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PD 98-1321 **01/15/02**

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SES - DECISION RISK & MANAGEMENT SCI

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TITLE OF PROPOSED PROJECT **Collaborative Research: Speaking the Truth in Maritime Risk Assessment**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$ **158,472**	**24** months	**08/01/02**	

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☐ SMALL GRANT FOR EXPLOR. RESEARCH (SGER) (GPG II.C.11)
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PI/PD DEPARTMENT **Engineering Management and Systems Engin**	PI/PD POSTAL ADDRESS **707 22nd Street, NW** **Washington, DC 20052** **United States**
PI/PD FAX NUMBER **202-994-0245**	

NAMES (TYPED)	High Degree	Yr of Degree	Telephone Number	Electronic Mail Address
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CO-PI/PD				
CO-PI/PD				
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CERTIFICATION PAGE

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By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is: (1) certifying that statements made herein are true and complete to the best of his/her knowledge; and (2) agreeing to accept the obligation to comply with NSF award terms and conditions if an award is made as a result of this application. Further, the applicant is hereby providing certifications regarding debarment and suspension, drug-free workplace, and lobbying activities (see below), as set forth in Grant Proposal Guide (GPG), NSF 02-2. Willful provision of false information in this application and its supporting documents or in reports required under an ensuing award is a criminal offense (U. S. Code, Title 18, Section 1001).

In addition, if the applicant institution employs more than fifty persons, the authorized official of the applicant institution is certifying that the institution has implemented a written and enforced conflict of interest policy that is consistent with the provisions of Grant Policy Manual Section 510; that to the best of his/her knowledge, all financial disclosures required by that conflict of interest policy have been made; and that all identified conflicts of interest will have been satisfactorily managed, reduced or eliminated prior to the institution's expenditure of any funds under the award, in accordance with the institution's conflict of interest policy. Conflicts which cannot be satisfactorily managed, reduced or eliminated must be disclosed to NSF.

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Is the organization or its principals presently debarred, suspended, proposed for debarment, declared ineligible, or voluntarily excluded from covered transactions by any Federal department or agency? Yes ☐ No ☒

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(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

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(3) The undersigned shall require that the language of this certification be included in the award documents for all subawards at all tiers including subcontracts, subgrants, and contracts under grants, loans, and cooperative agreements and that all subrecipients shall certify and disclose accordingly.

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AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME **Helen Spencer**	**Electronic Signature**	**Jan 14 2002 2:17PM**

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER
202-994-6255	**osr@gwu.edu**	**202-994-9137**

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COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

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TITLE OF PROPOSED PROJECT **Collaborative Research: Speaking the Truth in Maritime Risk Assessment**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PREPROPOSAL NO., IF APPLICABLE
$ **154,442**	**24** months	**08/01/02**	

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PI/PD DEPARTMENT **Mathematical Sciences/Mechanical Enginee**	PI/PD POSTAL ADDRESS **Oliver Hall Box 842014** **1015 W. Main St** **Richmond, VA 232842014** **United States**
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CERTIFICATION PAGE

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AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
NAME **Sheryl D Baldwin**	**Electronic Signature**	**Jan 14 2002 9:34AM**

TELEPHONE NUMBER	ELECTRONIC MAIL ADDRESS	FAX NUMBER
804-828-6772	**sdbaldwi@mail2.vcu.edu**	**804-828-2521**

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A. Project Summary

The PIs at The George Washington University (GWU) and Virginia Commonwealth University (VCU) are pleased to re-submit this collaborative research proposal between GWU and VCU entitled: "Speaking the Truth in Maritime Risk Assessment". We are indebted to the NSF program director and the NSF reviewers for their valuable comments and suggestions, which have improved the presentation and the content of the first version.

Over the past 6 years the research interests and experience of the PI's have been concentrated in the area of maritime risk assessment. The Prince William Sound (PWS) Risk Assessment was conducted for a steering committee representing all local stakeholders, including the PWS Shipping Companies, the PWS Regional Citizens Advisory Council, the Alaska Department of Environmental Conservation and the U.S. Coast Guard. The methodology developed for the PWS study is based on probabilistic risk assessment combined with system simulation. A simulation of the maritime system is used to estimate the frequency of the occurrence of system states defined by organizational and situational factors. Available data is next extended using expert judgment techniques to estimate the conditional probability of an accident in each of the defined system states. Finally, both methodologies are integrated in an overall framework to analyze system wide maritime risk in terms of annual accident frequencies. The National Research Council (NRC) established a panel in response to a request from the PWS Steering Committee for a peer-review of the PWS study. "*The Prince William Sound Risk Assessment is an important step forward in using probabilistic risk assessment methods to assess the safety of transporting oil in large tankers in PWS …. Because the data were very limited, the analysis results and the resulting conclusions are not robust and are necessarily uncertain*" [National Research Council, 1998].

The PWS Risk Assessment methodology has been improved in a later study assessing passenger risk for the Washington State Ferries. However, to live up to the promise of the approach followed in the PWS and WSF risk assessment uncertainty needs to be addressed. "*The truth is that we are uncertain. Therefore, speaking the truth implies that we express our analysis results in terms of probability curves rather than fixed points estimates*". [See e.g., Kaplan, 1997]. To propagate uncertainty through the PWS and WSF maritime risk models, the following tasks must be completed:

- Task 1: Representation of uncertainty in the maritime simulation;
- Task 2: Representation of uncertainty in the expert judgment estimates;
- Task 3: Propagation of the uncertainties through the whole model;
- Task 4: Conduct a trial uncertainty analysis.

Throughout the development a Bayesian paradigm will be followed and parallel computing techniques will be used to spread the computational workload across a network of workstations.

The intellectual merit of the research proposed herein stems from the development of an overarching Bayesian framework for addressing uncertainty when simulation of systems states is combined with available data and expert judgment to assess risk and risk intervention effectiveness. The development of a Bayesian pairwise accident probability model utilizing expert judgment elicitation is new to the best of our knowledge. Bayesian simulation analysis techniques have only been proposed in theoretical settings [Chick, 2001], thus their use in a large complex system may be considered state of the art in the field of computational sciences. Furthermore, the techniques of Bayesian simulation have not thus far been combined with parallel computing techniques to facilitate the added computational complexity. Finally, as suggested by one the NSF reviewers, the project can also be characterized as a feasibility study of uncertainty propagation in large-scale risk assessments.

The broader impact of the proposed work is primarily drawn from its applicability to areas other than maritime accident risk. In the aftermath of the September 11 attacks, port security risk (intentional as opposed to accidental) has now been recognized as an integral part of homeland security [Loy, 2002]. In a recent Washington Post article, Sen. Joseph I. Liebermann (D-Conn) was quoted "*The plain fact is that the movement of goods into the U.S. is now so efficient that **port security** has been compromised* " [Booth, 2002]. The PI's have recently submitted a white paper in response to a DOT BAA announcement on transportation security [Harrald et al., 2001]. Subsequent uncertainty assessment of security risk and propagation in security intervention effectiveness needs to be accounted for, since lack of data will even be of greater concern. As suggested by each of the NSF reviewers, despite the focus on maritime risk, the framework and methodologies developed will be applicable to other transportation modes, such as aviation or road safety. Aside from aviation security and accident risk, the technique will be directly transferable to the ever-increasing problem of runway incursions as a result of increased traffic congestions at our national airports.

The proposed research effort is collaborative in nature drawing together the necessary expertise in probabilistic risk assessment, Bayesian analysis techniques and parallel computing. The funding requested for this project is $158,471 for GWU and $154,442 for VCU, totaling $312,913. The duration of the project is two years.

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For font size and page formatting specifications, see GPG section II.C.

Section		Total No. of Pages in Section	Page No.* (Optional)*
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A	Project Summary (not to exceed 1 page)	1	
B	Table of Contents (NSF Form 1359)	1	
C	Project Description (plus Results from Prior NSF Support) (not to exceed 15 pages) **(Exceed only if allowed by a specific program announcement/solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**	15	
D	References Cited	5	
E	Biographical Sketches (Not to exceed 2 pages each)	4	
F	Budget (NSF Form 1030, plus up to 3 pages of budget justification)	5	
G	Current and Pending Support (NSF Form 1239)	2	
H	Facilities, Equipment and Other Resources (NSF Form 1363)	1	
I	Special Information/Supplementary Documentation	0	
J	Appendix (List below.) **(Include only if allowed by a specific program announcement/ solicitation or if approved in advance by the appropriate NSF Assistant Director or designee)**		

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NSF Form 1359 (10/99)

C. Project Description

1. Introduction

"*The nation's economy depends on safe and efficient maritime transportation that uses major ports and waterways. U.S. ports and waterways are remarkably diverse in terms of the vessel traffic served, the variety of services provided, geography and environmental conditions. ... Formal analytical techniques often are not used to guide port and waterway managers when they make decisions about safety measures. ... Formal assessment can provide the most accurate results with regard to risk management by providing a systematic approach to determining levels of risk, opportunities to implement risk reduction measures, and relative benefits of alternative measure*" [National Research Council, 2000]

Over the past 6 years, the research interests and experience of the PIs have concentrated in the area of maritime risk assessment. The PIs have been involved in the detailed modeling, analysis and client interfacing of a number of major maritime risk assessment projects, specifically, The Prince William Sound Risk Assessment and most recently, The Washington State Ferry Risk Assessment. The principal investigators overall research objective is to develop and publish a theoretical framework for transportation risk assessment in the open literature based on the methodology of the PWS/WSF risk assessments. Such accessibility would allow others to avoid the steep learning curve costs experienced when conducting transportation risk assessments of similar scope. Accessibility to such a framework would promote the use of systematic risk assessment approaches in the maritime domain, as advocated by the National Research Council (1998, 2000), as well other transportation modes.

