Table of Contents

Figures and Tables

Executive Summary

The objective of the Ship Transit Risk project has been to investigate the relationship between factors such as environmental conditions, vessel characteristics, and operators' information about the waterway, and the incidence of groundings and collisions, using historical data. While the historical data on circumstances surrounding accidents in U.S. waters are neither perfect nor complete, we have found that they contain information that appears to be useful to understanding why accidents occur.

Groundings and collisions of commercial ships account for more than half of all commercial maritime accidents, including some of the most expensive in the United States' history, such as the *Exxon Valdez* grounding in Prince William Sound. These accidents represent a risk because they expose vessel owners and operators, as well as the public, to the possibility of losses such as vessel and cargo damage, injuries and loss of life, environmental damage, and obstruction of waterways. Strictly speaking, the risk associated with groundings and collisions is a product of the probability of the physical event and the probability, given that the accident has occurred, of economic losses (where "economic" is broadly defined). The project deals primarily with the physical risk component.

The general hypothesis behind our physical risk model is that the probability of an accident on a particular transit depends on a set of risk factors or "explanatory variables." Major categories of these variables include operator skill, vessel characteristics, traffic characteristics, topographic and environmental difficulty of the transit, and quality of operator's information about the transit.

In summary, the project determined that, based on historical data on navigational accidents involving commercial vessels in U.S. port approaches:

- one commercial ship grounds in a U.S. port approach roughly every 1300 transits, and one collision occurs roughly every 1200 transits;
- barge train accident rates are slightly higher than those for ships, and large ships have higher accident rates than small ships;
- high wind speed appears to increase the risk of accidents only slightly, whereas poor visibility appears to increase accident risk by one to two orders of magnitude;
- U.S. flag vessels appear to be involved in a disproportionately large number of accidents;
- water level forecast errors do not appear to contribute to accident risk; and
- due to data limitations, it is unclear whether uncertainty in water depth information resulting from older surveys contributes to grounding risk in U.S. port approaches.

Implications of these findings for transit risk management include possible benefits from greater emphasis on navigational aids and transit regulations for poor visibility conditions.

Two general observations can be made about historical data on maritime accidents in U.S. waters: (1) the data are incomplete, thereby limiting the type and depth of analysis that can be conducted, and (2) the data are inconsistent, making it difficult to compare accident rates across ports or over time. The project has resulted in the following suggestions for improved data collection on maritime accidents in the future:

U.S. Coast Guard casualty databases:

- establish and use consistent criteria for all ports for entering incidents into the database
- establish and use consistent criteria for obtaining information such as wind speed and direction, visibility, water level, current speed and direction, etc.
- eliminate/correct erroneous and duplicate entries (e.g. location information)
- record data on actual draft and trim, presence and use of tugs, presence of pilots

U.S. Army Corps of Engineers (and port authority) transit databases:

- report separately dry cargo and passenger vessel movements
- report "barge train" movements as well as individual barges
- improve temporal resolution (transits by day or hour)

1. Introduction

1.1. Background and Objectives

From 1995 to 1998, researchers at the Massachusetts Institute of Technology (MIT) Ocean Engineering Department and the Marine Policy Center (MPC) of the Woods Hole Oceanographic Institution (WHOI) collaborated on a project on Ship Transit Risk. The project was developed by MIT, in collaboration with MPC staff, as a three-year research activity. The focus of the first year was on collection and assimilation of data to support an improved understanding of the factors contributing to vessel casualties. Years 2 and 3 were spent analyzing the contribution of various factors to observed transit risk. This report describes the research findings of the project. A complete list of publications and reports produced by the project is in Appendix 4. Three graduate students from the MIT Ocean Engineering Department's Ocean Systems Management Program contributed to the project. Johan Jebsen and Vassilis Papakonstantinou worked as a team of graduate research assistants on the project from 1996 to 1997, and produced a master's thesis (Jebsen and Papakonstantinou 1997). Shu-Chiang (John) Lin worked as a graduate research assistant on the project during 1997 and 1998, and also produced a related master's thesis (Lin 1998).

Groundings and collisions of commercial ships account for more than half of all commercial maritime accidents, including some of the most expensive in the United States' history, such as the *Exxon Valdez* grounding in Prince William Sound. These accidents represent a risk because they expose vessel owners and operators, as well as the public, to the possibility of losses such as vessel and cargo damage, injuries and loss of life, environmental damage, and obstruction of waterways. Strictly speaking, the risk associated with groundings and collisions is a product of the probability of the physical event and the probability, given that the accident has occurred, of economic losses (where "economic" is broadly defined). The project deals primarily with the physical risk component.

Many factors contribute to vessel maritime accidents. Some of these factors are of particular concern to federal agencies charged with responsibility for the nation's marine transit routes. For example, the National Oceanic and Atmospheric Administration (NOAA) is responsible for the survey of U.S. waters, for the publication of nautical charts, and for environmental condition forecasts. The U.S. Coast Guard (USCG) and the U.S. Army Corps of Engineers (ACE) are responsible for navigation aids and for channel design and maintenance, respectively. All of these factors may influence how likely groundings and collisions are to occur.

The objective of the Ship Transit Risk project has been to investigate the relationship between these sort of factors and grounding and collision incidents, using historical data. While the historical data on circumstances surrounding accidents in U.S. waters are neither perfect nor complete, we have found that they contain information that appears to be useful to understanding why accidents occur. Note that we have investigated only the *association* between circumstances surrounding a transit and the occurrence of accidents. We emphasize the word “association” as distinct from “cause.” It is not our intent here to prove causal relationships between attending factors and accidents. Such proof is difficult to accomplish without conducting exhaustive controlled experiments; the data required exceed those available in the historical record. The present research aims to establish associations, to identify and investigate factors that, on the basis of association and by rational consideration, appear to contribute meaningfully to risk.

The available data limited the number and type of factors we could evaluate explicitly. Ultimately, this work should lead to a comprehensive model of transit risk that includes additional factors such as traffic type and density, navigational aid configuration, and channel design. We would like to have included these factors in our analysis, but were not able to find sufficient data in the historical record to support their inclusion. Because of the limitations imposed by historical data, more comprehensive models of transit risk will have to rely on the integration of simulation results and expert judgement with the sort of historical data analysis presented here (see Amorozowicz, 1996).

1.2. Physical Risk Model Approach

The general hypothesis behind our physical risk model is that the probability of an accident on a particular transit depends on a set of risk factors or “explanatory variables.” Formally, the model can be described as follows: let A denote the event that a transit results in a grounding (G) or a collision (C), and let $X = (X_1, X_2, X_3, ..., X_p)$ be the vector of explanatory variables. These variables may be categorical (including binary) or continuous. Let S denote the event that the transit is completed safely. The model attempts to estimate the conditional probability of A given a specified value x of X. By Bayes' Theorem, this probability is given by:

$$p(A|x) = \frac{l(x|A) * p}{l(x|A) * p + l(x|S) * (1 - p)}$$

where p is the unconditional probability of A and where $l(x|A)$ and $l(x|S)$ are the likelihoods of x given A and S, respectively.

To implement this approach, it is necessary to select a set of explanatory variables that discriminates between A and S (Hand, 1981) and to estimate the unconditional grounding probability p and the likelihoods $l(x|A)$ and $l(x|S)$. In practice, the attributes that can be examined are limited by the available data. Major categories of attributes include:

a. operator skill (training, experience, local knowledge, fatigue, etc.)

b. vessel characteristics (maneuverability, etc.)
c. traffic characteristics (density of vessel traffic, small boats, etc.)
d. topographic difficulty of the transit (channel size and complexity, shoals and water depth, navigation aid configuration, etc.)
e. environmental difficulty of the transit (wind, visibility, current, waves, etc.)
f. quality of operator's information (charts, water level, wind/visibility, VTS, etc.)

2. Background on Study Ports

Following a decision reached with the project advisory group, the project team focused on four study areas: the Port of New York/New Jersey, Tampa Bay, Houston/Galveston, and San Francisco Bay (Boston Harbor was included initially but dropped because of insufficient data). Site visits and meetings with maritime safety organizations were held in San Francisco, Houston, and New York.

Data on historical accidents, transits, and environmental conditions were collected for each study area for the period 1981 to 1995. Data sources include national and local units of the U.S. Coast Guard (USCG) and the U.S. Army Corps of Engineers (ACE); NOAA's National Ocean Service, National Climate Data Center, National Geophysical Data Center, and National Data Buoy Center; and local port authorities, marine exchanges, and pilots.

Accident data are drawn from the USCG's CASMAIN (1981-90) and MSIS (1992-95) databases. We consider separately large (draft 30 feet or greater) and small tankers and dry cargo vessels, tank barge trains, and dry cargo barge trains (a barge train is defined as a tug/towboat attached to one or more barges). As mentioned, we focus on groundings and collisions (including contact between two vessels and between a vessel and a fixed structure). We exclude from our analysis accidents caused primarily by mechanical failure, and focus on "navigational" incidents.

The distribution of explanatory factors associated with accident events, $l(x|A)$, is derived primarily from the USCG data on vessel casualties. The USCG data include information about vessel type (ship/barge, oil/dry cargo), vessel size (tonnage, converted by an approximation to draft), and wind and visibility. The USCG reported wind speed and visibility data are not complete. Where these data are missing, we use NOAA's National Climatic Data Center (NCDC) hourly average wind speed and visibility data. If the time of the accident is not reported in the USCG data, a daily average is used. The NOAA/NCDC data are taken from sensors located at airports near the study ports, and provide the only readily available proxy for on-site conditions.

The distribution of explanatory factors associated with safe transits, $l(x|S)$, is derived from a variety of data sources. Vessel type and size counts are calculated from ACE transit data, as described above. The distribution of flags of registry for ships' safe transits is based on data provided by local marine exchanges and port authorities. The joint distribution of wind speed and visibility conditions is derived from NOAA/NCDC data for "safe" days, when no accidents occurred. Lacking any specific information about the distribution of transits during the year, or about the joint distribution of ship size and flag, we assume no correlation between flag and ship size, and between safe transits and particular environmental conditions.

2.1. Transits

Transit data are based on ACE Waterborne Commerce Statistics annual summaries, 1981-1995. For our purposes, a "transit" is a vessel movement, so that a port call usually consists of two transits: one into and one out of the port. We examine safe transit data using the same vessel type and size breakdown as for accidents.

To avoid double counting, we based our transit count for each study port on data for only one "waterway" in each port, as shown in Table 1.

	waterways code
Port of Boston	0149
New York and New Jersey Channels	0388
Tampa Harbor	2021
Houston Ship Channel	2012
San Francisco Bay Entrance	4320

Table 1: Waterway Codes Used in Transit Data Collection

This procedure leads to underestimation of actual vessel movements, especially for Houston and New York. Unfortunately, there appears to be no simple way to build more accurate time series of transits for study port areas.

Table 2 shows average annual transits for each study port during the study period. Barge train transits are estimated using an average number of barges per train for each study port.

	ships	*barge trains*
New York	10,200	30,100
Tampa	3,700	3,000
Houston	9,900	18,600
San Francisco	7,800	400

Table 2: Average Annual Transits, 1981-95, based on ACE data

We examine transit data using the same vessel type and size breakdown as for grounding data. Figures 1 through 4 illustrate transits for ships and barge trains in each study port over the study period.

