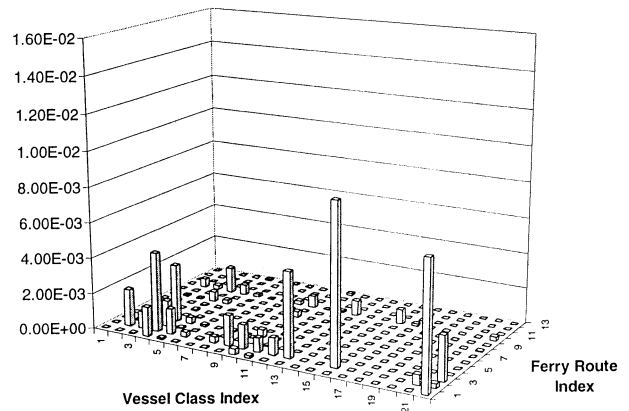**Fig. 10.** Average collision probability per interaction by ferry route and vessel class.

Fig. 12. Statistical expected number of collisions per year with a maximum required response time of less than 1 hr by ferry route and vessel class.

sion scenarios to the left. In other words, Fig. 13 contains the top collision scenarios that accumulate to 88% of the statistical expected number of collisions per year in the less than 1 hr MRRT category.

4.2. Evaluation of Risk Interventions

All cases were tested to evaluate their effect on the annual frequency of collisions and on the annual frequency of collisions in each of the MRRT categories. The results of these analyses are represented in Fig. 14. For each risk intervention class, the total percentage reduction in the statistical frequency of collisions is comprised of the percentage reduction in the statistical frequency of collisions in each of the three MRRT categories relative to the baseline scenario in Table IV.
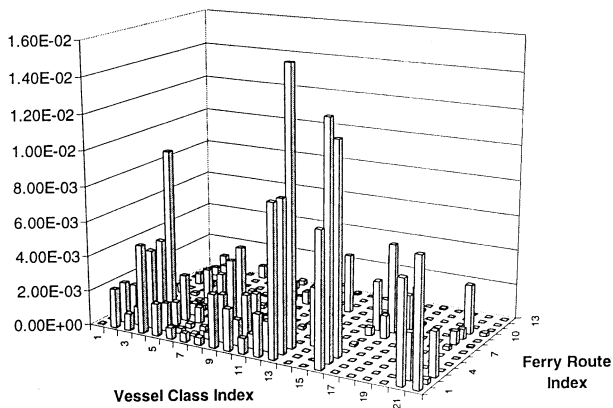

Fig. 11. Statistical expected number of collisions per year by ferry route and vessel class.