The PWS Risk Assessment was conducted for a steering committee representing all local stakeholders, including the Prince William Sound Shipping Companies, the Prince William Sound Regional Citizens Advisory Council, the Alaska Department of Environmental Conservation and the U.S. Coast Guard. The steering committee hired a team of consultants (of which the PIs were members) who were charged with assessing the current risk of accidents involving oil tankers operating in the Prince William Sound and evaluating measures aimed at reducing this risk. The methodology developed for the PWS study is based on probabilistic risk assessment (PRA) combined with system simulation. A simulation of the maritime system was used to estimate the frequency of the occurrence of system states defined by organizational and situational factors. Available data was next extended using expert judgment techniques to estimate the conditional probability of an accident in each of the defined system states. Finally, both methodologies are integrated in an overall framework to analyze system wide maritime risk in terms of annual accident frequencies. The National Research Council (specifically, The Marine Board's committee on Risk Assessment and Risk Management of Maritime Systems (RARMMS)) established a panel in response to a request from the PWS Steering Committee to evaluate the PWS risk assessment study. The RARMMS committee was quite critical. Specifically, the RARMMS committee indicated that the changes in the following four areas would make the methodology followed in the PWS Risk Assessment more generally applicable:

- Providing an overarching study framework;
- Expanding the consideration of human factors;
- Disclosing the underlying data;
- Analyzing the sensitivities and uncertainties.

Significant progress has been made with respect to addressing the concerns of the RARMMS Committee mentioned in items 1, 2 and 3 above. Such progress was made partially by publications in the archival literature [Harrald et al., 1998; Merrick et al., 2000; van Dorp et al., 2001; Grabowski et al., 2000] and partially by applying the lessons learned from the PWS Risk Assessment in the WSF Risk Assessment. The WSF Risk Assessment was conducted in 1998 for the Washington State Transportation Commission. The Final Report and Technical Appendices are public documents that can be requested from the Transportation Commission. This final report, the technical appendices and the previous mentioned journal publications address items 1 to 3 of the RARMMS committee in a comprehensive manner. With respect to item 4 some progress has been made in the sense that sensitivity analysis on all major model assumptions was conducted during the WSF study. However, a theoretical framework for modeling uncertainty is still lacking.

2. Objectives and Scope

The objective of this project is the development of an overarching Bayesian framework for addressing uncertainty when simulation of systems states is combined with available data and expert judgment to assess risk and risk intervention effectiveness. This work is intended to specifically address item 4 of the concerns of the RARMMS committee listed above and to address the needs of the maritime industry:

"Risk management ... should answer whether evidence is sufficient to prove specific risks and benefits." [A. Elmer, President, SeaRiver Maritime, Inc., National Research Council, 2000]

The underlying methodology in the PWS and WSF Risk Assessments have shown promise to serve as a systematic approach for making risk management decisions for marine systems:

"The PWS Study should be considered as a first step in marine systems risk assessment." [RARMMS Committee, National Research Council, 1998]

In addition it is worth noting that both risk assessments have resulted in significant investments to enhance the safety in the marine systems following their recommendations.

To live up to the promise of the approach, to provide decision-makers with the necessary information to make good risk management decisions and to withstand the scrutiny of peer review, uncertainty in the risk assessment model needs to be addressed. The principal investigators fundamentally agree with the almost classical "speaking the truth in risk assessment" argument [see e.g., Kaplan, 1997] originating from the early 1980's when the International Society for Risk Analysis was founded. The crux off the argument goes as follows:

"The truth is that we are uncertain. Therefore, speaking the truth implies that we express our analysis results in terms of probability curves rather than fixed points estimates".

3. Background

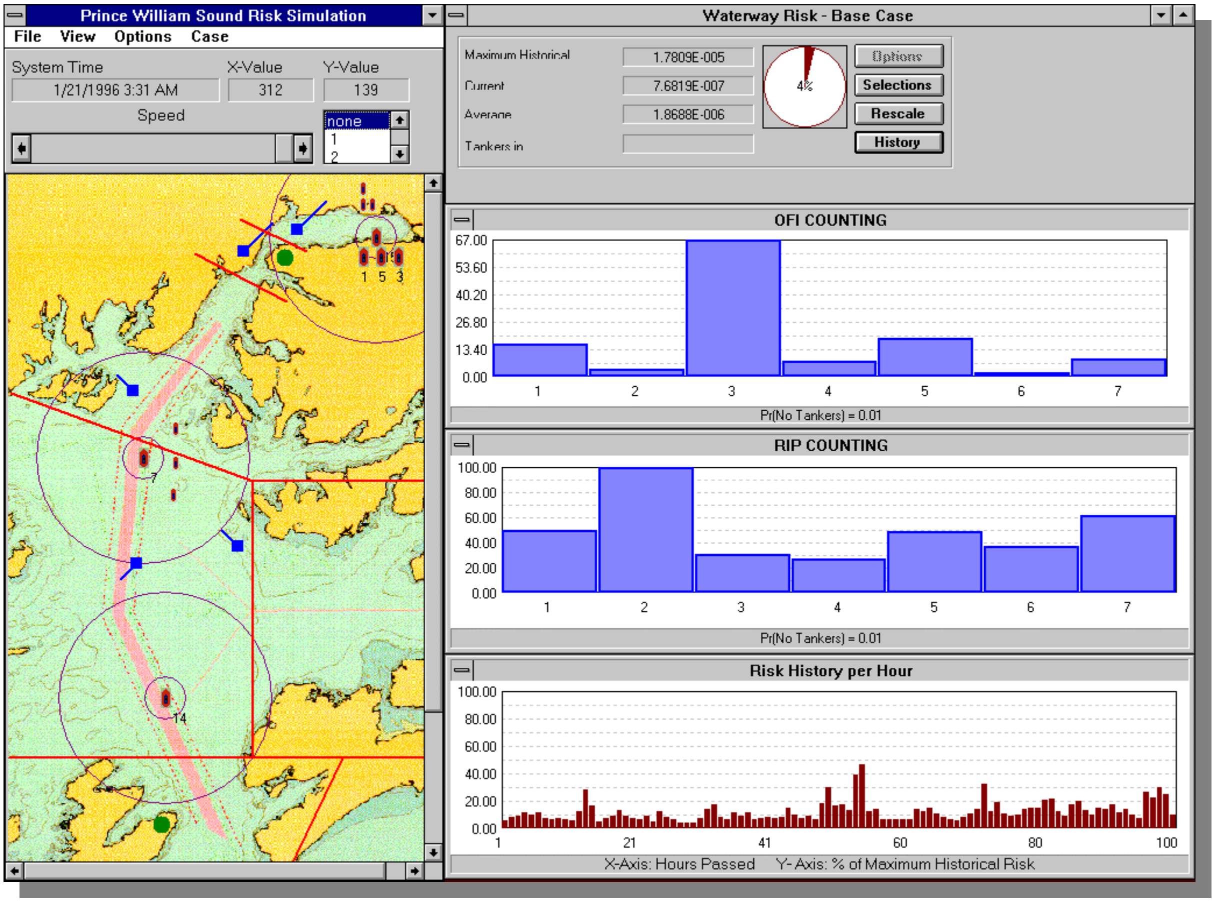
This section discusses relevant previous work and introduces the theoretical framework used in the PWS and WSF risk assessments.