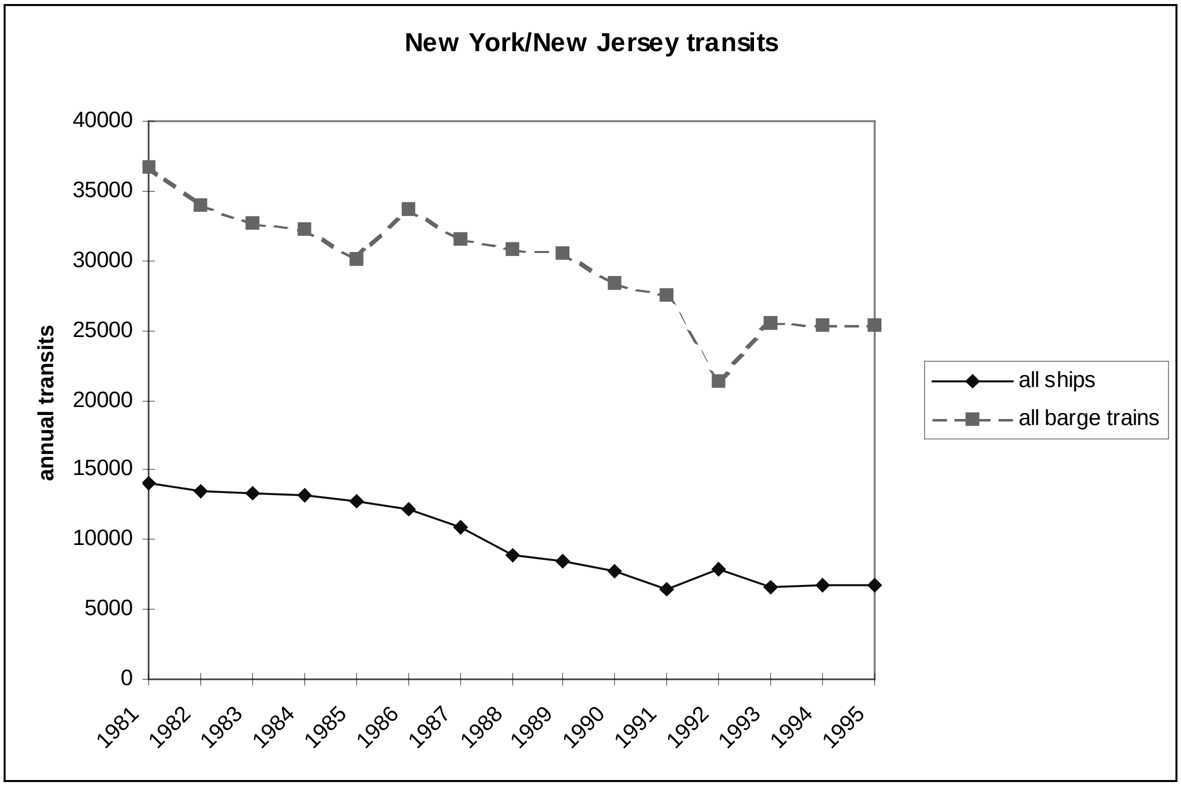

Figure 1: Transits in New York/New Jersey, 1981-95

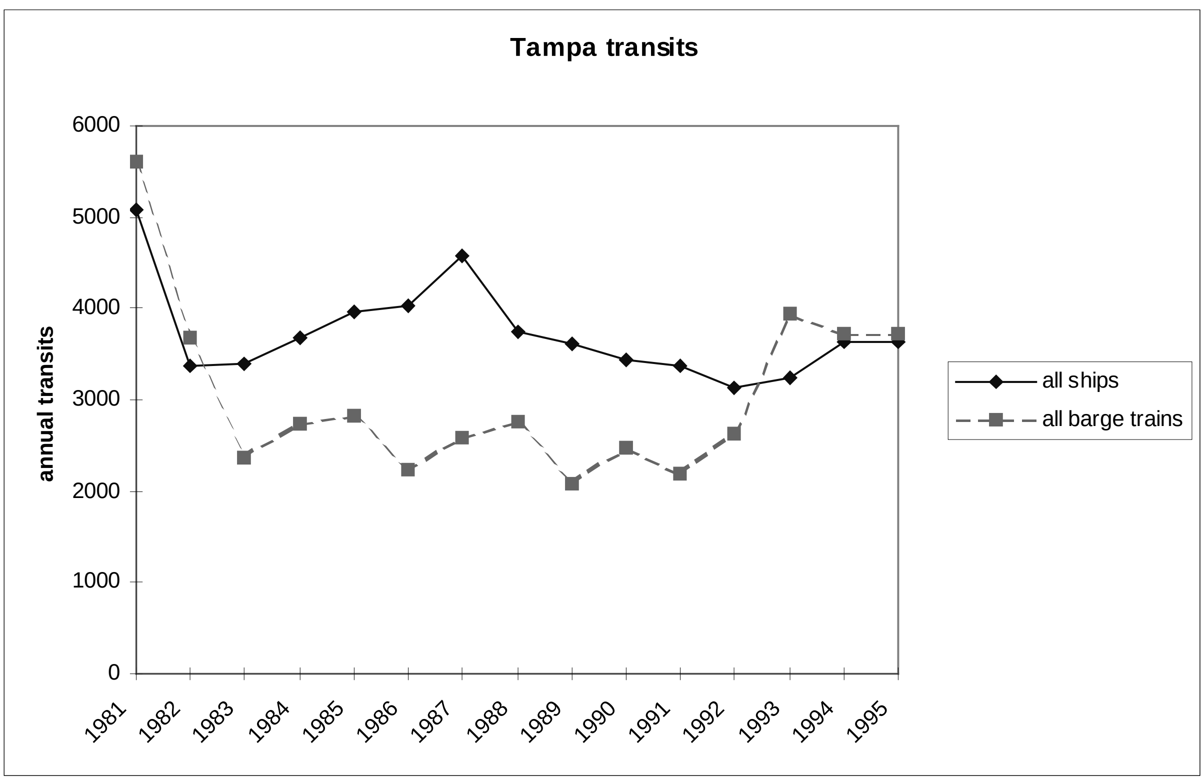

Figure 2: Transits in Tampa Bay, 1981-95.

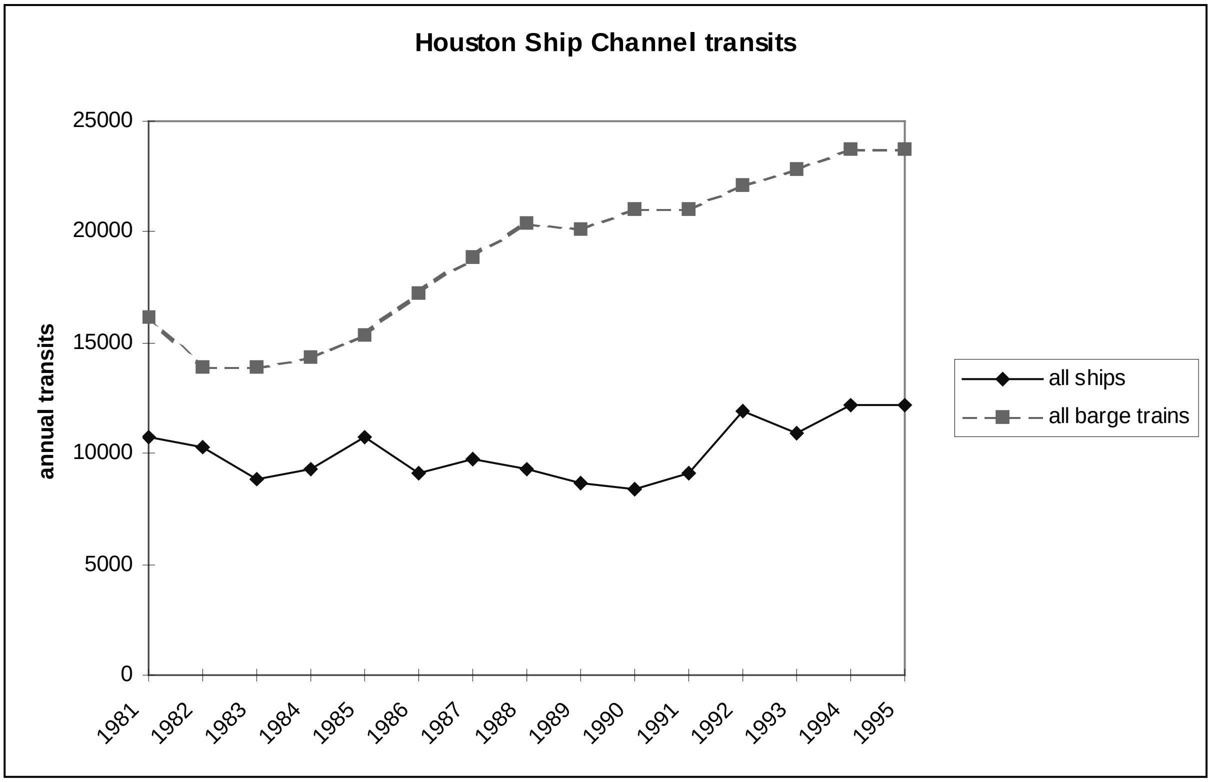

Figure 3: Transits in Houston/Galveston, 1981-95.

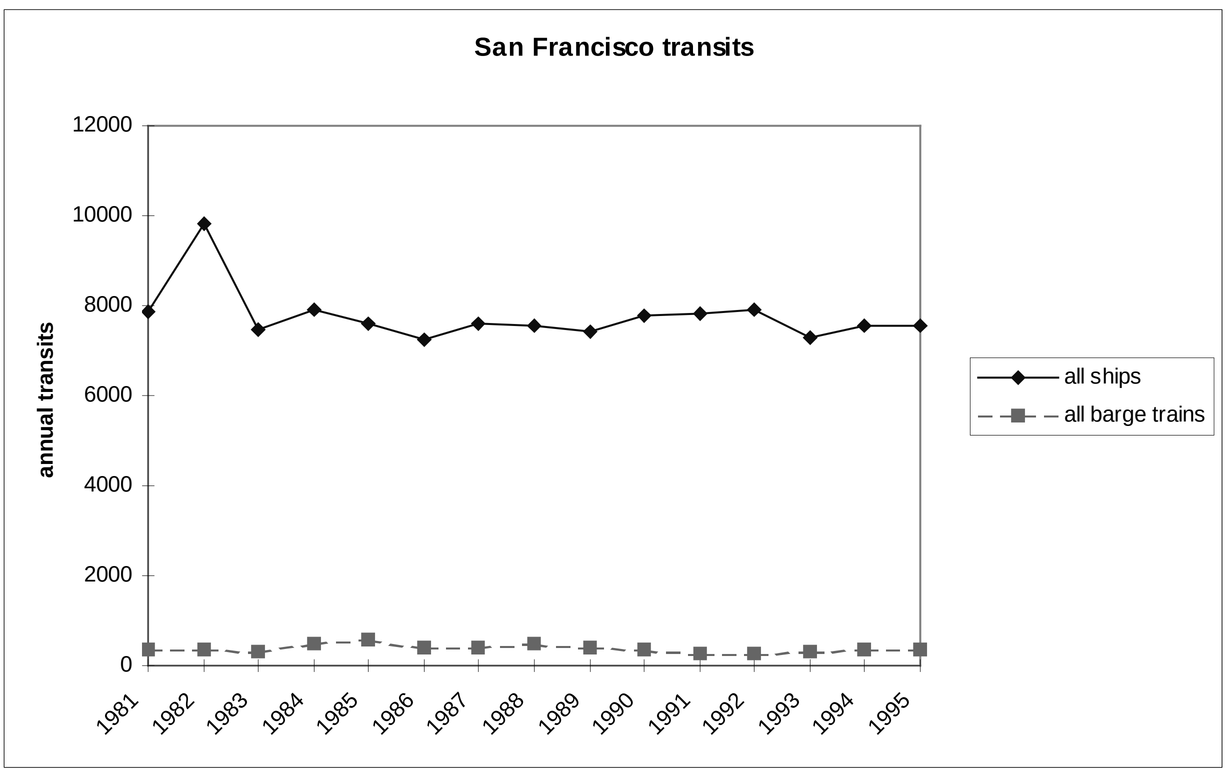

Figure 4: Transits in San Francisco Bay, 1981-95.

2.2. Groundings and Collisions

Grounding and collision data are drawn from the USCG's CASMAIN (1981-90) and MSIS (1992-95) databases. Data for 1991 are sparse and obviously incomplete in each dataset; we replace the 1991 counts by averages of the surrounding years for purposes of analysis. From the USCG data we selected for inclusion in this study only accidental, navigational groundings, and ignored those identified as intentional or due to mechanical failure or other, clearly non-navigational cause. We consider separately large (draft greater than 30 feet) and small tankers and dry cargo vessels, tank barge trains and dry cargo barge trains (a barge train is defined as a tug/towboat attached to one or more barges). Table 3 shows the number of groundings in the data for each study port and year. Table 4 shows a summary of collisions.