Case 1 has the largest risk reduction at 16% and reflects the effect of the fleetwide implementation of the International Safety Management (ISM) code. Noted is a large reduction for both the less than 1 hr and the more than 6 hr MRRT categories. Case 2, the implementation of mechanical-failure-reducing measures, is the next most effective at 11%. Of note is a large reduction in each MRRT category as well as the large reduction predicted for collisions with a MRRT of 1 to 6 hr. The implementation of traffic separation rules for the high-speed ferries, Case 5, causes a 6% reduction in the total statistical expected number of collisions. 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 hr. A 5% reduction in the total statistical expected number of collisions is predicted for the implementation of visibility restrictions, Case 4. The implementation of high-speed ferry rules (ISM restricted to high-speed ferry routes), Case 3, decreases the total statistical expected number of collisions by 2%, with all the reduction being for collisions with an MRRT of less than 1 hr. Case 7 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 hr—survival craft. Reducing the speed of commercial vessels in Puget Sound, Case 6, also does not reduce the total statistical expected number of collisions. The statistical expected numbers of collisions with an MRRT of less than 1 hr and an MRRT of 1 to 6 hr are both reduced, however, while the statistical expected number of collisions with an MRRT of more than 6 hr increased by the same amount.
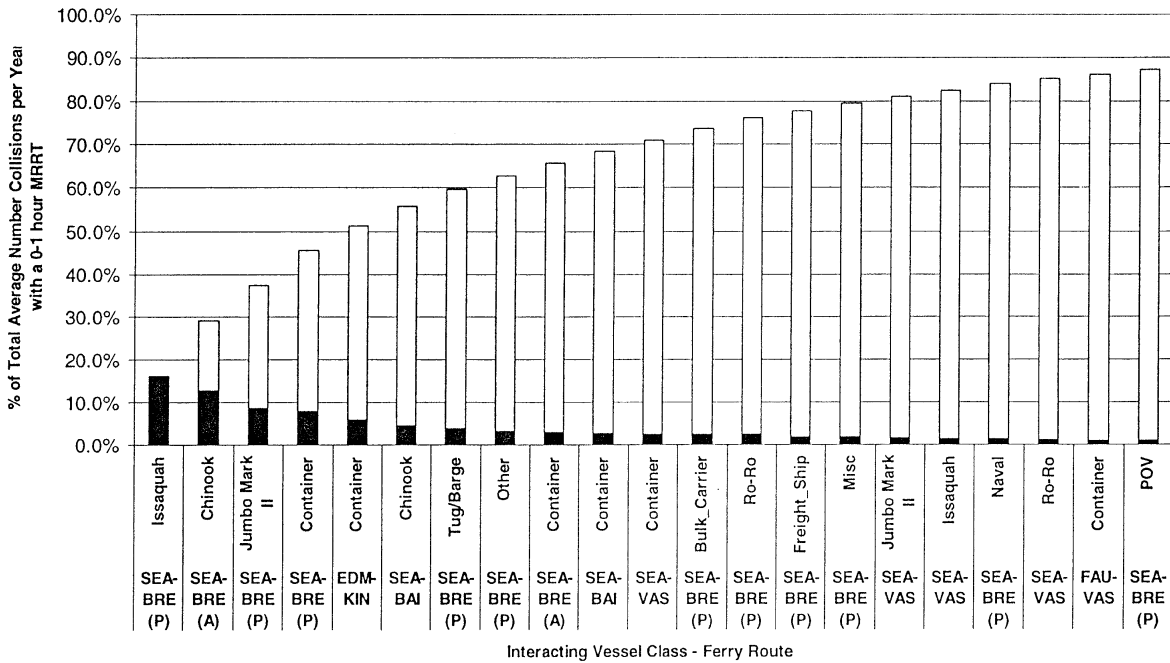
Fig. 13. Distribution of the statistical expected number of collisions per year with a maximum required response time (MRRT) of less than 1 hr by ferry route and vessel class. See Table V for abbreviations.

5. SENSITIVITY ANALYSIS RESULTS

The analysis of the WSF risk assessment provides the basis for determining 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 levels of the analysis. Sources of this uncertainty include incomplete 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."[12]

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 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.[13] The methodology thus provides many safeguards to remove bias and to detect error. The general approach toward modeling assumptions in the WSF risk assessment was that of reasonableness rather than pursuing one worst case assumption after the other. The latter approach may lead to risk assessment results related to highly unlikely scenarios and therefore less-useful results. The approach of using reasonable assumptions rather than worst case assumptions is supported by scientists in the field of risk analysis.[12]

Although a formal uncertainty analysis has not been presented with these results, sensitivity of the results to some of the more contentious modeling assumptions has been tested. The assumptions tested/challenged through the sensitivity cases were