3.1 Risk Assessment and Management in Maritime Transportation

The assessment and management of risk in maritime transportation has been identified by the National Research Council as an important problem domain [NRC, 1986; NRC, 1991; NRC, 1994; NRC, 2000]. The literature of the National Research Council captures the knowledge base of the extensive work performed in this domain. Earlier work concentrated on assessing the safety of individual vessels or marine structures, such as nuclear powered vessels [Pravda & Lightner, 1966], vessels transporting liquefied natural gas [Stiehl, 1977] and offshore oil and gas platforms [Paté-Cornell, 1990]. The USCG attempted to prioritize federal spending to improve port infrastructures using a classical statistical analysis of nationwide accident data [USCG, 1973; Maio et al., 1991]. More recently,
PRA [USNRC, 1975] has been introduced in the assessment of risk in the maritime domain [Hara and Nakamura, 1995; Roeleven et al., 1995; Kite-Powell, 1996; Slob, 1998; Fowler and Sorgard, 2000; Trbojevic and Carr, 2000; Wang, 2000; Guedes Soares and Teixeira, 2001]. This latter work has examined risk in the context of Maritime Transportation Systems [NRC, 1999]. In a Maritime Transportation System (MTS) traffic patterns change over time in a complex manner and system simulation has been proposed and used as a modeling tool to assess MTS service levels [Andrews et al., 1996], to perform logistical analysis [Golkar et al., 1998] and to facilitate the design of ports [Ryan, 1998]. In addition to the dynamic nature of traffic patterns, situational variables such as wind, visibility and ice conditions change over time occasioning risk to be a dynamic property of the MTS. The PWS Risk Assessment and WSF Risk Assessment differ from previous maritime risk assessments in that this dynamic nature of risk is captured by integrating system simulation [Banks et al., 2000] with available techniques in the field of PRA [Bedford and Cooke, 2001] and expert judgment elicitation [Cooke, 1991].

3.2 Prince William Sound Risk Assessment

One port in the United States where a systematic approach was used for evaluation of risk reduction measures is Valdez, Alaska. The grounding of the Exxon Valdez in 1989 caused public and government concern about the safety of oil transportation in the Prince William Sound, Alaska. As a result, a large number of proposals and recommendations were made to improve safety, but stakeholders could not achieve a consensus on their effectiveness at reducing risk. A steering committee representing all local stakeholders, including the Prince William Sound Shipping Companies, the Prince William Sound Regional Citizens Advisory Council, the Alaska Department of Environmental Conservation and the U.S. Coast Guard, was formed to address the issue of risk intervention effectiveness. The steering committee hired a team of consultants in 1994, with team members from the George Washington University (GWU), Rensselaer Polytechnic Institute/Le Moyne College (RPI) and Det Norse Veritas (DNV), who were charged with assessing the current risk of accidents involving oil tankers operating in the Prince William Sound and evaluating measures aimed at reducing this risk. The team created a detailed model of the Prince William Sound oil transportation system, using system simulation, data analysis and expert judgment, capable of answering the majority of the questions posed by the Steering Committee. Figure 1 displays the PWS System Risk Simulation in graphics mode. A simulation of the PWS Oil Transportation System for 25 years (the analysis period in the PWS Risk Assessment) would take 8 hours on high-end PC's when run in batch mode (i.e. with graphics turned off).



System Time: 1/21/1996 3:31 AM
X-Value: 312
Y-Value: 139
Speed: none

Maximum Historical: 1.7809E-005
Current: 7.6819E-007
Average: 1.8688E-006
Tankers in:

Figure 1. The System Risk Simulation program was created to perform the analysis and demonstrate the results to the Steering Committee. On the left, the dynamic behavior of the PWS Marine Transportation System is displayed including traffic patterns and environmental conditions, for example wind speed and direction. On the right, the analysis shown is broken down by location, with estimates of the frequency of the system states at the top and the probabilities of an accident in each system state in the middle. The dynamic variation in the total expected frequency of accidents is shown at the bottom.

The project spanned a time frame of two years, involving bi-monthly meetings with the steering committee and contract team. The contract cost amounted to approximately 2 million U.S. dollars (not including the cost of the Steering Committee attending the bi-monthly meetings in Anchorage, Alaska). The success of the project has been demonstrated by the acceptance of the major recommendations by all stakeholders and has, to date, resulted in multi-million dollar investments. The success of the Prince William Sound Risk Assessment has not gone unnoticed and

NSF funding (e.g. NSF SBR-9520194, NSF SBR-9710522) has been awarded to understand the risk assessment process that was followed in the Prince William Sound Risk Assessment project. The study is now presented as an example collaborative analysis [Busenberg, 1999; Busenberg, 2000; Charnley, 2000]. We quote from a paper by George J. Busenberg, 1999, titled "Collaborative and adversarial analysis in environmental policy":

"All ten of the participants who were interviewed agreed that this process allowed the steering committee to gain a better understanding of the technical dimensions of maritime risk assessment ... The results of the risk assessment were released in late 1996, and were unanimously accepted as valid by the RCAC, oil industry, and government agencies involved in this issue. The participating groups agreed that the study showed the need for an ocean rescue tug vessel in the Sound. In 1997, the oil industry responded by deploying a vessel of this class in the Sound (RCAC, 1997b)."

3.3 Washington State Ferry Risk Assessment

Another port in the United States where a systematic approach was used for evaluation of risk reduction measures is Seattle, Washington. 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 (WSF), based in Seattle.

On July 9, 1998, the Blue Ribbon 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.

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 on board 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 Washington State Transportation Commission.

The Washington State Ferry Risk Assessment was completed in July 1999, and is a maritime risk assessment similar in size, scope and methodology as the PWS Risk Assessment Study. Similar to the PWS Risk Assessments monthly meetings were scheduled with the Blue Ribbon Panel on Ferry Safety and were conducted in an open forum (meetings were announced to the public) and may also be considered based on the paradigm of collaborative analysis.

The methodology followed in the Washington State Ferry Risk Assessment build on the experiences of the GWU/RPI Team in the PWS Risk assessment and may be considered a refinement of the methodology followed in the PWS Risk Assessment, addressing some of the criticism stated by the RARMMS Committee. The total cost of the WSF Risk Assessment amounted to $800,000, which clearly indicates the beneficial effect of a learning curve when conducting similar projects. The Washington State Ferry Risk Assessment study may be considered "a success" in the sense that it helped establish legislative funding for the implementation of the International Safety Management (ISM) code fleet wide though out the Washington State Ferries, as opposed to only its international routes (one of its major recommendations).

3.4 The PWS and WSF Risk Assessment Framework

An accident is not a single event, but the culmination of a series of cascading events [Garrick, 1984] starting with a triggering incident. In this model, triggering incidents have been further categorized as mechanical failures and human errors. Accidents and triggering incidents occur within the context of a system event defined by a combination of organizational factors (OF) and situational factors (SF).

Figure 2 summarizes the accident probability model used in the study, including both the time sequence of the accident event chain and the influence of organizational and situational factors on this chain. To simplify the probability model, it was assumed that organizational factors influence the occurrence of triggering incidents and situational factors influence the occurrence of accidents, while both affect the consequences of an accident.

The accident probability model discussed herein was based on the notion of conditional probability. The levels of conditional probability reflected in Figure 2 are

- **P(OF,SF):** the probability that a particular set of organizational and situational factors occur in the system
- **P(Incident| OF):** the probability that a triggering incident occurs given the organizational factors and

- **P(Accident| Incident, SF):** the probability that an accident occurs given that a triggering incident has occurred.

To perform an assessment of the risk of an accident using this model, each term in the probability model needs to be estimated.

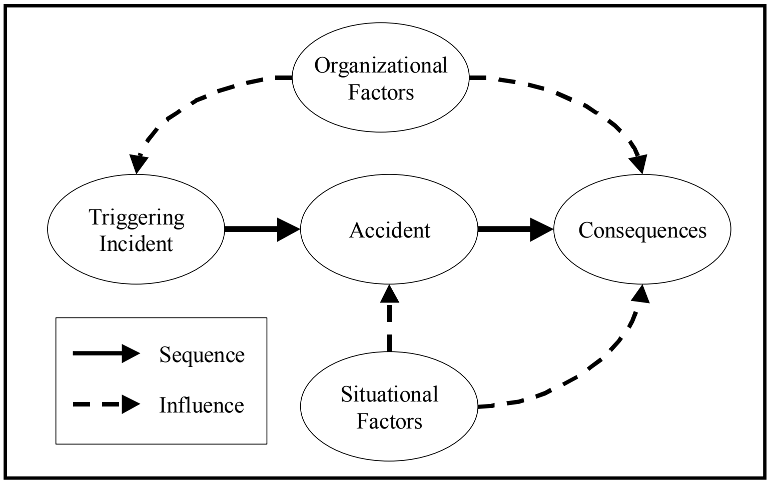


Figure 2. The accident probability model.

The simulation was used to count the occurrence of combinations of organizational and situational factors. The state of the system in the simulation was calculated once every five minutes based upon the traffic location, environmental conditions and the previous state of the system. For each PWS tanker (or WSF Ferry) in the system at any given time, a system event was counted that included the organizational and situational factors. A system event was also counted for each vessel considered to be interacting with the PWS tanker (or WSF Ferry). A multi-year simulation was run and for each five-minute period the system events that occurred were counted. Thus the average yearly frequency of particular combinations of organizational and situational factors **P(OF,SF)** could be estimated using the simulation.