	New York				**Tampa**				**Houston**				**San Francisco**			
	ships		barge trains		ships		barge trains		ships		barge trains		ships		barge trains	
	tank	dry	tank	dry	tank	dry	tank	dry	tank	dry	tank	dry	tank	dry	tank	dry
1981	7	5	3	0	1	4	5	5	9	4	37	5	1	1	1	0
1982	1	1	1	1	0	1	3	3	2	3	26	9	2	3	1	1
1983	1	2	2	0	2	0	1	1	8	10	13	3	3	4	0	0
1984	3	3	3	0	5	4	3	4	8	5	17	6	0	3	1	0
1985	8	9	6	1	4	4	6	6	2	1	4	1	3	2	1	0
1986	6	2	3	3	2	1	6	2	0	2	1	1	3	2	1	0
1987	4	3	2	4	3	3	2	2	6	3	6	0	2	5	1	0
1988	2	4	9	2	6	9	1	3	8	5	18	1	1	3	0	0
1989	14	2	9	3	5	3	1	1	6	1	5	3	4	3	2	1
1990	6	2	2	2	1	2	1	4	7	2	11	3	3	3	0	0
1991*	0	2	0	0	0	0	0	1	1	0	0	0	0	1	0	0
1992	5	4	5	0	2	4	4	1	8	2	16	2	1	3	0	0
1993	3	4	4	0	2	1	3	4	4	1	29	6	3	2	1	0
1994	2	1	6	1	2	2	3	4	9	6	49	4	3	6	1	0
1995	1	0	1	0	1	0	1	0	8	3	43	8	3	3	0	1
1981-95	**63**	**44**	**56**	**17**	**36**	**38**	**40**	**41**	**86**	**48**	**275**	**52**	**32**	**44**	**10**	**3**

Table 3: Groundings in study ports, 1981-95.
*1991 data are incomplete.

	New York			Tampa			Houston			San Francisco		
	Barge Train	Tank Ship	Other Ship	Barge Train	Tank Ship	Other Ship	Barge Train	Tank Ship	Other Ship	Barge Train	Tank Ship	Other Ship
1981	27	2	6	2	2	3	19	9	12	1	0	0
1982	2	0	1	4	2	3	18	1	6	0	1	3
1983	6	0	4	2	0	0	3	2	1	2	1	0
1984	19	2	4	6	2	0	6	1	7	3	0	5
1985	19	2	4	10	2	3	9	1	5	4	2	3
1986	33	2	4	6	1	0	3	0	3	4	2	2
1987	22	1	7	6	0	2	4	1	2	2	1	4
1988	45	5	12	2	0	2	13	5	3	1	1	2
1989	29	4	6	2	0	4	10	3	4	2	1	0
1990	18	3	2	2	0	0	16	2	3	2	0	0
1991*	18	3	2	7	3	2	34	6	7	4	2	2
1992	19	2	2	12	7	3	52	11	11	7	3	4
1993	22	3	5	3	0	4	44	13	14	3	4	6
1994	21	2	6	4	1	2	91	11	11	5	3	9
1995	5	0	1	0	1	5	54	6	8	5	2	12
1981-95	**305**	**31**	**66**	**68**	**21**	**33**	**376**	**72**	**97**	**45**	**23**	**52**

Table 4: Collisions in study ports, 1981-95.
*1991 data have been adjusted.

Seasonal trends appear in the incidence of both groundings (Figure 5) and collisions (Figure 6). In the east coast and Gulf coast ports, accidents are more frequent during the winter months than during the summer. This is likely due to seasonal differences in environmental conditions (see Figures 11 and 13). Seasonal fluctuations in traffic volumes are not significant and do not appear to coincide with the fluctuations in accident counts.

The data also suggest different levels of risk for groundings during transits during daylight and at night. Because no data are available on the distribution of safe transits over the course of the day/night, we make the conservative assumption that safe transits are distributed evenly throughout the day. The distribution of groundings over parts of the day, shown in Table 5, must be treated with caution, since the two USCG accident datasets treat time stamps differently: the new data (post-1991) contains hour:minute time stamps, while older data indicate only day/night/twilight. Nonetheless, the data appear to suggest that navigation is more risky during the night than during the day in most of the study ports. This is consistent with our hypothesis about visibility.

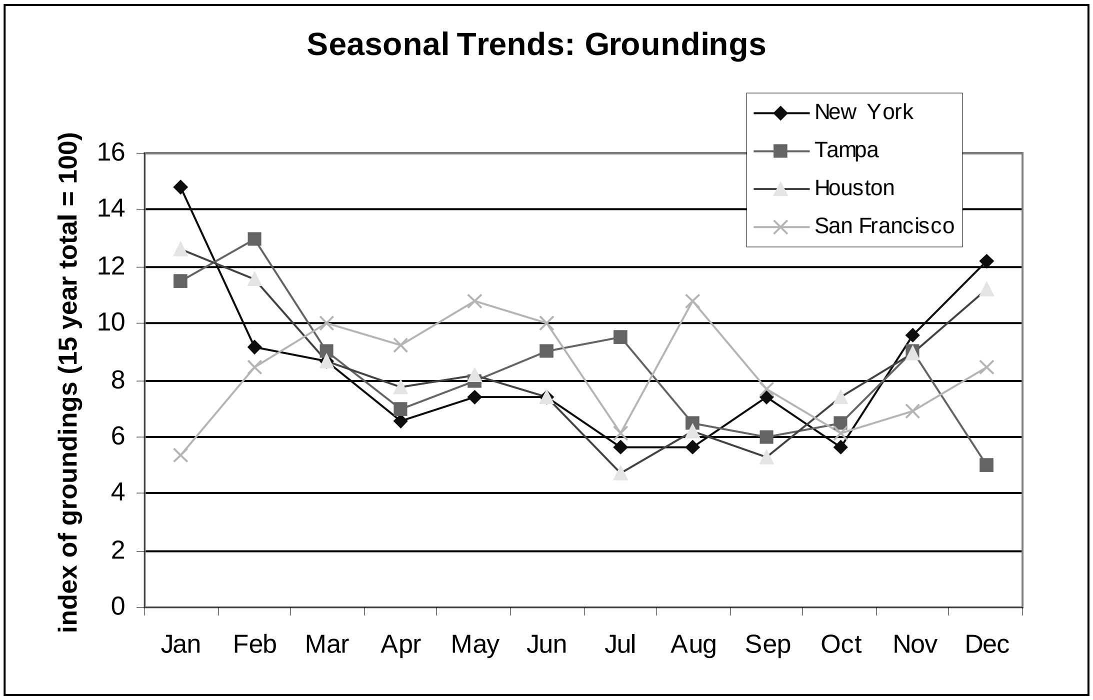

Figure 5: Seasonal trends, groundings.

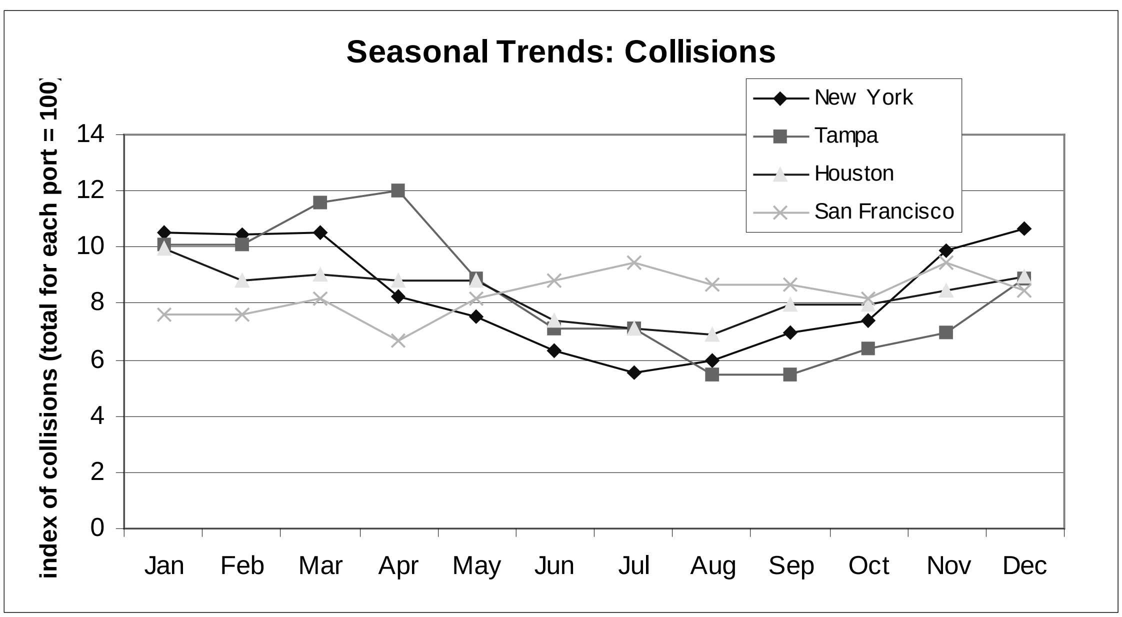

Figure 6:Seasonal trends, collisions.

	New York	Tampa	Houston	San Francisco
% of groundings during daytime	50	4	7	3
% of groundings during night	39	46	44	47
% of groundings during morning/evening	7	41	45	40
% of groundings with no time stamp	5	9	5	10

Table 5: Groundings as a function of time of day.

2.3. Grounding and Collision Rates

Accident rates are calculated by dividing the number of accidents by transits for each port. To illustrate the trends in accident rates, we show smoothed (five-point moving average) grounding rates for all ships in Figure 7 and all barge trains in Figure 8. Collision rates are shown in Figures 9 (ships) and 10 (barge trains). Caution is in order when comparing these grounding rates across ports. Local USCG offices may employ different reporting criteria from one port to another, and our procedure for building transit counts may underestimate actual traffic densities to varying degrees in different ports (which would lead to inflated accident rates).

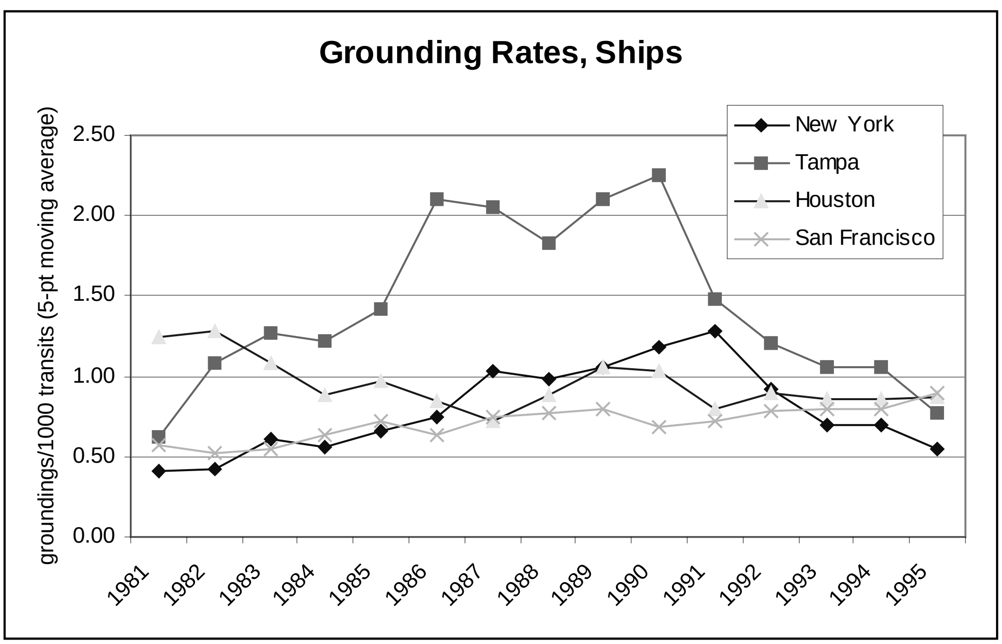

Figure 7: Grounding rates: ships, 1981-95.

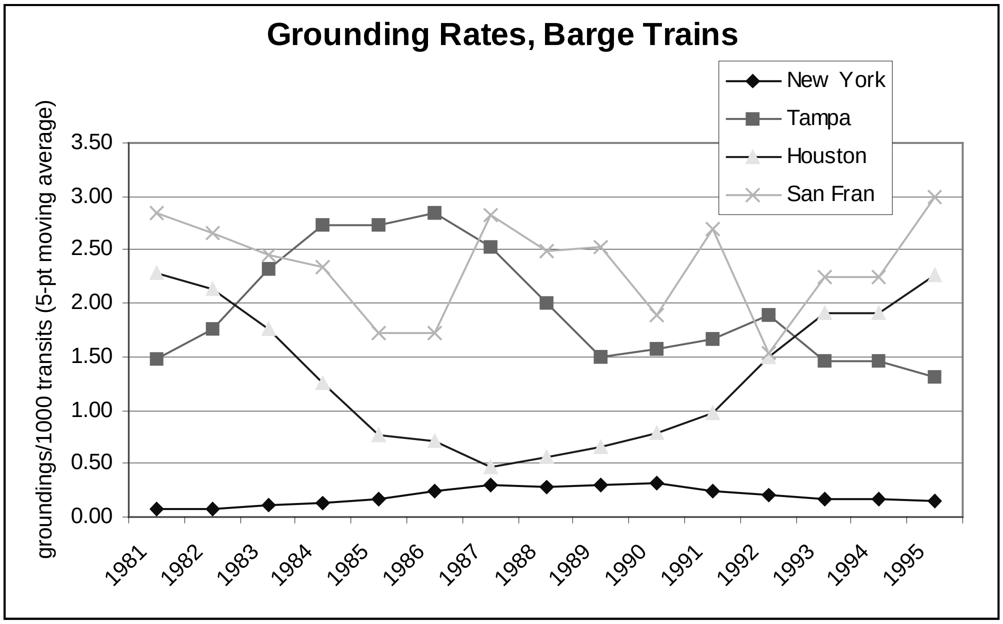

Figure 8: Grounding rates: barge trains, 1981-95.