1. All collisions involving a high-speed ferry fall in the category of collision with an MRRT of 0–1 hr
2. The vertical bow angle reduces the damage penetration below the waterline
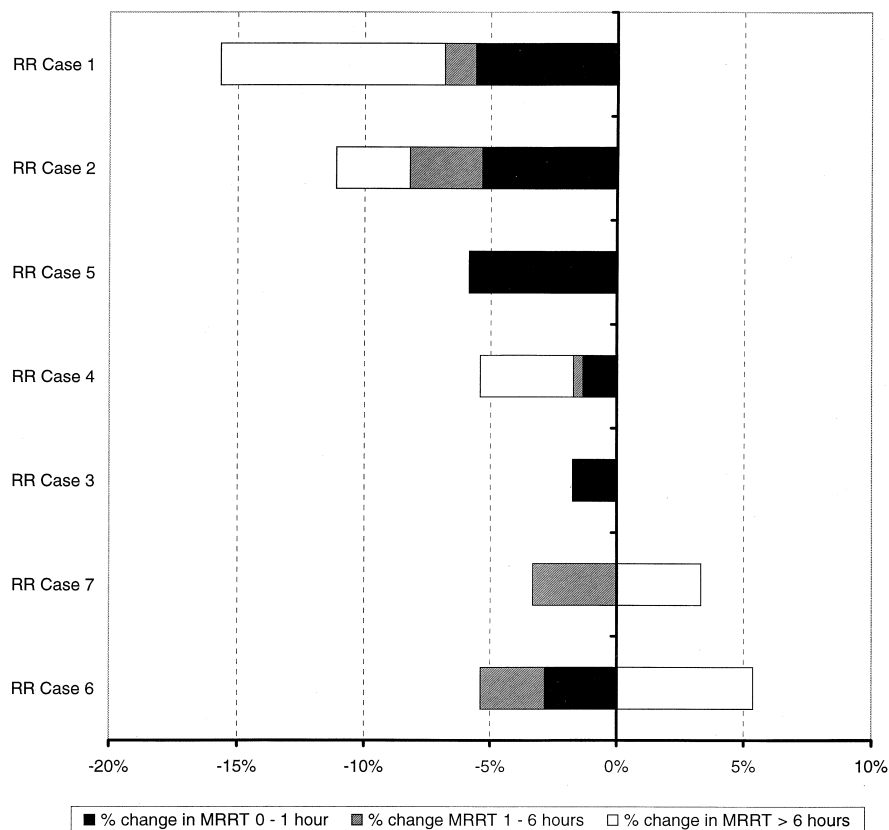3. The horizontal bow angle for vessels in the WSF system is, on average, 66°

Fig. 14. Estimated risk reduction (RR) for the seven tested cases. MRRT = maximum required response time.

4. The collision speed for non-WSF vessels is 80% of the traveling speed, and the collision speed of WSF vessels is 50% of the traveling 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 collisions 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

To test these six assumptions, nine sensitivity cases were developed and analyzed. For demonstrative purposes, the first listed assumption (Assumption 1) is that all collisions involving the new high-speed passenger-only ferries fall in the less than 1-hr MRRT category. This assumption was modified so that all three MRRT categories are equally likely in case of a collision involving the high-speed passenger-only ferry

and is henceforth referred to as Sensitivity Case 1. This assumption is more optimistic than Assumption 1. The results of the sensitivity analysis are shown in Fig. 15.

Figure 15 shows that the statistical frequency of collisions in the less than 1 hr MRRT category reduces by 9% in Sensitivity Case 1. Also of note is that the combined percentage increase in statistical frequency of collisions in the 1–6 hr MRRT category and more than 6 hr MRRT category equals the percentage reduction in the less than 1 hr 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 tested as well.

Figure 16 summarizes the collision analysis by ferry route under Sensitivity Case 1. Comparing Figs. 8 and 16, it can be observed that by altering Assumption 1 the statistical frequency of collisions in the less than 1 hr MRRT category has primarily been reduced on the Seattle Bremerton passenger ferries, Seattle
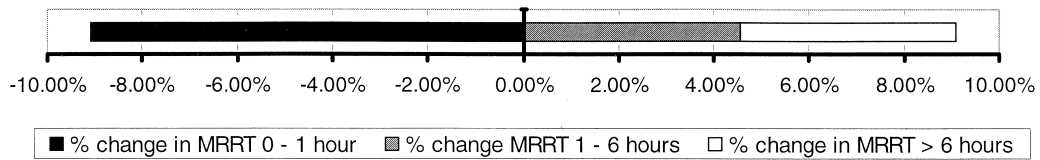
Fig. 15. Percent change in the annual collision frequency in each maximum required response time (MRRT) category under Sensitivity Case 1.

Bremerton car ferries, and the Seattle Bainbridge ferries. The predominant WSF ferry routes in terms of the statistical frequency of collisions in the less than 1 hr MRRT category, however, are the same under the original assumption and the modified assumption for high-speed passenger-only ferries. Similar conclusions can be drawn when analyzing these results for the other sensitivity cases as well.