The next step in the estimation of accident frequency was to estimate the two levels of conditional probability of triggering incidents and accidents. i.e. **P(Incident|OF)** and **P(Accident|Incident,SF)**. The preferred method for estimating the above probabilities is through the statistical analysis of accident data. However, both in the PWS Risk Assessment and WSF Risk Assessment only local accident was to be used in the risk assessment. In each case less than three relevant accidents had been recorded. Thus analysis had to rely, at least in part, on expert judgment solicited from the PWS/WSF community. Expert judgment elicitation is often crucial in performing risk analyses [Cooke, 1991] and has been used in areas as diverse as aerospace programs, military intelligence, nuclear engineering, evaluation of seismic risk, weather forecasting, economic and business forecasting and policy analysis. The approach developed was built on the premise that the judgments of experts that have a deep understanding of the system would provide a basis for the assessment of risk; see [Harrald, 1992]. It must be noted, however, that when applicable all available data was used in this approach.

In addition to the requirement of accurately counting the frequency of system events, the use of a systems model is important for system wide evaluation of risk mitigation measures. The use of a discrete-event simulation captures the complex dynamic nature of the maritime transportation systems and thus allows for the system wide evaluation of risk migration effects potentially associated with the implementation of particular risk intervention measures [see, e.g., Merrick et al., 2000, Merrick et al., 2001].

3.5 Format of Results in PWS and WSF Risk Assessment

One of the advantages of the risk assessment approach common to both the PWS and WSF Risk Assessment is the separation of base rates of combinations **(OF,SF)** occurring and probability of accidents per combination **P(Accident|OF,SF)** and, finally, the combination of the two to arrive at an overall risk picture. Consider for example collision accidents in case of the Washington State Ferries in Figure 3 below.

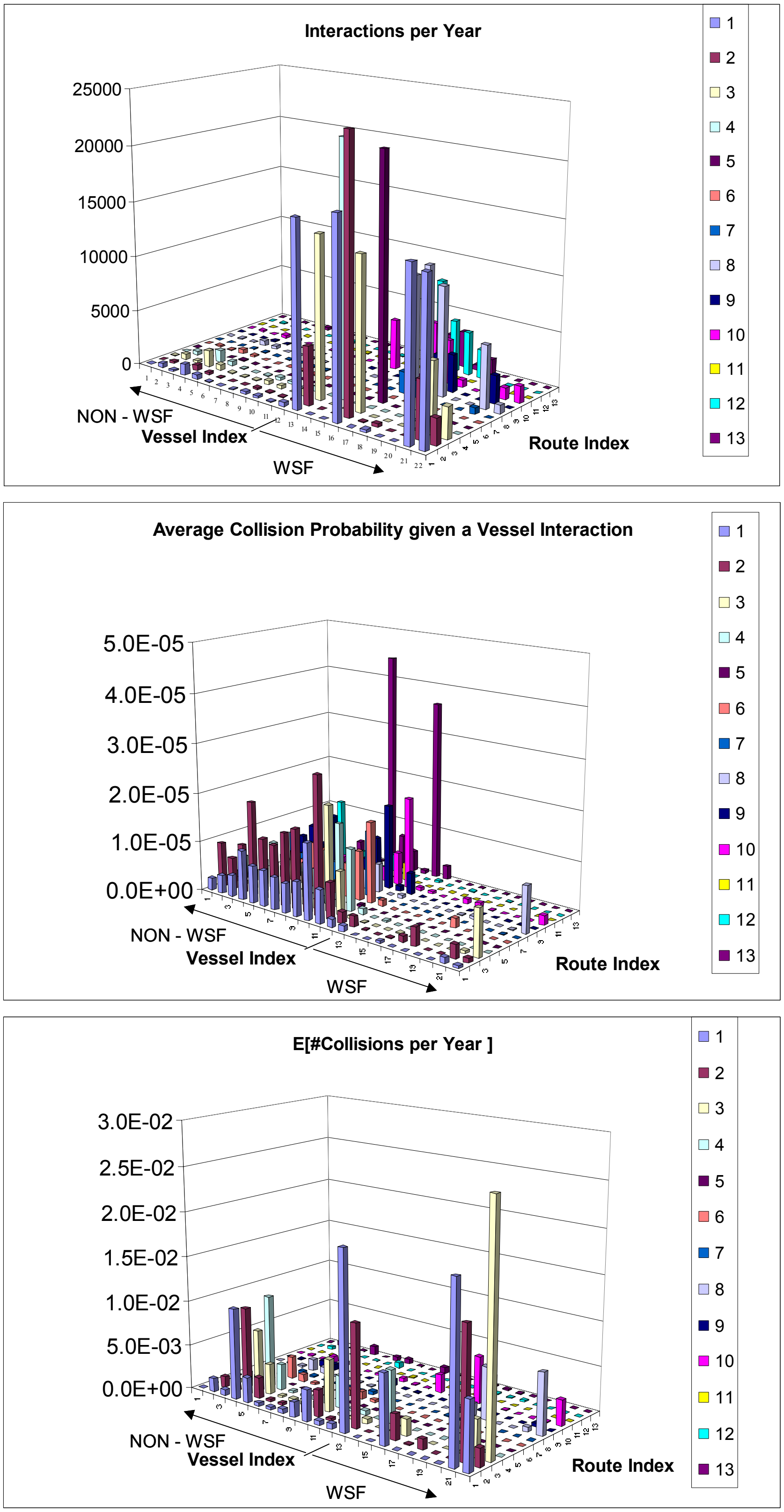


Figure 3. Example format of Base Case Scenario Risk Assessment Results.

Figure 3 presents 3-dimensional graphs displaying the collision risk levels by ferry route and interacting vessel type. The first graph shows the average number of interactions per year by ferry route and by interacting vessel type and is generated using the simulation. The higher bars to the right of the Vessel Index axis shows that the number of interactions is much higher with Washington State ferries (keys 13 to 22) than with non-WSF vessels (keys 1 to 12). The second graph shows the average collision probability per interaction by ferry route and interacting vessel type and is calculated using a combination of expert judgment and calibration to available collision data. The higher bars to the left of the Vessel Index axis (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 (keys 13 to 22) on a per interaction basis. The third graph shows the annual collision frequency by ferry route and type of interacting vessels and is a combination of the information in the first two graphs. 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 the second figure it can be observed that the annual frequency of collisions with non-WSF vessels is driven by the collision probability for each interaction. From the first figure it can be observed that the number of interactions per year drives the annual frequency of collisions with WSF ferries. Such a detailed understanding of the *risk*-picture is useful for the identification of potentially effective risk intervention measures, but also for the explanation of evaluated effectiveness of any planned risk intervention measures.

Risk intervention effectiveness is evaluated by first formulating a baseline scenario and analyze the maritime transportation system along the lines of the three-dimensional graphs discussed. Changes are then made to the baseline scenario to reflect the implementation of the risk intervention measure and evaluate the maritime transportation system with the changed baseline scenario. Comparison of the analysis in both scenarios allows for assessment of risk intervention effectiveness. Figure 4 shows the graphical format using the tornado diagram approach to show risk intervention effectiveness. The actual risk intervention cases modeled are described in van Dorp et al. (2001). One problem with the representation in Figure 4 is the apparent finality of the results. The decision-maker is led to believe that the results are definitive and are in no way uncertain. To speak the truth in maritime risk assessments, the degree of uncertainty needs to be communicated.