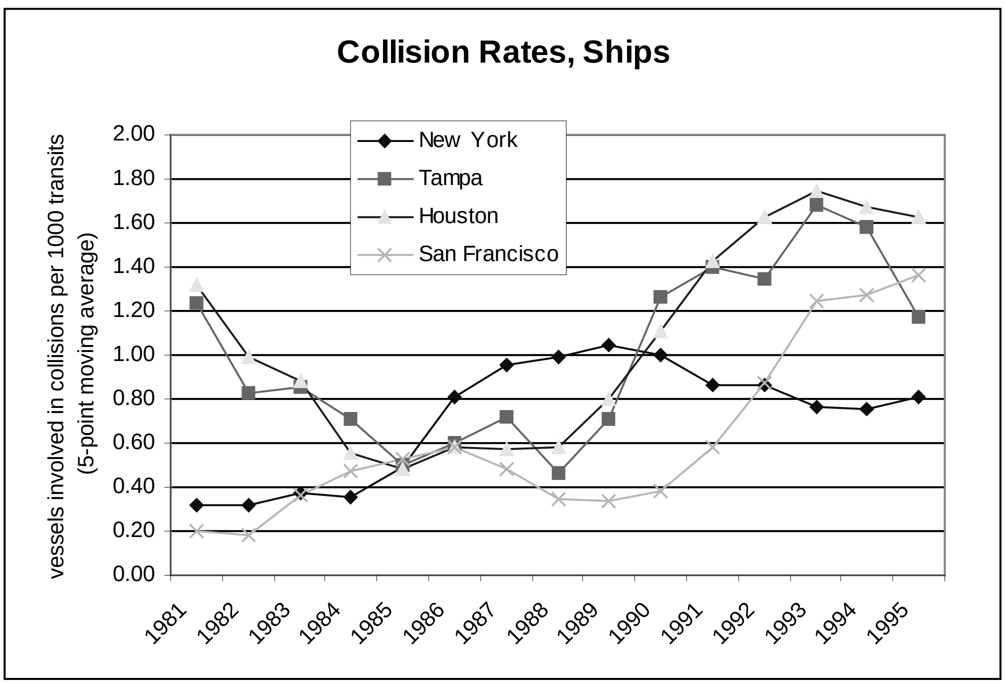

Figure 9: Collision rates: ships, 1981-95.

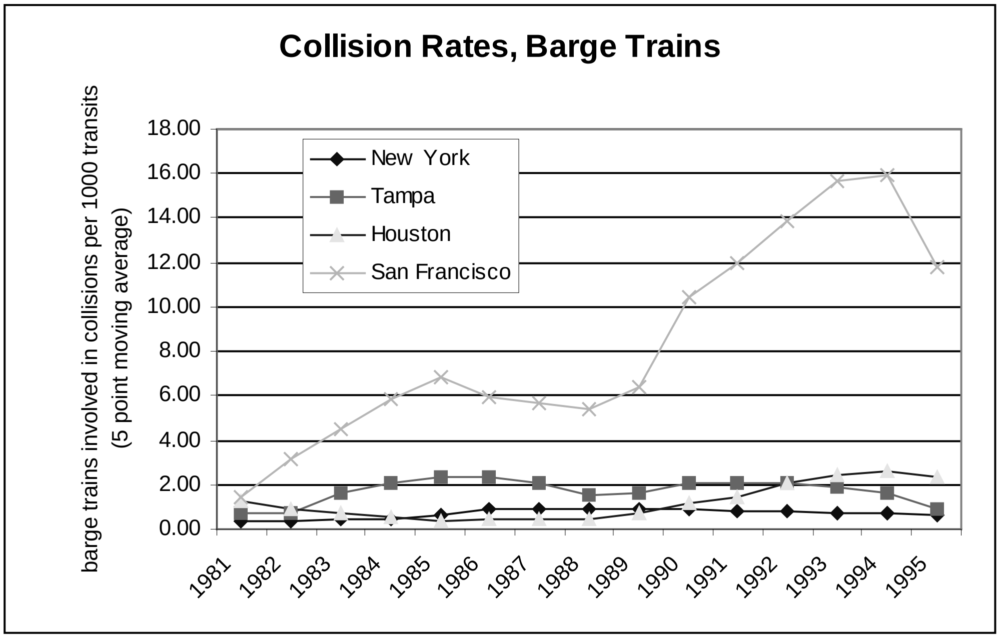

Figure 10: Collision rates: barge trains, 1981-95.

Given these caveats, it appears that the time-averaged grounding rate for ships is highest in Tampa, and clustered at a slightly lower level (around 0.75 groundings per 1000 transits, or one grounding in 1300 transits) for New York, Houston, and San Francisco. Grounding rates for barge trains appear to be lower in New York than in other ports. Collisions rates are lowest in New York (both ships and barges) and San Francisco (for ships); the rates are somewhat higher in Tampa and Houston (about 0.85 vessels involved in a collision per 1000 transits, or one collision in 1200 transits). In most cases, these rates remained fairly constant over the 1981 to 1995 study period.

The most obvious temporal change occurred in Tampa, where ship grounding rates rose significantly from 1986 to 1990 and then declined again to pre-1985 levels. The Houston barge train rate declined during the early and mid 1980s but has risen again since then. In Tampa, the barge train grounding rate surged and then declined again, much like the ship grounding rate, but slightly earlier in time. Barge train collision rates rose dramatically in San Francisco during the early 1990s.

Because the criteria used to include accidents in the USCG accident database change over time within a port, it is problematic to assign great significance to temporal changes in the accident rates. Our analysis therefore focuses on average accident rates over the 15 year study period. Average accident rates are shown in Table 6.

	groundings		*collisions*	
	ships	*barge trains*	*ships*	*barge trains*
New York	0.72	0.18	0.71	0.69
Tampa	1.32	1.84	1.00	1.68
Houston	0.89	1.28	1.07	1.20
San Francisco	0.65	2.28	0.65	8.52

Table 6: Average Accident Rates, 1981-95. Accidents per 1000 transits.

These underlying historical accident rates form the basis for an estimate of p, the unconditional (underlying) probability of an accident, in the physical risk analysis. The underlying probability p is a weighted average, taking into account the number of transits of the ship and barge train numbers summarized in Table 2. For example, the unconditional probability of grounding for commercial vessels in the ports of New York/New Jersey is estimated to be (0.72*10,200 + 0.18*30,100)/(10,200+30,100), or about 3.2 groundings per 10,000 transits. The same calculation for Tampa, Houston/Galveston, and San Francisco yields 15.5, 11.4, and 7.3 groundings per 10,000 transits, respectively.

2.4. Environmental Conditions

Other things equal, a transit characterized by unfavorable environmental conditions, such as high wind, poor visibility, or strong currents, may be expected to involve a greater risk of accidents than a transit through the same area under more favorable conditions.

2.4.1. Wind Speed

Two sources of wind speed data are used. The USCG casualty data provide reported wind speed at the time of accidents (these data are not complete). NOAA’s National Climatic Data Center (NCDC) maintains hourly average wind speed data from sensors located at airports near the study ports, covering the entire study period. Seasonal fluctuations in mean wind speed are shown in Figure 11.

As an example, the distribution of mean wind speed on "safe" (no grounding) and "accident" or "grounding" days is shown for New York/New Jersey in Figure 12. Figures for the other study ports look similar and can be found in Appendix 1. These plots show the cumulative distribution of mean wind speed w, $p(w>x)$, given either "grounding" or "safe" days. A higher “tail” of this distribution in the higher wind speed range for grounding days, which is evident in Figure 12, indicates that higher wind speeds are more commonly associated with groundings. The plots also show the distribution for the USCG wind speed data and the NOAA hourly data for comparison.

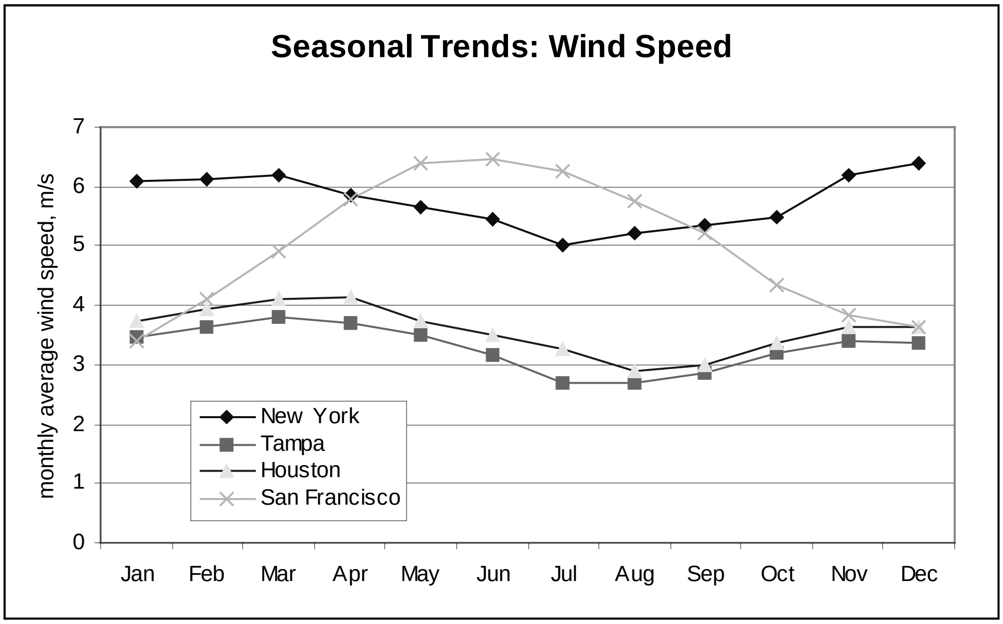

Figure 11: Seasonal trends: wind speed.

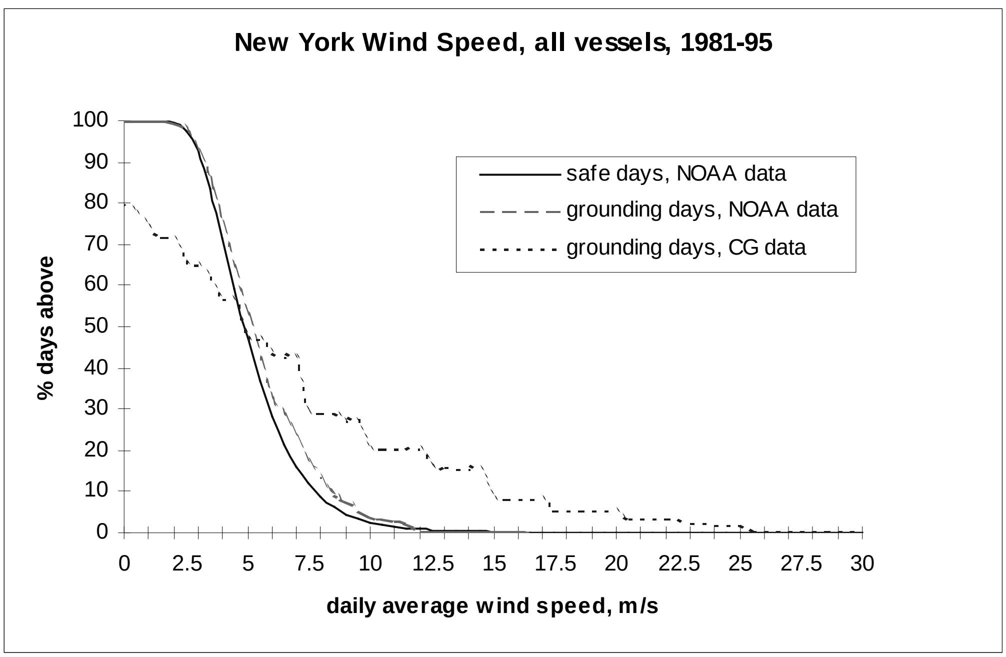

Figure 12: Wind speed distribution, New York.