6. GENERAL CONCLUSIONS

Sixteen specific risk reduction recommendations are cited in Harrald et al.[11] Recommendations derived from the analysis were divided into three categories: (1) general risk management recommendations for the Washington state ferries to manage risk in the system, (2) recommendations for reducing the likelihood of accidents, and (3) recommendations for minimizing the potential consequences of accidents. Interested readers are referred to Harrald et al.[11] for

the specific recommendations. Below are general conclusions in terms of the previous three categories of risk management recommendations.

In terms of general risk management, it was recommended that the Washington state ferries should improve their capabilities to detect and manage risk and to prepare for potential emergencies. This requires a continuing set of systems, capabilities, and structures in order to be effective. Maintaining and enhancing safety in the WSF system requires management and resources devoted to risk prevention, accident response, and consequence management. The WSF risk assessment report supports the currently planned and funded fleetwide implementation of the ISM system.

In terms of reducing the likelihood of accidents, it was recommended that the WSF should continue to implement safety management and training programs, provide adequate relief crews as necessary to accomplish training, and coordinate with the USCG to minimize the likelihood of an accident. It was
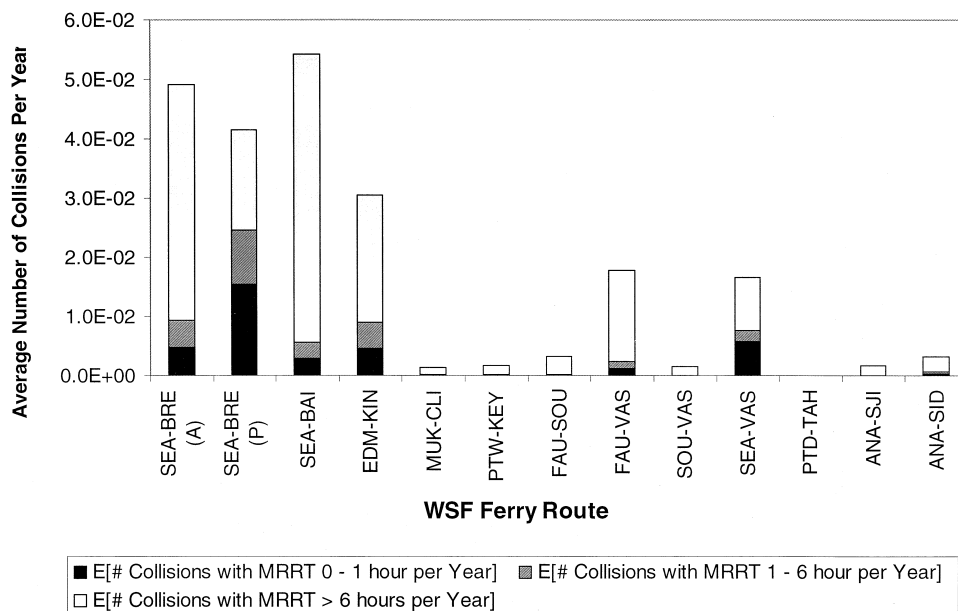

Fig. 16. Distribution of statistical frequency of collisions over the three maximum required response time (MRRT) categories by ferry route—Sensitivity Case 1. See Table V for abbreviations.

noted that since the consequences of an intentional act of destruction (sabotage or attack) aboard a ferry could be severe, the WSF should work with the Washington State Patrol and federal agencies to determine the need for additional security measures to combat the threat of intentional acts of destruction aboard ferries.

In terms of minimizing the potential consequences of accidents, it was recommended that the WSF, the USCG, and other response organizations should work collaboratively to ensure that consequences will be minimized for any accident that does occur. Specifically, it strongly recommends that the WSF and the USCG and other public safety agencies address the problem of minimizing injury and loss of life from very low-probability but potentially high-consequence accidents through planning, implementing, and exercising adequate response plans and procedures. It recognizes that the skills of the ferry crew will be crucial in any emergency situation and strongly recommends enhancing these emergency skills through training, certification, drills, and exercises.