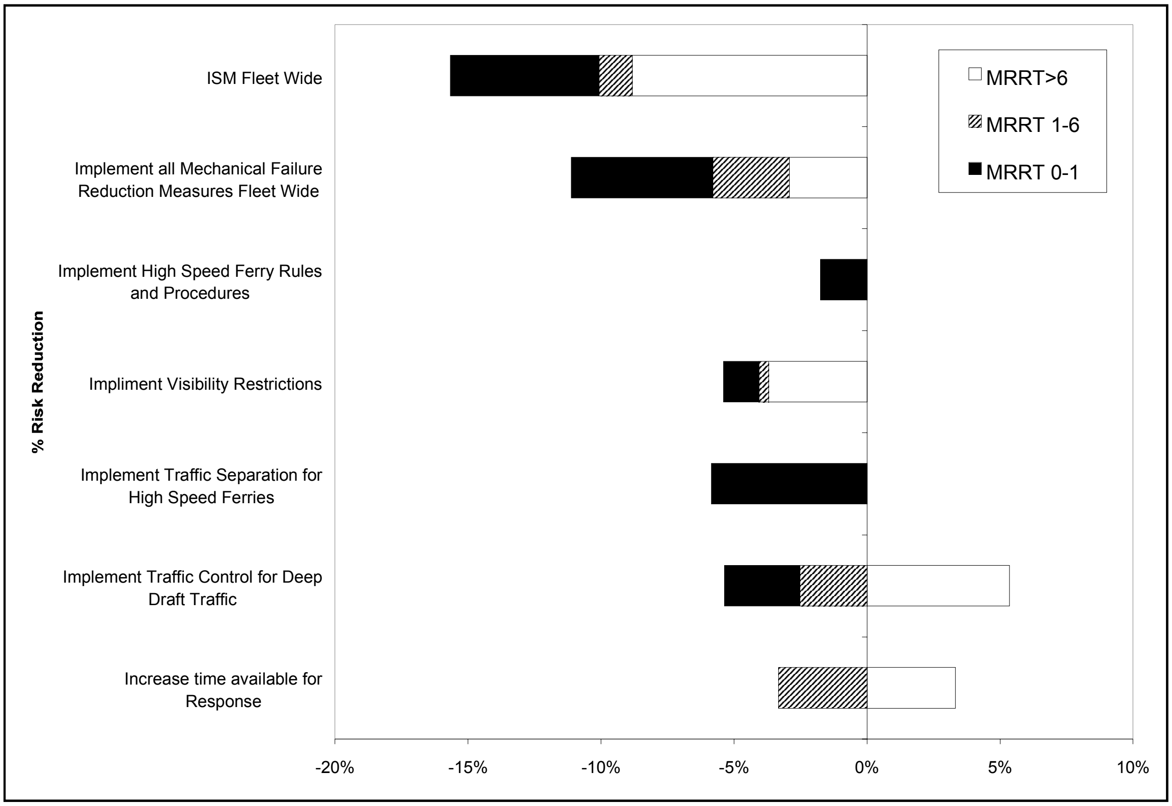


Figure 4. Example format of Risk Intervention Effectiveness Evaluation.

3.6 Validity of the Approach

An important question in any study is the validity of study results. In a complex system, such as a maritime system, it is impossible to capture all the subtleties of system behavior and, therefore, any model is at best an approximation. Furthermore, since a PRA is used to model very rare events with high consequence, there can be no experimental verification of its validity [Parry, 1996]. At the time of the PWS Risk Assessment, criticisms were leveled at certain results. In the minds of some stakeholders events that had not occurred were much less likely than events that had, even when the risk models indicated otherwise. One such example is the identification by the models that large numbers of fishing vessels in the Valdez Narrows and surrounding areas during a tanker transit would increase the risk of collisions and powered groundings. Such an event had not occurred and the simulation-based result was seen as an indication that the model was overestimating the collision risk. In September 1999, however, 4 million gallons of oil spilled accidentally from the tanker Diamond Grace near Tokyo Bay when the tanker, attempting to steer around fishing vessels, ran aground. More recently, on July 10th 2001, the tugs escorting the Chevron Mississippi had to halt the tanker in two ship lengths to avoid a collision with two fishing vessels that had strung their net across the channel in Valdez Narrows.

Capturing the dynamic behavior of a maritime system through simulation is pertinent given the prevalent use of simulation as an analysis tool in transportation systems. In the PWS and WSF risk assessments, graphical comparison to the actual system and numerical comparison using summary statistics validated the simulation part of the model. However, the expert judgment based estimates of accident and incident probabilities are more difficult to validate. Expert judgment is the best available source of information in an environment where the data is too sparse to populate the parameters of the probability model. Risk assessments typically deal with low probability, high consequence events and thus statistical validation of their results is difficult even when nationwide or global accident databases are used. The use of nationwide or global accident data in localized risk assessments is also questionable which lead to the requirement of the PWS steering committee to use only PWS specific data. The requirement of using only PWS specific data meant that risk estimates could not be validated in the traditional sense. In the case of the probability of triggering incidents such as mechanical failures, where there was an overlap between available data and expert judgments, good correspondence was observed. Although this correspondence is encouraging, the question of validity of other expert based estimates, where such comparisons could not be made, still remains. This implies that the communication of the remaining uncertainties is crucial to allow fully informed decision-making.

4. Speaking the Truth in Maritime Risk Assessment

The PIs realize the complexity and effort involved to address the uncertainties under item 4 in studies with a scope similar to the PWS and the WSF Risk Assessments. In both studies additional funding was requested to investigate the uncertainties in the risk evaluation conducted. In both cases, however, this request for funding was denied primarily due to time and budget constraints of the contracting agencies, but also because such an exercise was considered to be academic. Due to the level of trust instilled in the risk assessment through the collaborative analysis approach, an uncertainty analysis was not deemed necessary to support the recommendations.

At this time the theoretical framework for addressing uncertainty in the PWS and WSF methodology in a coherent manner is not developed. Both the PWS Risk Assessment and WSF Risk Assessment rely heavily on the use of expert judgment and simulation. Both studies follow classical techniques in codifying, collecting and analyzing the result of the expert elicitation and the simulation, resulting in point estimates of assessed risk. To address the uncertainties, i.e. express risk in terms of probability curves, a coherent theoretical framework needs to be developed combining the uncertainties in the Simulation and the expert judgment within the transportation risk assessment methodology of the PWS and WSF Risk Assessments. In principal, the PIs propose to follow the paradigm of “Evidence Based Decision Making” advocated by Kaplan (1997) and Kaplan & Garrick (1981).

The presence of uncertainty in analyzing risk is well recognized and discussed in the literature. However, these uncertainties are often ignored or under-reported in studies of controversial or politically sensitive issues [Pate-Cornell, 1996]. Two types of uncertainty are discussed in the literature, aleatory uncertainty (the randomness of the system itself) and epistemic uncertainty (the lack of knowledge about the system). In a modeling sense, aleatory uncertainty is represented by probability models that give probabilistic risk analysis its name, while epistemic uncertainty is represented by lack of knowledge concerning the parameters of the model [Parry, 1996]. In the same manner that addressing aleatory uncertainty is critical through probabilistic risk analysis, addressing epistemic uncertainty is critical to allow meaningful decision-making. Cooke (1997) offers several examples of the conclusions of an analysis changing when uncertainty is correctly modeled.

While epistemic uncertainty can be addressed through frequentist statistical techniques such as bootstrap or likelihood based methods [Frey and Burmaster, 1999], the Bayesian paradigm is widely accepted as a method for dealing with both types of uncertainty [Apostolakis, 1978; Hora, 1996; Hofer, 1996; Cooke, 1991]. However, as pointed out by Winkler (1996), there is no foundational Bayesian argument for the separation of these types of uncertainty. Ferson and Ginzburg (1996) use the terminology variability for aleatory uncertainty and ignorance for epistemic. Winkler's argument essentially says that variability is purely ignorance of which event will occur.

The distinction of types of uncertainty, however, does have certain uses in the risk assessment process [Anderson et al., 1999]. Specifically, the distinction is useful when explaining model results to decision-makers and the public and when expending resources for data collection. In the communication case, the distinction must be drawn between the statements "we don't know if the event will occur" and "we don't know the probability that the event will occur." In the data collection case, epistemic uncertainty can be reduced by further study and data collection, whereas aleatory uncertainty is irreducible, as it is a property of the system itself [Hora, 1996].

Bayesian modeling can allow for the distinction and handle the underlying differences inherently. Monte Carlo simulation [Vose, 2000] can be used to propagate uncertainty through a model (requiring significant computer power), while Bayesian analytical techniques can be used for analyzing data and expert judgments [Berger, 1985; Bernado and Smith, 1994; Gilks et al., 1996].

Pate-Cornell (1996) defines six levels of treatment of uncertainty in risk analysis.

0. Identification of hazards.
1. Worst case analysis.
2. Plausible upper bound analysis.
3. Best estimates.
4. Probability and risk analysis.
5. Display of risk uncertainties.

The PWS and WSF Risk Assessments were conducted at level 4, considering only aleatory uncertainty. The results in Figures 3 and 4 are generated using point estimates (i.e. expected values) for all quantities involved. To address the uncertainties in the PWS/WSF Risk Assessment approach in a comprehensive and coherent manner we need to separately address uncertainty in the simulation estimates of the bases rates **P(OF,SF)** and uncertainties in the assessment of the conditional probability **P(Accident| OF,SF)** within the theoretical framework of the PWS/WSF Risk Assessment methodology. Hence, the following natural division of tasks that need to be completed.

4.1 Task 1: Representation of Uncertainty in Simulation

The simulation is used to estimate the frequency of the various possible system states **P(OF,SF)**. Random processes control the arrival of vessels and environmental conditions in to the simulation. The parameters of the random processes must be estimated from data collected from the system. This introduces inherent input uncertainty in the simulation. Estimates from simulations are also uncertain as the simulation cannot be run infinitely many times or for an infinite run time. Thus there is output uncertainty. Estimation of the level of confidence achieved in simulation estimates is standard in simulation analysis [Law and Kelton, 2001]. To propagate the uncertainty through the estimates of accident risk in a coherent manner, a Bayesian paradigm will be followed.