2.4.2. Visibility

The same sources of data are used for visibility information. USCG casualty data include reported visibility at accidents (again, the data are not complete). NOAA/NCDC hourly average horizontal visibility data are from sensors located at airports near the study ports. Seasonal fluctuations in mean visibility are shown in Figure 13.

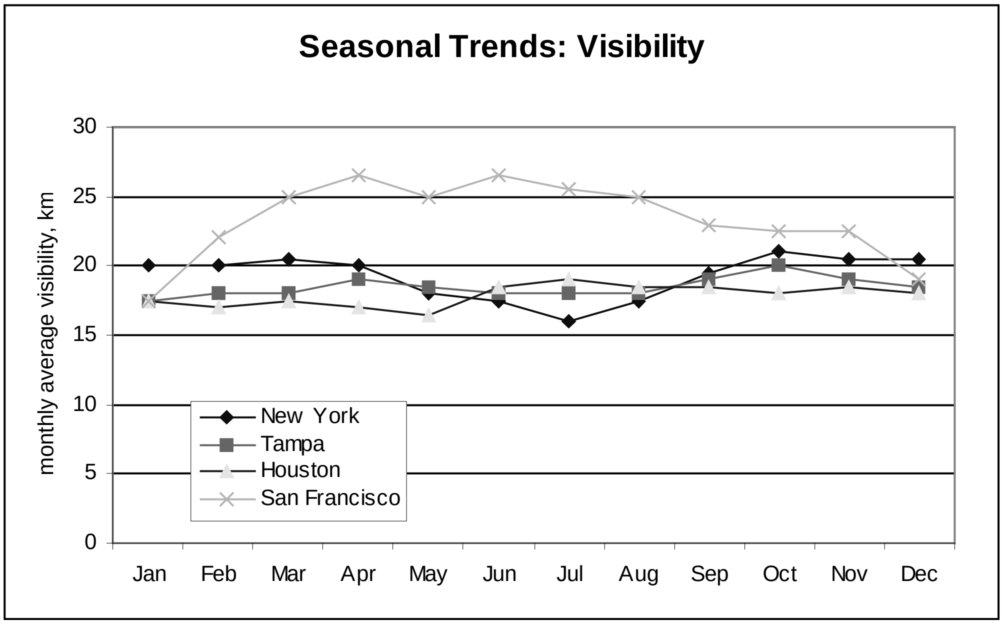

Figure 13: Seasonal trends: visibility.

The analysis of visibility data for “safe” and “accident” days parallels the approach used for wind speed. The distribution of mean visibility on safe and grounding days is shown for Tampa/St. Petersburg in Figure 14; figures for the other study ports look similar and can be found in Appendix 2. These plots show the cumulative distribution of mean visibility v, $p(v<x)$, given either grounding or safe days. A higher “tail” of this distribution in the lower visibility range for grounding days, which is evident in Figure 14, indicates that lower visibility is more commonly associated with groundings. The plots also show the distribution for the USCG visibility data and the NOAA hourly data for comparison.

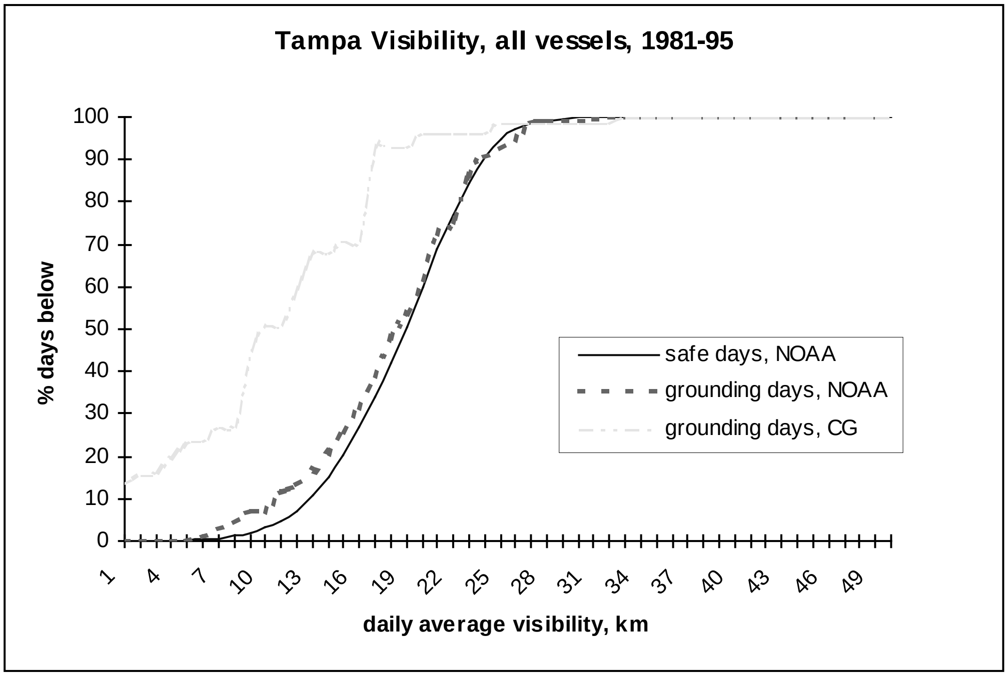

Figure 14: Visibility distribution, Tampa/St. Petersburg.

2.4.3. Water Level

Low water level, or large (negative) errors in the tide forecasts used by vessel operators, could be a risk factor for groundings. We obtained and analyzed data from NOAA on historical water level and water level forecasts in the study ports. Figure 15 shows the distribution of water level (observed and predicted), and the associated forecast error, for a representative tide station in the Port of New York/New Jersey. Plots for the other study ports are in Appendix 3.

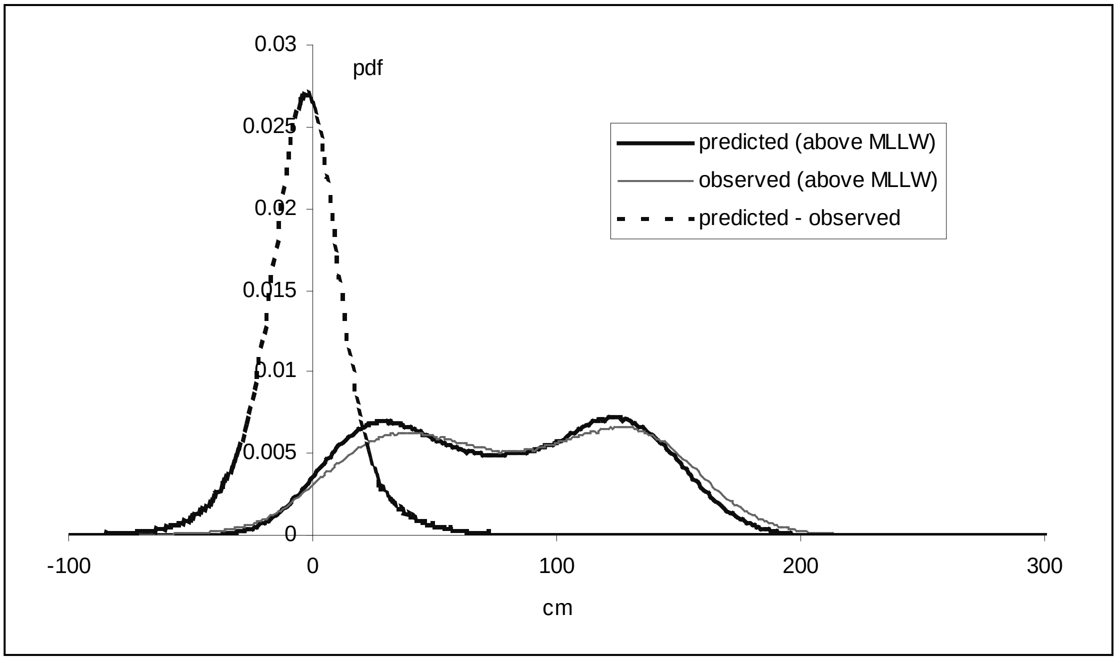

Figure 15: Water level and forecast distribution: New York.

2.5. Surveys and Chart Data

Other things equal, a transit through an area for which perfect charts are available may be expected to involve less risk of grounding than a transit through an uncharted or poorly charted region. Historically, navigators' knowledge of their own position was uncertain enough to make them cautious of approaching charted hazards. The charts, and their underlying surveys, had generally far greater accuracy, and were constructed with much better instruments, than those available to the average mariner. However, during the last 15 years we have experienced a shift in the technology available to navigators. Today, GPS users can position themselves with more accuracy than most surveyors could when they collected the data for charts in use today. This may have eroded some of the safety margin that was previously incorporated into the charts (Kielland and Tubman, 1994). We have examined the possibility that the uncertainty in paper charts based on older surveys have made a contribution to the incidence of groundings in U.S. port approaches. To do so, we have analyzed hydrographic data for uncertainty using the Hydrostat software package, and combined the results with grounding locations data to check for correlations between cartographic uncertainty and historical groundings.

2.5.1. Hydrostat Algorithm

The main function of the Hydrostat software is quality control of bathymetric data (Kielland *et al.*, 1992). This hydrographic data processing program was developed by Geostat Systems International Inc. under contract with the Canadian Hydrographic

Service (Dagbert, 1993). It is based on the requirement to make survey procedures more efficient, and the theory that survey errors no longer are negligible compared to other uncertainties facing navigators. By providing electronic chart users with statistically valid error estimates for the data they are using, for example, it is believed that this program will increase the utility and improve the safety of nautical chart data.

There are three main error sources when charts are designed from survey data: instrumental errors, interpolation errors, and design errors. Instrumental errors consist of positioning errors and depth measurements errors, and are assumed to be constant over the survey. The approximate size of these errors depends on the particular survey, but they are usually smaller than interpolation errors. Design errors are document handling errors and safety biased errors when data are transferred to navigational documents. Since both design errors and instrumental errors are well known and incorporated in the charts, they are of no particular interest to our investigation. Interpolation errors are bathymetric uncertainties that exist in the unsounded zones between measured soundings. They are the least controllable error for chart design and the focus of our investigation. If the surveyed depths are far apart then, depending on the topography of the sea floor, these interpolation errors can be much greater than the instrumental errors in the measurements themselves. They vary continuously and are unique to every location on a chart.

The Hydrostat software computes the depth in the unsounded zones between measured soundings using a geostatistical depth interpolation algorithm which also predicts the depth estimation errors inherent to each point on the interpolated bathymetric model. The results of the computation are two specific features: a bathymetric surface and a stochastic surface. The bathymetric surface is the digital terrain model interpolated from the observed sounding profiles, and is strictly a function of water depth. The stochastic surface is composed of the vertical error estimates for every point on the bathymetric surface. This surface is a function of both seabed texture and data sampling density. We used the stochastic surface (the interpolated errors of the depth estimate) as a proxy for cartographic uncertainty.

2.5.2. Survey Data

Within the four study areas, for the period 1981-90 and 1992-95, we found 1090 groundings in the Coast Guard accident database of interest to this investigation. Of these 1090 groundings, 202 accidents (18.5%), all from the CASMAIN database (1981-90), have no latitude/longitude location information. This leaves 888 accidents to evaluate (see Table 7). Based on plots of these remaining locations on nautical charts, 678 of these accidents happened around dredged channels or rivers, and 144 appeared to have a faulty entry for location (they plotted within very shallow areas or on dry land). Groundings around dredged channels are not due to the sort of bathymetric uncertainty for which Hydrostat is designed (Hydrostat assumes the sea floor to be isotropic and the variation in depth to be normally distributed). Hence the basis for this part of our evaluation was reduced to 82 accidents, or 7.5% of the original number.

	New York	Tampa	Houston	San Francisco
total number of groundings in dataset	**210**	**171**	**615**	**94**
of which:				
no lat/long info	53	18	107	24
groundings with lat/long information	**157**	**153**	**508**	**70**
of which:				
in dredged channels	137	135	362	44
in open water	8	14	24	20
questionable location	12	4	122	6

Table 7: Summary of Grounding Location Information.