The report finally concludes that the most cost-effective way to minimize the risk of potential accidents is to invest in WSF people and systems and to make improvements and changes to WSF policies, procedures, and management systems—rather than to merely invest in capital equipment such as survival craft. The creation of a safety culture that will enable these recommendations to be realized will require the support and leadership of WSF management; shoreside operations; and fleet deck officers, engineers, and other shipboard personnel.

The conclusions and recommendations made to the WSF were driven by the total statistical frequency of collisions and by the distribution of the total statistical frequency of collisions over the three MRRT categories. Based on the results of the sensitivity analysis performed, it was concluded that the conclusions and recommendations made were robust relative to the modified assumptions tested.

As a closing note, it might be of interest to mention that it is impossible for any risk analysis performed in a dynamic public arena to foresee changes as a result of political processes. An example is the passage of Initiative 695, which eliminated the state motor vehicle excise tax. The effect for the WSF is a disproportional loss in operating and capital budget potentially impacting the level at which recommendations from this study will be implemented. Loss of operating budget already temporarily interrupted the service of two high-speed ferries, the *Chinook* and the *Snohomish*. The current legislative plan, includes funding to maintain the operations of the *Chinook* and *Snohomish*. A simulation scenario including two high-speed ferries in the WSF schedules was analyzed in the WSF risk assessment report as well. For detailed results interested readers are referred to the WSF risk assessment report in Harrald *et al.*[11]

REFERENCES

1. Washington State Ferries. (2000). http://www.wsdot.wa.gov/ferries/info_desk/route-maps/. (9 January 2001).
2. Lifesaving Systems for Certain Inspected Vessels, 46 C.F.R. 199, Subchapter W (1 October 1998).
3. Implementation of the 1995 Amendments to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978 (STCW). 62 Fed. Reg. 123, 34506–34541.
4. International Maritime Organization, Subcommittee on Ship Design and Equipment. (1998). Revision of the HSC Code, Formal Safety Assessment of High Speed Catamaran (HSC) Ferries Submitted by the United Kingdom (41st Session, Agenda Item 5), E/DE/41/5–6.
5. Harrald, J. R., Mazzuchi, T. A., Merrick, J. R. W., Shrestha, S. K., Spahn, J. E., & van Dorp, J. R. (1996). *Final report: Prince William Sound risk assessment.* Submitted to the Prince William Sound Risk Assessment Steering Committee, Anchorage, AK.
6. Dyer, M. D., Schwenk, J., Watros, G., & Boniface, D. (1997). *Scoping risk assessment, protection against oil spills in the maritime waters of northwest Washington State.* Cambridge, MA: John Volpe National Transportation Systems Center.
7. Cooke, R. M. (1991). *Experts in uncertainty: Expert opinion and subjective probability in science.* New York: Oxford University Press.
8. Paté-Cornell, M. E. (1996). Uncertainties in risk analysis: Six levels of treatment. *Reliability Engineering and System Safety, 54*(2–3), 95–111.
9. Harrald, J. R., Mazzuchi, T. A., & Stone, S. M. (1992). Risky business: Can we believe port risk assessments? In D. Torseth (Ed.), *Ports '92 Conference Proceedings* (pp. 657–669). New York: American Society of Civil Engineers.
10. Minorsky, V. U. (1959). An analysis of ship collisions with reference to protection of nuclear power plants. *Journal of Ship Research, 3,* 1–4.
11. Harrald, J. R., van Dorp, J. R., Mazzuchi, T. A., Merrick J. R. W., & Grabowski, M. (1999). Final report: Washington state ferry risk assessment. Submitted to the Washington State Transportation Commission, Seattle, WA.
12. Hattis, D., & Anderson, E. L. (1999). What should be the implications of uncertainty, variability, and inherent "biases"/"conservatism" for risk management decision making. *Risk Analysis, 19,* 95–107.
13. Marine Board, National Research Council. (1998). *Review of the Prince William Sound, Alaska, risk assessment study.* Washington, DC: Committee on Risk Assessment and Management of Marine Systems, National Academy Press.