There is an extensive literature on the theory of Bayesian simulation analysis [Glynn, 1986; Chen and Schmeiser, 1995; Chen, 1996; Chick, 1997; Nelson et al., 1997; Chen et al., 1999; Cheng, 1999; Chick and Inoue, 2001; Chick 2001]. The general paradigm of this research is that simulation analysis is a decision-making tool and therefore should be used under a decision-analytic framework. The use of Bayesian methods in building and analyzing simulation models takes the analysis from level 4 to level 5 on Pate-Cornell's scale of uncertainty modeling. Barton and Schruben (2000) show several examples of the conclusions of simulation studies changing when input uncertainty is incorporated rather than using mean input estimates. Chick (2000) gives an excellent review of Bayesian methods, separating the work into 3 focus areas: input uncertainty, sensitivity and best system selection procedures.

Input uncertainty should be incorporated in the analysis to reflect the limited data available to populate the parameters of the arrival processes in a simulation model [Chick, 2001]. In the Washington State Ferries Risk Assessment, if we consider traffic arrivals to the system only, there were 224 separate arrival processes for various types of vessels and routes taken [Merrick, 2000]. These arrival processes were modeled by the standard renewal process [Law and Kelton, 2001]. Historical inter-arrival times were calculated from data supplied by the Vessel Traffic Service at Tofino. This data was used obtain point estimates of the parameters of a variety of inter-arrival time distributions and classical goodness of fit tests were used to choose a suitable distribution. Under the Bayesian paradigm, prior distributions are specified for the parameters of the postulated distributions and the data is used to update these priors through the standard Bayesian machinery. The most difficult problem is choosing the best fitting probability model. Recent work in the field of Bayesian statistics has included criteria such as Bayes factors [Kass and Raftery, 1995], posterior predictive densities [Gelfand, 1996] and the recently proposed Decision Information Criterion [Spiegelhalter et al, 1996]. Due to the large number of processes to be modeled, conjugate prior-model combinations should be chosen wherever possible. The input uncertainty can then be incorporated in the simulation analysis using the following algorithm where the index $r=1,\ldots,n$ indicates a simulation replication:

1. Sample values for the r-th replication of the parameters of the inter-arrival time distributions from the posterior distributions obtained in the Bayesian input analysis.
2. Perform the r-th replication of the simulation using sampled values of the parameters of the inter-arrival time distributions.
3. Collect the appropriate output statistics for the r-th replication.

In the analysis of output data, the focus has been on estimating means of important output statistics, rather than attempting to define its probability distribution. Bayesian Model Averaging is the commonly used term when the average of the n output statistics obtained by the above algorithm is used to estimate the statistic's expected value. However, as we wish to propagate uncertainty throughout the model, a probability model will be hypothesized for the output statistic. The output values for the replications of the simulation are treated as data to update the prior distributions on the output statistic model's parameters. Chick (2000) notes that this can be thought of as a Bayesian version of metamodeling [Law and Kelton, 2001]. Such treatment of output data flows naturally in to a decision-analytic handling of choosing the best system [Nelson et al., 2000; Chick and Inoue, 2001]. In our risk assessment methodology, the quantity of interest is the **P(OF,SF)** for each possible combination of organizational and situational factors; the data obtained from the simulation in each replication will be the number of times each combination occurred in the total simulated time. We could either estimate the frequency of each **(OF,SF)** combination using a Poisson model, with the conjugate gamma prior on the rate of occurrence, or we could estimate the probability using a Binomial model, with conjugate beta prior. In either case, the appropriate likelihood function is used to update the prior (usually uninformative) with the data, thus obtaining posterior distributions of the frequencies or probabilities that have been updated from the simulation runs. These distributions will incorporate the input uncertainty, as we have used the above algorithm, and the output uncertainty, due to our Bayesian meta-models.

Previous work on Bayesian methods for simulation has concentrated on theoretical developments; implementation has been restricted to demonstrations using simple models, rather than full-scale development of complex simulations. The high level of computation necessary for propagating uncertainty through complex simulation models, with large numbers of arrival processes and extremely large numbers of output statistics, suggests the use of parallel and distributed computing methods. Fujimoto (1999) gives an excellent review of such methods as applied to simulation modeling. The majority of the work in this area involves splitting the execution of a single simulated experiment across multiple processors. Two types of algorithms are used to ensure correct time sequencing; conservative algorithms that ensure correct operation through intensive communication and optimistic algorithms that clean up after an error. Pasquini and Rego (1999) report efficient results using a network of workstations to provide the parallel platform. Wieland (1998) reports great success at MITRE Corporation in using parallel simulation methods in aviation applications.

The success of the various applications of parallel and distributed methods in simulation analysis would suggest that their application in our problem area should be advantageous. The use of a network of workstations rather than purpose built multi-processor machines should enable others to replicate the work. However, our application differs from the previous work in that each processor will run a single replication, the parallelism coming from the need to perform a large number of highly intensive simulation (8 hours to run the PWS simulation once) to propagate input and output uncertainty in the risk assessment models. The handling of such parallel simulations and the integration of the results will require the correct use of parallel computing techniques.

The intellectual merit of this task is a state-of-the-art implementation of Bayesian simulation methods in addition to the development of new techniques to incorporate parallel computing methods to allow for the computational complexity of Bayesian simulation.

4.2 Task 2: Representation of Uncertainty in Expert judgment

The preferred method for estimating **P(Incident|OF)** and **P(Accident|Incident,SF)** is through the statistical analysis of accident data. In the history of the PWS oil transportation system, there have been only two accidents involving oil tankers, the well-known Exxon Valdez grounding and the collision of the Overseas Ohio with ice. Clearly, this data was insufficient to estimate the effect of the situational and organizational factors on accident and incident frequency. Thus the PWS analysis had to rely, at least in part, on expert judgment solicited from the PWS community. The situation was a little improved during the WSF Risk Assessment, with an accident database of 47 events. However, collisions were the primary focus of that study and only 2 of the 47 events were collisions involving WSF vessels.

Expert judgment was used to estimate the effect of organizational and situational factors on the two levels of conditional probability of triggering incidents and accidents. Harrald et al. (1998) and Merrick et al. (2000) discuss the form of the elicitation used in each risk assessment. The key to good expert judgment elicitation is to define both a methodology and an instrument that can be easily comprehended by the experts and yet is powerful enough to be useful in the analysis. As discussed in Cooke (1991), indirect elicitation of probabilities is preferable to direct probability elicitation, especially when the experts are unfamiliar with probability assessments.

The expert judgments in the PWS Risk Assessment were elicited indirectly using paired comparisons [Bradley & Terry, 1952] with an extended scale [Saaty, 1977] as shown in Figure 5. The paired comparisons presented to the experts were at a level of detail defined by the organizational and situational factors. This level of detail was necessary for the questions to reflect actual situations observed by the experts. However, the numerical judgments of the multiple experts were pooled using a simple geometric averaging technique [Moslesh and Apostolakis, 1983]. Point estimates were then obtained for the parameters of the accident probability models using a least squares regression analysis.

The quantification of risk models for policy and decision-making often requires the elicitation of expert judgments [Moslesh et al., 1988; Bonano et al., 1989; Morgan and Henrion, 1991; Cooke, 1991]. In fact, as long as the fundamental mechanisms that drive a system remain poorly known, the encoding of expert knowledge will be required [Pate-Cornell, 1996]. As noted by Anderson et al. (1999) expert judgment must be used with care. It is not evidence, but an individual's or group's inference based on available evidence. Kahneman et al. (1982) discuss the many biases and heuristics that are introduced when humans process information and attempt to give judgments.

Winkler (1996) points out that due to the general belief that several heads are better than one, information is usually elicited from multiple experts. Numerous techniques exist for the aggregation of multiple experts' responses [Morris, 1974; Winkler, 1981; Genest and Zidek, 1986; Clemen, 1989; Mendel and Sheridan, 1989; Cooke, 1991; Diwispelare et al., 1995]. In recent reviews of the techniques, Clemen and Winkler (1990, 1999) note that often the simple aggregation techniques work just as well as the more complex methods. However, the Bayesian paradigm again supplies the most natural approaches to the problem [Cooke, 1991].