Unfortunately, not all of these 82 accidents are reported to sufficient accuracy to be useful for this analysis. In theory, the location of each accident is given in the USCG database to an accuracy of +/-0.1 minutes latitude/longitude, or +/-150 to 200 meters in the areas of interest to this study. However, many of the accident locations are reported without the last decimal, which results in an accuracy of +/- 1500 to 2000 meters and makes them worthless to our study (see Table 8). This leaves us with 45 "useful" groundings for this part of the evaluation. Although we would prefer to have more data available, this is still a statistically useful sample.

	New York	Tampa	Houston	San Francisco
number of groundings in Hydrostat analysis area	**12**	**18**	**30**	**22**
of which:				
lat and long minute decimal = 0	3	6	4	6
lat minute decimal = 0	0	1	2	6
long minute decimal = 0	4	0	4	1
number of groundings usable in Hydrostat analysis	**5**	**11**	**20**	**9**

Table 8: Accuracy of Grounding Location Information.

The hydrographic survey data were obtained from the National Geophysical Data Center (NGDC) of NOAA, and includes depth measurements and bottom features. These data are part of the base from which NOAA charts are designed. We analyzed the most recent surveys for the areas of interest. These surveys differed greatly in age, quality, and density of data.

2.6. Channel Complexity

There are insufficient data in the historical record to analyze the effect of accident risk of differences in channel configuration in our study ports. However, the USCG's Port Needs Study (1991) includes an analysis of channel complexity at the national level. The Port Needs Study empirically derived the following relationship between accident risk and channel complexity parameters:

$$R = -0.37231 - 3.5297C + 16.3277N + 0.2285L - 0.0004W + 0.01212H + 0.0004M$$

where

R = predicted VTS-addressable casualties per 100,000 transits
C = 1 for an open approach area and 0 otherwise
N = 1 for a constricted waterway and 0 otherwise
L = length of the traffic route in statute miles
W = average waterway/channel width in yards
H = sum of total degrees of course changes along the traffic route
M = number of vessels in the waterway divided by L

Table 9 shows the length, width, and heading changes for major traffic routes in the four study ports, based on data from the Port Needs Study. In the right-most column, a risk index is computed for each traffic route using the PNS formula.

The results suggest that accident risk increases by a factor of about 5 from the open approach level to an enclosed harbor area, and by a factor of about 10 in a constricted channel. This is roughly consistent with our observation that about 90 percent of groundings take place in or near constrained channels. Beyond such general comparisons, it is difficult to draw comparisons between the PNS risk estimation and the results of our study. The PNS approach may serve as a starting point for work on a more complete risk prediction tool.

	transit area length (nm)	transit area average width (m)	sum of heading changes (degrees)	risk index (New York approach = 100)
New York/New Jersey				
Seaward Approaches	25.7	402	4	100
Eastward Approaches	7.3	266	61	104
New York Entrance	3.2	952	91	58
Upper New York Bay	5.3	2297	25	890
East River	2.9	1656	112	52
Hudson River	15.3	517	391	1291
Tampa/St. Petersburg				
Gulf Offshore Approaches	28.0	1431	35	126
Inshore Approaches	31.5	212	270	539
Tampa Bay	10.9	149	263	283
Houston/Galveston				
Galveston Bay Approaches	27.3	7711	10	0
Galveston Entrance	11.2	282	102	1057
Bolivar Roads	2.7	350	173	118
San Francisco Bay				
Ocean Approaches	29.8	666	0	142
Gulf of the Farallons	22.0	749	11	242
San Francisco Bay	32.2	962	274	534
San Pablo Bay	4.6	145	49	65
Carquinez Strait/Suisun Bay	68.0	359	743	1293

Table 9: Channel complexity parameters and relative predicted risk.
Based on the Port Needs Study (USCG 1991).

3. Risk Factors and the Historical Record

Of the categories of factors listed in section 1.2,

a. operator skill
b. vessel characteristics
c. traffic characteristics
d. topographic difficulty of the transit
e. environmental difficulty of the transit
f. quality of operator's information

data limitations allowed us to conduct fairly complete analyses on (b) and (e) and partial analyses on (a) and (f). We will discuss results from each of the areas in turn. First, we present a simple example of how Bayes' Theorem (see section 1.2) is applied in practice to produce the kind of results shows in the following sections.

Suppose that we wish to estimate the risk of grounding in the Port of New York/New Jersey for a commercial ship, given that the visibility is below 3 km. (Most of the numbers used in this example are artificial and chosen for illustration only.) From Table 6, we know the unconditional grounding rate for ships in New York/New Jersey is 0.72 per 1000 transits, or $p = 0.00072$. The factor x is "visibility < 3 km." To compute $p(G|x)$, we also need $l(x|G)$ and $l(x|S)$.

$l(x|G)$ is the likelihood that visibility is less than 3 km given that a grounding has taken place. From the historical data, we select all groundings of commercial ships in the Port of New York/New Jersey and collect the associated visibility data. Suppose there have been 100 such groundings, of which 65 occurred when visibility was below 3 km. $l(s|G)$ is then equal to 0.65.

$l(x|S)$ is the likelihood that visibility is less than 3 km given that a safe transit has taken place. Because we do not know from the historical data exactly when every safe transit took place, we must make an assumption. One simple assumption is that safe transits are distributed uniformly over the study period, in which case $l(x|S)$ is equal to the unconditional probability that visibility is less than 3 km. Suppose that in the historical NOAA data, we find that visibility in New York/New Jersey was less than 3 km 28 percent of the time. It follows that $l(x|S)$ is equal to 0.28.

Using these values in Bayes' Theorem, we compute the estimate of the probability of a commercial ship grounding in the Port of New York/New Jersey, given that visibility is less than 3 km, as

$$p(G|x) = \frac{l(x|G) * p}{l(x|G) * p + l(x|S) * (1-p)} = \frac{0.65 * 0.00072}{0.65 * 0.00072 + 0.28 * (1 - 0.00072)} = 0.0017$$

According to this result, our estimate of the risk of grounding is 58% greater given the information that visibility is less than 3 km.

3.1. Effect of Operator Skill

Other things equal, more highly skilled or seasoned operators, and those with better local knowledge, may be expected to produce a lower risk of accidents. Unfortunately, no direct measures of operator skill are available in the historical data. One (admittedly rough) proxy for this factor that can be constructed readily from historical data is the flag of the vessel. This proxy is relevant only to ships; tugs/tows and barges in U.S. waters are almost without exception U.S.-registered.

	transits	*groundings*	*collisions*
New York	17	52	33
Tampa	16	36	35
Houston*	13	43	32
San Francisco	67	29	47

*based on incomplete data

Table 10: U.S. Flag Share of Ship Transits and Accidents

The relationship between registry and accident risk is illustrated in Table 10, with further detail in Tables 11 through 14. The data suggest that during the study period, U.S.-registered ships were involved in both groundings and collisions relatively more frequently than foreign-flag ships in New York, Tampa, and Houston; the reverse is true in San Francisco.

It must be noted that the “flag” factor embodies many variables other than operator skill. For example, the size distribution of U.S. vs. non-U.S. ships in general is not known from available data. It is possible that the practice of allowing U.S. flag vessels to enter port under certain circumstances without taking on board a local pilot may contribute to the relatively higher rate of accidents.

3.2. Effect of Vessel Characteristics

Other things equal, a more maneuverable vessel may be expected to have a lower probability of navigational accidents than a less maneuverable vessel. It is difficult to obtain meaningful summary measures of maneuverability. As a result, our analysis has to rely on proxies such as vessel type and vessel size. Whether tugs were present/used during the transit is not known from the USCG casualty data.

The data suggest that, in most cases, barge trains are more likely to be involved in groundings and collisions than ships (see Table 6). This is consistent with our expectations about maneuverability: barge trains are, in general, likely to be less maneuverable than ships. As illustrated in Tables 11 through 13, the data also suggest that large ships are consistently more likely to ground than small ships (draft less than 30 feet). This result is also consistent with our expectations about maneuverability.

3.3. Effect of Environmental Factors

We were able to analyze the effect of wind speed, visibility, and water level on accident risk.

3.3.1. Wind Speed and Visibility

Other things equal, a transit through an area characterized by unfavorable environmental conditions, such as high wind or poor visibility, may be expected to involve a greater risk of accidents than a transit through the same area under more favorable conditions.

The results on the effect of wind speed are mixed. They show increases in grounding risk in high wind conditions (more than 10 m/s) for small non-U.S. flag ships in New York/New Jersey (300% increase), for barge trains in Tampa (160%), and for large U.S. flag ships and barge trains in Houston/Galveston (1200% and 200%, respectively) (see Kite-Powell *et al.*, in press). The model results show no significant effect of wind speed on the risk of collision in any of the study ports. High wind conditions are relatively rare along the Gulf Coast (Tampa and Houston/Galveston).

Poor visibility might be expected to increase the risk of groundings and collisions. This is borne out consistently across all vessel types and all four study ports, as shown in Tables 11 through 14. The increase in accident risk due to poor visibility is more consistent and more significant than the change associated with high wind.

	good vis. (>=2km)	*poor vis. (< 2km)*	*change w/ poor visibility*
grounding risk			
small ships (draft < 30 ft)			
U.S. flag	0.0019	0.0070	+270%
non-U.S. flag	0.0002	0.0014	+540%
large ships (draft >= 30 ft)			
U.S. flag	0.0045	0.0937	+1960%
non-U.S. flag	0.0015	0.0139	+820%
barge trains	0.0002	0.0015	+660%
collision risk			
all vessels	0.0005	0.0034	+630%

Table 11: Accident Risk in New York/New Jersey

	good vis. (>=2km)	*poor vis. (< 2km)*	*change w/ poor visibility*
grounding risk			
small ships (draft < 30 ft)			
U.S. flag	0.0023	0.0125	+450%
non-U.S. flag	0.0008	0.0072	+750%
large ships (draft >= 30 ft)			
U.S. flag	0.0048	0.0407	+750%
non-U.S. flag	0.0016	0.0160	+880%
barge trains	0.0017	0.0170	+890%
collision risk			
all vessels	0.0008	0.0071	+810%

Table 12: Accident Risk in Tampa Bay

	good vis. (>=2km)	*poor vis. (< 2km)*	*change w/ poor visibility*
grounding risk			
small ships (draft < 30 ft)			
U.S. flag	0.0014	0.0139	+910%
non-U.S. flag	0.0003	0.0026	+670%
large ships (draft >= 30 ft)			
U.S. flag	0.0051	0.0429	+750%
non-U.S. flag	0.0009	0.0013	+50%
barge trains	0.0012	0.0100	+740%
collision risk			
all vessels	0.0010	0.0068	+600%

Table 13: Accident Risk in Houston/Galveston

	good vis. (>=2km)	*poor vis. (< 2km)*	*change w/ poor visibility*
grounding risk			
all vessels	0.0007	0.0013	+90%
collision risk			
all vessels	0.0008	0.0021	+160%

Table 14: Accident Risk in San Francisco

3.3.2. Water Level

We have constructed distributions of water level in the study ports at the time when groundings occurred and compared these to the overall distributions of water levels. An example is shown in Figure 16 for the Port of New York/New Jersey. Plots for other study ports are in Appendix 3.

Figure 16 shows the distribution of predicted and observed water level in the Port of New York/New Jersey, using a tide gauge station at the Battery as a proxy. The distribution of predictions and observations are similar but do not coincide perfectly; see section 3.4.1 below for a discussion of forecast errors. Figure 16 also shows the distribution of observed water level during grounding events in the Port of New York/New Jersey. This distribution is less smooth because it is based on far fewer observations. However, its general shape matches that of the predicted and observed water level at all times, which we assume is representative of the distribution during safe transits. If the distribution during groundings had a larger peak in the low water level part of the scale, we might conclude that low water level is associated with an increased risk of groundings. However, this is not the case, and we conclude that there appears to be no significant correlation between groundings and low water levels. (The fact that groundings occur more frequently during high water levels in some instances (see Tampa in Appendix 3) is likely attributable to deep draft vessels making transits during high water to maximize underkeel clearance.)

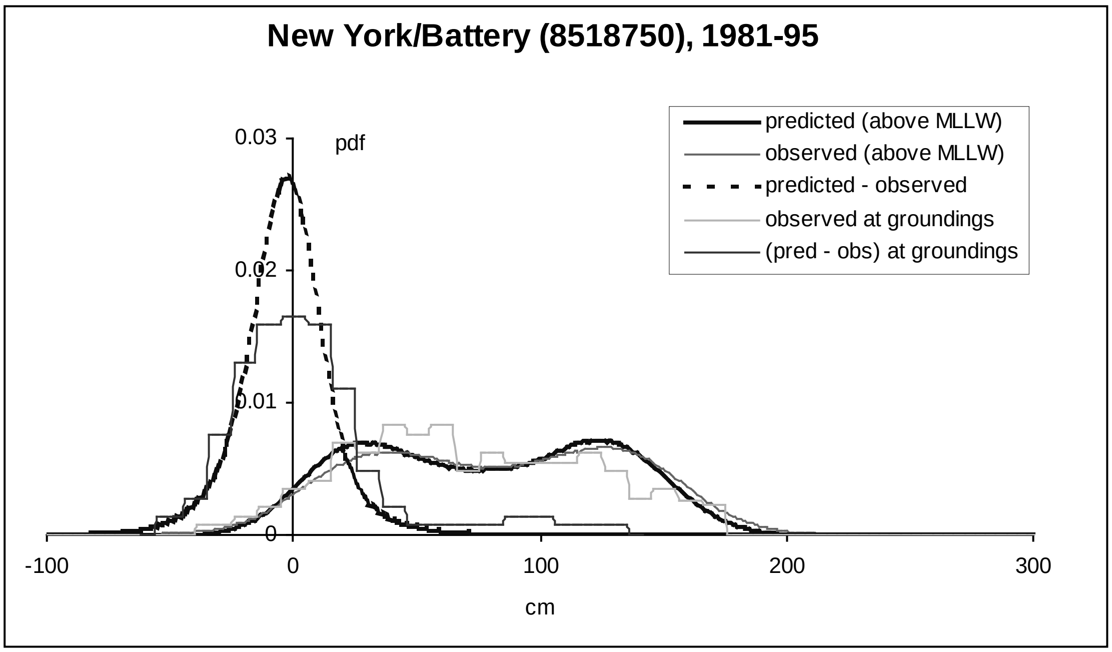

Figure 16: Water level and forecast during groundings: New York.

3.4. Effect of Operator's Information

We were able to analyze the effect on accident risk of errors in tide forecasts and of uncertainty in charts based on older surveys. We also have some anecdotal information about possible effects of real-time environmental information services.

3.4.1. Tide Forecast Error

We have constructed distributions of water level (tide) forecast error in the study ports at the time when groundings occurred and compared these to the overall distributions of water level forecast errors. An example is shown in Figure 16 for New York/New Jersey. Plots for other study ports are in Appendix 3.

Figure 16 shows the distribution of water level forecast error (predicted minus observed water level) both for all times during the study period and specifically during grounding events in the Port of New York/New Jersey. This latter distribution is less smooth because it is based on far fewer observations. However, its general shape matches that of the overall forecast error, which we assume is representative of the distribution during safe transits. If the distribution during groundings had a larger peak on the positive side part of the distribution, we might conclude that large positive forecast errors (when actual water level turned out to be less than what was predicted) is associated with an increased risk of groundings. However, this is not the case, and we conclude that there appears to be no significant correlation between groundings and and large forecast errors resulting in lower-than-forecast actual water levels.

3.4.2. Uncertainty in Surveys/Charts

We examined charted depth uncertainty for two of the five study ports in detail: New York and Houston/Galveston. Only 6 of the 114 New York accidents are located in the right kind of region and have sufficient location accuracy to be evaluated by Hydrostat.

The analysis proceeds as follows: the locations of the accidents are plotted on a chart. The underlying hydrographic survey data are identified and reformatted and analyzed by Hydrostat to produce the interpolated error estimates. Both the interpolated errors at the location of the accidents and a general distribution of the errors are computed. These two results are compared to check for correlation between cartographic uncertainty and historical groundings. A correlation would be indicated by a concentration of the point-errors on the high side of the general error distribution.

Figure 17 shows depth error, depth curves, and accident locations for a sample New York survey area. Figure 18 shows the overall distribution of interpolated errors of estimated depth in the same survey, as well as the interpolated errors of the depth estimates at locations where the accidents occurred. Results are similar for other New York survey areas, and for survey areas in the Houston/Galveston region. At a first level of analysis, these figures suggest no compelling evidence that “open water” groundings tend to happen in high uncertainty areas. (In fact, more than 85 percent of groundings take place around dredged channels.) However, the general validity of this conclusion is questionable because the distributions of all transits through the survey areas are not known and because of the small number of analyzable accidents.

It would be interesting in a future study to examine the frequency of groundings in a region before and after charts based on modern surveys are made available. It may also be interesting to develop and analyze the geographic distribution of transits through and open water approach survey area to refine the analysis conducted here.

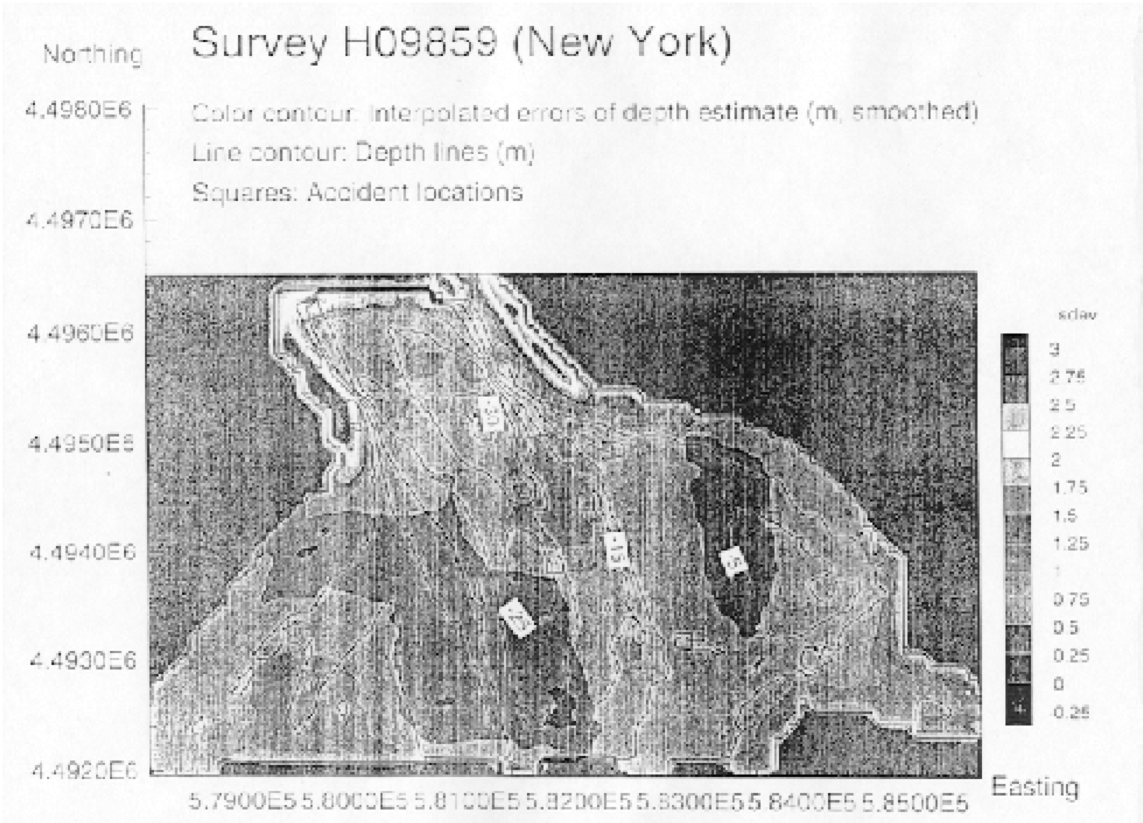

Figure 17: Depth error estimates for New York survey H09859

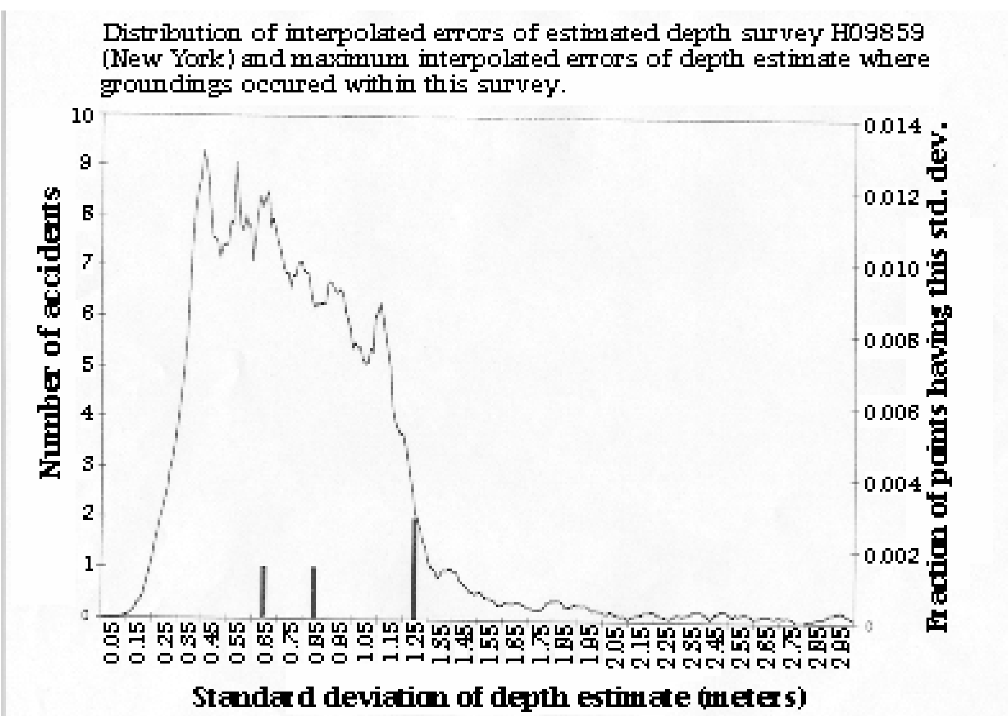

Figure 18: Depth error distributions for New York survey H09859

3.4.3. Real-time Environmental Information

As mentioned previously, it is important to use caution when comparing accident rates across ports and over time because of differences in reporting criteria. Nonetheless, the data on annual accident rates suggest some observations about possible temporal factor changes. One factor we have not explicitly analyzed, but about which the present data from Tampa may suggest interesting results, is operators' quality of information about environmental conditions. Other things equal, better information about currents, tide levels, and winds may be expected to reduce the likelihood of grounding. This factor can be tested by distinguishing between study areas and time periods for which information from real-time monitoring systems was available to vessel operators (such as Tampa Bay in the 1990s) and those for which it is not. Our data show that grounding rates in Tampa have indeed declined dramatically, for both ships and barge trains, in the 1990s. Further analysis is required to determine how much of this decline is attributable to the availability of real-time environmental information.

3.5. Data Issues

In the course of our evaluation, we have identified certain deficiencies and limitations in the available historical data. We describe these briefly for each major data source. If future data collection efforts can address these deficiencies, improved analysis and understanding of accident risk will be made possible.

3.5.1. USCG Vessel Casualty Data

The USCG vessel casualty databases, CASMAIN and MSIS, are the most comprehensive source of commercial vessel casualty information available for U.S. waters. However, these databases (particularly the older CASMAIN data) are occasionally difficult to work with because of missing entries, duplicate entries, and inaccuracies. Also, some categories of information useful for the analysis of accidents are not collected in these datasets at all.

The locations of accidents are reported in theory to tenths of minutes latitude/longitude. As discussed in secton 2.5.2 above, this level of accuracy is not met for many entries; 18 percent of CASMAIN grounding records have no latitude/longitude information at all; and several groundings have erroneous location information (they plot on dry land). In several cases, a single casualty is described by two (slightly different) entries, one of which is probably erroneous and should have been removed from the database.

No data are presently collected on the actual draft or trim of vessels at the time they were involved in accidents; and it is difficult to reconstruct actual water depth at the time of the accident from the environmental data. Further, the presence and use of escort tugs is not quantified in the data, and the newer MSIS data no longer include information about the presence of pilots on board vessels. These data could be usefully included in future USCG casualty data.

The USCG casualty dataset could be further improved by the adoption of a consistent set of criteria to govern what incidents are included in the dataset and how the information is to be obtained (i.e. wind speed and direction, visibility, water level, current speed and direction at time of the accident, etc.).

3.5.2. ACE Transit Data

The ACE Waterborne Commerce transit data annual summaries are useful but suffer from several limitations for the purposes of our analysis. Dry cargo and passenger vessels are mixed in a single reporting category. The breakdown of transits by specific waterways is useful, but makes the compilation of a composite "port region" transit history difficult because of potential double counting. Finally, barge movements are reported for individual barges, and there is no completely accurate way to determine the number of barge train movements.