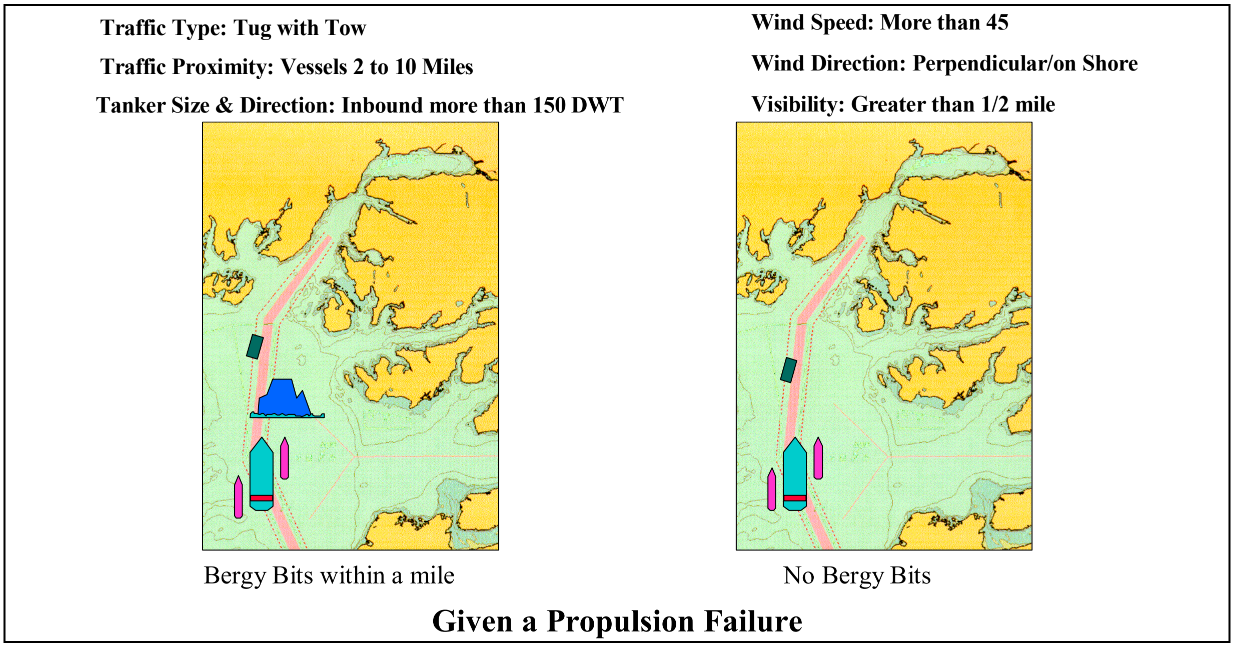


Figure 5. An example of a scenario pictured in the questionnaires.

Roeleven et al. (1995) suggested the following flexible probability model for maritime accidents given a system state described by a vector $\underline{X}$

$$P(Accident \mid \underline{X}) = P_0 \exp(\underline{\beta}^T \underline{X}),$$

where P_0 is the base rate probability and the parameters $\underline{\beta}$ describe the effect of the systems attributes on the accident probability. This accident probability model was used in the PWS and WSF Risk Assessment and models the aleatory uncertainty. Mosleh and Apostolakis (1984) discuss Bayesian models for aggregation of expert opinion utilizing conjugate analysis of normal priors with a normal likelihood model. The Bayesian paired comparison approach for accident probabilities proposed herein combines the accident probability in Roeleven et al. (1995) with the approach of Mosleh and Apostolakis (1984). Specifically, let a paired comparison of two systems states (comprised of a combination of organizational factors and situational factors) in question *j* of a questionnaire be summarized in paired comparison of a single vector $\underline{X}_1{}^j$ (system state 1) and $\underline{X}_2{}^j$ (system state 2). Suppose a single expert responds "y_j" to the question of the relative likelihood of an accident in $\underline{X}_1{}^j$ compared to $\underline{X}_2{}^j$. From the accident probability model above it follows that

$$y_j = \frac{P(Accident \mid \underline{X}_1^j)}{P(Accident \mid \underline{X}_2^j)} = \exp\left(\underline{\beta}^T (\underline{X}_1^j - \underline{X}_2^j)\right)$$

Taking logarithms on both sides yields

$$\underline{\beta}^T \underline{Z}^j = Log(y_j),$$

where $\underline{Z}^j = \underline{X}_1^j - \underline{X}_2^j$. The linear form above, combined with a normal model for the prior distribution of the parameters $\underline{\beta}$ and a normal model for the expert responses (similar to Mosleh and Apostolakis (1984)) will result in a conjugate analysis for a single expert. However, this approach needs to be extended to incorporate the correct aggregation of the expert responses to fully assess the level of uncertainty in the estimates obtained. Different aggregation schemes will be considered including simple averaging techniques, such as the linear opinion pool and the logarithmic opinion pool [Clemen & Winkler, 1999], techniques for weighting the judgments of the experts [Cooke, 1991] and Bayesian techniques that require the decision maker to express judgments concerning the abilities of the experts [Clemen & Winkler, 1990; Mendel & Sheridan, 1989]. Such a treatment of uncertainty can provide a description of the level of disagreement between experts [Pate-Cornell, 1996].

The intellectual merit of this task is the development of a Bayesian paired comparison accident probability model utilizing expert judgment elicitation. Note that, the proposed development is generic in nature and not restricted to a maritime transportation audience (or transportation accidents for that matter).

4.3 Task 3: Propagation of the Uncertainties Through the Whole Model

Completion of Task 1 will yield a posterior predictive distribution of the number of times a year each possible combination of the levels of organizational and situational factors occurs. Completion of Task 2 will yield a posterior predictive distribution of the conditional probabilities of each type of incident and accident given any possible combination of the levels of organizational and situational factors.

In the level 4 analysis, the analysis program runs through each possible combination of the levels of organizational and situational factors, multiplying each conditional probability and summing over each such combination and each type of incident and accident to obtain the overall accident risk estimate. This calculation can then be performed conditionally, giving estimates of accident risk broken down by accident type or incident type or by any organizational or situational factor. This type of analysis yields the graphs in Figure 2 where the results of the WSF Risk Assessment are broken down by ferry route and between WSF and non-WSF vessels.

However, this multiplication of conditional probabilities involves only best estimates of each term, yielding only best estimates of each piece of the analysis. The results appear to be certain and interpretation can be easily overstated. It should be noted though that there are a very large number of possible combinations of the levels of organizational and situational factors; during the WSF Risk Assessment each such analysis ran for 30 minutes on a Pentium III 400 Mhz machine. Current technology could significantly reduce this calculation time, but the calculation of the mean estimate would still be a significant task.

Monte Carlo simulation is the most commonly used tool for propagating uncertainty through a risk analysis model. As noted by Winkler (1996) analytical solutions should be used if at all possible. In most cases, closed form solutions are not possible and the brute force simulation method must be used [Pate-Cornell, 1996]. Propagating uncertainty using Monte Carlo simulation through fault trees or event trees common to probabilistic risk assessments is highly computationally intensive.

Using these methods with the WSF Risk Assessment models will require running the analysis program once for each sampled value of the conditional probabilities. To ensure that the analysis including uncertainty can be performed in a reasonable period of time, parallel computing methods will once again be developed to break down the task into manageable pieces that can be re-integrated to yield final results. This is critical as such analyses must be performed iteratively to interrogate the model in order to achieve a deep understanding of the results. Furthermore to estimate the effect of the risk mitigation measures, each alternative must be analyzed, again compounding the calculation time. Parallel Monte Carlo simulation methods will be developed to propagate the uncertainties through the risk models using a network of workstations.

The intellectual merit of the research proposed herein stems from the development of an overarching Bayesian framework for addressing uncertainty when simulation of systems states is combined with available data and expert judgment to assess risk and risk intervention effectiveness.

4.4 Task 4: Conduct a Trial Uncertainty Analysis

To test the viability of the proposed approach, a trial uncertainty analysis will be performed. Rather than re-create large risk models for a new maritime system, the results of the WSF Risk Assessment will be used as the example. The intent of this analysis is not to provide an uncertainty analysis for the WSF, but to test the methodology on a real life, full sized risk assessment model and to give realistic examples of the possible effects of uncertainty on the conclusions reached [Cooke, 1997].

We anticipate every bar represented in Figures 3 and 4 to be modeled via an uncertainty distribution rather than a fixed-point estimate that can be viewed individually. Perhaps more importantly, using these distributions, we can present Figure 3 at any desired common quantile level. Such information would provide sensitivity of risk identification to such quantile levels, but also allows a worst-case analysis (quantile level = 100%) and a best-case analysis (quantile level = 0%) of the risk picture as well. In addition, we anticipate to be able to develop tornado diagrams like Figure 4 for every common quantile level between the baseline scenario and risk intervention scenario's. Such information would be incredibly useful as it would indicate the sensitivity of risk intervention effectiveness to such a quantile level thereby communicating to the decision-makers whether we truly know that one risk mitigation measures is better than another.

The intellectual merit of this task, as suggested by one the NSF reviewers, stems from the observation that its completion can be characterized as a feasibility study of uncertainty propagation in large-scale risk assessments.

4.5 Task 5: Publish Journal Papers

The PIs anticipate submitting three journal papers as deliverables over the course of the project. For emphasis the publication of these three journal papers is organized in a separate task. Below target journals are identified for the three journal papers:

- 1 Journal paper developed at the end of Task 1, Target journal: *Simulation Practice and Theory*, Elsevier Science.
- 1 Journal paper developed at the end Task 2, Target journal: *Management Science*, INFORMS.
- 1 Journal paper developed at the end of Task 4, Target journal: *Risk Analysis, an International Journal*, Blackwell Publishers.

The first two papers will be technical in nature focusing on the framework for addressing uncertainty and the necessary theoretical developments. Examples will be included from the maritime domain.

5. Project Implementation

The PIs will conduct this study in two years (Fig. 6). *They will disseminate the results through journal papers, conference presentations and a project website. The project website will be created upon project award. The website will immediately post documentation related to the maritime risk assessment framework, i.e. the final report of the Washington State Ferry Risk Assessment and its technical appendices as well as the published journal papers [van Dorp et al., 2001; Merrick et al., 2000; Grabowski et al. 2000; Harrald et al., 1999]. Copyright release will be requested for published journal papers. Journal paper deliverables, to be completed at the end of Task 1, 2 and 4, will be posted on the web site after submission to the journals in question.*

Research assistants from GWU and VCU will participate in all aspects of the research. While the PI's will offer consistent guidance through weekly meetings with the research assistants, the students are encouraged to become more independent as their research skills improve. At the start of the project the guidance may need to be more intense to familiarize the student with the theoretical framework of the Prince William Sound and Washington State Ferry risk assessment. Through participation the students will develop intellectual excitement and research skills to pursue a career in engineering risk analysis research. The collaboration between the universities GWU and VCU will expose them to different academic environment, specifically a private and a state university. *Efforts are being made to recruit students from underrepresented groups at both universities. Project results will be incorporated into courses taught by the investigators, specifically the course "Risk and Vulnerability Analysis for Natural and Technological Hazards" at GWU and a new course "Engineering Risk Analysis" to be developed at VCU.*

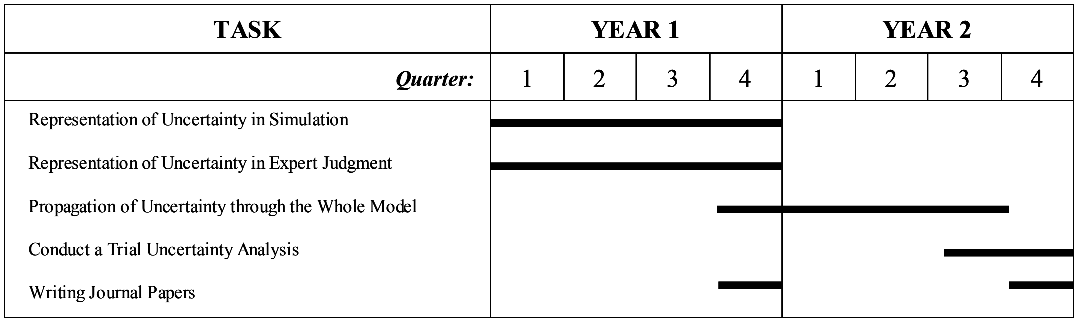


Figure 6. Project timeline

The cost of funding for this theoretical development amounts to $158,471 for GWU and $154,442 for VCU, totaling $312,913 and spans a total duration of two years. A detailed budget is attached. The funding amount requested is small, when seen in light of the cost of the PWS Risk Assessment project and WSF Risk Assessment project. The primary reason being that only 1 month of summer funding is requested for the PIs and less than 1 month for the Co-PIs and full time funding for 2 research assistants. One senior faculty member of the risk assessment team, J.R. Harrald (The George Washington University) will make contributions at no cost to the sponsor.

The proposed research effort is collaborative in nature to draw together the necessary expertise in risk assessment, Bayesian analysis techniques and parallel computing. Rene van Dorp and his student from GWU will work with Jason Merrick at VCU to develop the Bayesian methodology that will model uncertainty in the simulation and expert judgment components of the model. Thomas Mazzuchi at GWU will assist them in this effort. This work comprises part of Task 1 and all of Task 2. David Primeaux and the student at VCU will work towards the parallel implementation of the simulation model. Tasks 3 and 4 will require the full participation of all members of the collaborative research team.

The intellectual merit of the research proposed herein stems from the development of an overarching Bayesian framework for addressing uncertainty when simulation of systems states is combined with available data and expert judgment to assess risk and risk intervention effectiveness. The development of a Bayesian pairwise accident probability model utilizing expert judgment elicitation is new to the best of our knowledge. Bayesian simulation analysis techniques have only been proposed in theoretical settings [Chick, 2001], thus their use in a large complex system may be considered state of the art in the field of computational sciences. Furthermore, the techniques of Bayesian simulation have not thus far been combined with parallel computing techniques to facilitate the added computational complexity. Finally, as suggested by one the NSF reviewers, the project can also be characterized as a feasibility study of uncertainty propagation in large-scale risk assessments.

This research will bring benefits as it completes addressing the concerns of The National Research Council (specifically, The Marine Board's committee on Risk Assessment and Risk Management of Maritime Systems (RARMMS)) associated with their evaluation of the PWS risk assessment study (See Section 1). Through the journal papers Van Dorp et al. (2001), Merrick et al. (2000), Grabowski et al. (2000), Harrald et al. (1998) and the three journal papers to be developed over the course of this project, a comprehensive framework for risk management analysis, and its uncertainties, in transportation environments is available in the open literature. The combined journal papers will promote the use of formal assessment with regard to risk management by providing a systematic approach to determining levels of risk, opportunities to implement risk reduction measures, and relative benefits of alternative measure as advocated by Transportation Research Board of the National Research Council (See Section 1).

The broader impact of the proposed work is primarily drawn from its applicability to areas other than maritime accident risk. In the aftermath of the September 11 attacks, port security risk (intentional as opposed to accidental) has now been recognized as an integral part of homeland security. In a recent Washington Post article, Sen. Joseph I. Liebermann (D-Conn) was quoted "The plain fact is that the movement of goods into the U.S. is now so efficient *that* ***port security*** *has been compromised " [Booth, 2002]. The PI's have recently submitted a white paper in response to a DOT BAA announcement on transportation security [Harrald et al., 2001]. Subsequent uncertainty assessment of security risk and propagation in security intervention effectiveness needs to be accounted for, since lack of data will even be of greater concern. As suggested by each of the NSF reviewers, despite the focus on maritime risk, the framework and methodologies developed will be applicable to other transportation modes as well, such as aviation or road safety. Aside from aviation security and accident risk, the technique will be directly transferable to the ever-increasing problem of runway incursions as a result of increased traffic congestions at our national airports.*

6. Results of Previous Funding

J. René van Dorp:

1. CO-PI the Washington State Ferry Risk Assessment awarded by the Washington State Department of Transportation [Harrald et al., 1999; Grabowski et al., 2000; van Dorp et al., 2001].
2. CO-PI on $mall Accelerated Reliability Testing ($MART) contract awarded by the IIT Research Institute, IITRI Purchase Order Number 1231964
3. Investigator on Oil Spill Risk Analysis, Prince William Sound Risk Assessment Project, for ADEC, APSC/SERVS, PWS Regional Citizens Advisory Council, US Coast Guard, PWS Shipping Companies. [Harrald et al., 1998; Merrick et al., 2000; Harrald et al., 2000; Merrick et al., 2001].
4. Consultant to Dutch Civil Engineering firm HAM to develop a risk analysis tool for risk-based bidding on large construction/dredging projects.
5. Investigator, Cost Risk Analysis on a Ship Building Process, For Shipbuilding Ventures, Inc., ARPA grant December 1994, Design of Virtual Shipyard.
6. Investigator, Evaluating and Monitoring Waterway Risk for Passenger Vessels on the Lower Mississippi River, National Ports and Waterways Institute. Risk Analysis funded by the New Orleans Port Authority.
7. Investigator, Development of Uncertainty Analysis Tool for Risk Analyses of Large Chemical Manufacturing Plants, DSM, Geleen, Holland.

Jason Merrick has not been a PI or Co-PI on a NSF-funded grant:

1. Investigator on NSF grant 9874924. The work on this grant is coming to a close, but has already had significant success in developing a multi-criteria decision analysis model for watershed management and has led to 2 publications being submitted to refereed, archival journals [Barnett et al., 2001; Garcia and Merrick, 2001].
2. PI for the federal funded development of the Ports and Waterways Safety Assessment tool for the United States Coast Guard [Harrald and Merrick, 1999] and
3. PI for the state government funded WSF Risk Assessment [Harrald et al., 1999; Grabowski et al., 2000; van Dorp et al., 2001].
4. Investigator for the PWS Risk Assessment funded by the oil shipping companies and the Regional Citizen's Advisory Committee [Harrald et al., 1998; Harrald and Merrick, 1999; Merrick et al., 2000; Harrald et al., 2000; Merrick et al., 2001].
5. Investigator for the analysis of escort requirements in Prince William Sound.
6. Investigator for the NASA review of the application of satellites in emergency management.
7. Investigator for the Association of American Railroads analysis of the efficacy of maintenance practices on the frequency of rail failures.
8. Investigator for the United States Post Office maintenance optimization project for mail sorting systems.

All completed work has been extensively published in both academic and industry journals with the aim of disseminating the knowledge gained to all interested parties.

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