3.5.3. NOAA Environmental Data

NOAA wind and visibility are available as hourly averages, allowing for fairly detailed time-analysis. However, they are general to each port area, and measured at an airport location that does not necessarily reflect conditions on the water.

Historical information on currents is not available with the same detail and consistency as wind and visibility, and water level and current conditions during historical accidents cannot readily be reconstructed. This will change as real-time oceanographic data systems, such as PORTS in Tampa, become more common in U.S. ports.

3.5.4. Port-Specific Data

More detailed information about safe transits could be collected either by the U.S. Army Corps of Engineers or by local port authorities. Transits counts categorized by flag, vessel type, vessel size, with tug escort and piloting information, would be useful at temporal scales as small as one hour.

4. Economic Loss Estimation

The economic loss associated with an accident can be calculated as the sum of all costs associated with the accident. Costs are classified as either internal or external. Internal costs are those arising from the vessel involved in the accident and other parts of the marine transportation system; they include damage to the vessel, loss of cargo, injury or death of crew members, cleanup costs, and delays due to blockage of the route, among others. External costs are those incurred outside the transportation system, including environmental degradation, human health risks, lost fishery revenues, and lost recreational benefits, among others. Both external and internal costs will vary with the severity of the accident; the size of the vessel(s) involved, their construction, and their cargo; and other factors. External costs will also vary greatly with the environmental and human health sensitivity of the location.

An algorithm has been developed to estimate the cost of accidents as a function of relevant parameters such as vessel size, nature of cargo, and nature of the transit area, following the approach taken in the Port Needs Study (PNS) (USCG, 1991). PNS provides information about the number and nature of groundings and collisions that can be avoided in each PNS port (including the four study areas of this project) with certain vessel traffic service (VTS) systems, and the associated (avoided) losses. The PNS study included in its loss estimation each of the following categories of losses (see Schwenk, 1991):

- loss of human life and personal injuries,
- vessel hull damage,
- cargo loss and damage,
- economic cost of the vessel being out of service,
- spill clean up costs,
- losses in tourism and recreation,
- losses in commercial fish species,
- impacts on marine birds and mammals,
- losses due to LPG/LNG fires and explosions, and
- bridge and navigational aids damage.

Not included in the estimation procedure are damages to on-shore facilities and water supplies, legal fees for litigation over vessel casualties, cumulative effects of consecutive spills, effects of chemical releases into the air, and non-use values.

A summary of the PNS loss estimation procedure is provided by Schwenk (1991). In addition to its own procedures, PNS draws on several sources for damage estimation models. These include the Natural Resource Damage Assessment Model (see below); several models developed by A.T. Kearney (1990) for losses in tourism, property values, and subsistence households; and models by ERG (1990) for losses due to cleanup costs and to vessel damage and repair. The PNS data, which reflect inputs from all of these models, are used to estimate the losses associated with one accident involving various vessel types (tanker, dry cargo, tug/barge) and sizes in each study area.

Perhaps the most volatile element in the PNS loss estimation procedure is the model used to calculate natural resource damages. These damages -- loss of fish, birds, marine plants, and other species -- account for between 10 and 40 percent of total damages, depending on the location and nature of the accident. The PNS results are based on a version of the Department of the Interior's Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME) which has been replaced by a new version of NRDAM/CME (see Federal Register 59(5):1062-1189). The new version includes a new model of restoration costs and makes use of updated biological, chemical, and economic data. Preliminary analysis of the new model's parameters suggests that there is no consistent way to scale results from the previous version to reflect the likely new model results. Present cost estimation algorithms therefore include natural resource damage estimates based on an "old" version of the NRDAM/CME.

Table 15 shows the total average economic losses estimated by these models for tanker and dry cargo ship groundings in the four study ports. These averages take into account the distribution of vessel size and cargo for each port, and also reflect seasonal averages for environmental losses.

	tanker grounding	**dry cargo ship grounding**
New York	1.7	0.5
Tampa	1.0	0.4
Houston	2.4	0.5
San Francisco	1.3	0.4

Table 15: Average Economic Losses Associated with Ship Groundings
Numbers in millions of 1993$. Based on PNS (USCG, 1991).

5. Squat Modeling

A web-based information system for modeling the ship squatting problem was developed as part of this project to pave the way for better navigation channel design analyses and transit risk management. This section describes the implementation of this system.

A vessel with a displacement hull moving at even moderate speeds in shallow water will experience vertical sinkage, or "squat," as a result of a pressure drop beneath its hull (Blaauw and van der Knaap 1983). To avoid ship groundings with possible severe economic and environmental consequences, the relevant governmental, port, and maritime agencies and organizations need a reliable method of predicting ship squat. An analytical squat model based on the physical characteristics of a port entrance channel and the ships that travel through it can be used to issue appropriate regulations regarding vessel size and speed and to plan channel dredging operations.

We have implemented a modeling system for ship squat and clearance. To provide maximum utilization, the system is configured as an information server accessible through the World-Wide Web (Berners-Lee 1994, 1996).

Four standard models for ship squat have been identified in the literature and implemented in our system: those proposed by Barrass (1979), Millward (1990), Norrbin (1996), and Tuck (1966).

Barrass' empirical formula is:

$$S = \frac{1}{30} * C_b * \left(\frac{A_s}{A_c - A_s} \right)^{2/3} * V_k^{\ 2.08}$$

Millward's empirical formula, based on extensive model tank testing, is:

$$S = \frac{L}{100} * \frac{(15 * C_b * \frac{B}{L} - 0.55) * Fn_h^{\ 2}}{1 - 0.9 * Fn_h}$$

Norrbin's "hydraulic approximation" formula, derived for block-form vessels, is:

$$S = \frac{L}{100} * \frac{\frac{100}{L/h} * \frac{A_s}{A_c} * Fn_h^{\ 2}}{1 - \frac{A_s}{A_c} - \frac{H * W_0}{A_c} * Fn_h^{\ 2}}$$

Tuck's formula, based on slender-body potential theory, is:

$$S = \frac{L * C_s * Fn_h^{\ 2}}{\sqrt{1 - Fn_h^{\ 2}}}$$

where

A_c = channel cross-sectional area (m^2)
A_s = ship cross-sectional area (m^2)
B = ship beam (m)
c = ship clearance = h - T - S (m)
C_b = ship block coefficient
C_s = Tuck's ship form factor
Fn_h = Froude number of depth (V/(g*h)**0.5)
g = gravitational acceleration, 9.81 m/sec^2
h = channel depth (m)
L = ship waterline length (m)
S = ship squat (m)
T = ship draft (m)
V = ship speed (m/sec)
V_k = ship speed in knots (nautical miles per hour; 1 knot = 0.5144 m/sec)
W_0 = channel waterline width (m)

Ship clearance is calculated identically for all of the models as:

$$c = h - T - S$$

The system is composed of several static HTML pages, four Perl scripts (squat.pl, plot.pl, plot2.pl, and plot3.pl) that dynamically generate additional HTML pages, two C programs (Squat and Plot) newly developed by us, and two public domain utility programs (Ghostscript[1,2] and Ppmtogif[3]).

The Squat program calculates ship squat (or clearance). The numerical models can be parameterized for zero to three variables.

The Plot program reads the output of Squat and for the one and two-dimensional problems produces a PostScript-formatted (Adobe Systems 1987a, b) representation of the appropriate plot, either y = f(x) or the iso-contours f(x,y) = c_i. For three-dimensional data, Plot produces a VRML (Virtual Reality Modeling Language) file (Pesce 1995) of the iso-surfaces f(x,y,z) = c_i, which can be viewed with a standard VRML-compliant web browser. Both programs are written in ANSI C (Kernighan and Ritchie 1988) for maximum portability.

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[1] R. Lang. Ghostscript, June 18, 1998. http://www.cs.wisc.edu/~ghost/aladdin/index.html.
[2] T. Merz. Ghostscript user manual, October 17, 1997. http://www.muc.de/~tm/gsmanual/ index.html.
[3] Netpbm, October 13, 1993. ftp://wuarchive.wustl.edu/graphics/graphics/packages/NetPBM.

The entry point to the system is a static HTML page

http://deslab.mit.edu/DesignLab/squat/

that provides background on the ship squat problem and several examples, defines the four analytic models, and documents the notation used by the models. From this page the user can select the degree of model parameterization, from zero to three. In response to this, the user is presented with an appropriate HTML Form with which to specify the range or ranges of the independent variables (if any) and the remaining constant values.

After submission, the data entered into the Form by the user is processed by one of the Perl CGI scripts, which dynamically generate customized HTML pages. In all instances the Squat program is invoked to calculate the numerical results. For the zero-dimension problem, the squat and clearance results are displayed numerically on the dynamically generated HTML page. For the one and two-dimensional problems the graphical results are generated as follows. First, the Plot program is invoked to produce the appropriate one or two-dimensional plot in the PostScript format. Then the public domain Ghostscript utility is used to convert the PostScript image to the Netpbm portable pixmap[4] (PPM) format. Finally, the Netpbm Ppmtogif utility is used to convert the PPM image to a GIF[5] image, which can be interpreted and displayed as an inline image by any standard web browser. For the three-dimensional problem the graphical result is generated by invoking the Plot program to produce a VRML-formatted file, which can be interpreted and displayed by any standard VRML-compliant browser.

The following examples are based on vessel traffic and channel configuration characteristics found at the Houston/Galveston Ship Channel (Z. Demirbilek, pers. comm., March 1998):

Channel cross-sectional area:	$A_c = 1189.04\ m^2$
Ship immersed cross-sectional area:	$A_s = 307.22\ m^2$
Ship beam:	$B = 32.31$ m
Ship block coefficient:	$C_b = 0.8$
Tuck's form factor:	$C_s = 0.02$
Channel mean low water depth:	$h = 12.19$ m
Ship nominal draft:	$T = 11$ m
Channel mean low water width:	$W_0 = 121.91$ m

Setting the ship waterline length $L = 236.21$ m, the squat and clearance (given in meters) can be calculated for all four squat models as a function of the Froude number of depth, $Fn_h = \{0.1, 0.2, 0.3, 0.4, 0.5\}$:

[4] Portable pixmap file format, August 18, 1995. http://www.dcs.ed.ac.uk/~mxr/gfx/2d/PPM.txt.
[5] Graphics interchange format, v. 89a, June 15, 1995. http://www.dcs.ed.ac.uk/~mxr/gfx/2d/GIF89a.txt.

	Barrass	Millward	Norrbin	Tuck
Fn_h = 0.1				
squat (m)	0.063	0.028	0.043	0.047
clearance (m)	1.128	1.163	1.148	1.144
Fn_h = 0.2				
squat (m)	0.268	0.126	0.182	0.193
clearance (m)	0.923	1.066	1.009	0.999
Fn_h = 0.3				
squat (m)	0.623	0.318	0.451	0.446
clearance (m)	0.569	0.874	0.741	0.746
Fn_h = 0.4				
squat (m)	1.133	0.644	0.931	0.825
clearance (m)	0.058	0.547	0.261	0.367
Fn_h = 0.5				
squat (m)	1.802	1.172	1.835	1.364
clearance (m)	-0.611	0.020	-0.644	-0.172

Table 16: Squat and Clearance as Predicted by Four Models.

As can be seen in Table 16 and Figure 19, the Barrass model predicts squat and clearance values that are at some variance from the other three models. For low Froude numbers (up to 0.3) the Millward, Norrbin, and Tuck models predict comparable values for clearance. However, for larger Froude numbers, these three models show significant differences in their predictions. In view of this, the results from these models should only be used for general guidance. Further research is necessary to validate the accuracy of these models, or if they all prove to be unreliable, to develop a more sophisticated model of the squatting phenomenon.

Figure 19 illustrates that all four models predict the vessel running aground at Froude numbers approximately between 0.4 and 0.5 (indicated by the curves representing clearance intersecting the x-axis). While the specific values of the negative clearances are not important, the trend of the curves indicating the Froude number (from which the ship velocity can be easily derived) at which grounding would occur (i.e., when clearance becomes 0) is useful in formulating regulations for vessel traffic.

Ship squat can be plotted as a bivariate function. The following examples vary both Froude number and ship waterline length and are displayed with 10 contour lines: SQUAT(Fn_h, L) = c_i = {0.1, 0.2, ..., 1.0}. Figures 20, 21, 22, and 23 illustrate the results for the Barrass, Millward, Norrbin, and Tuck models, respectively.

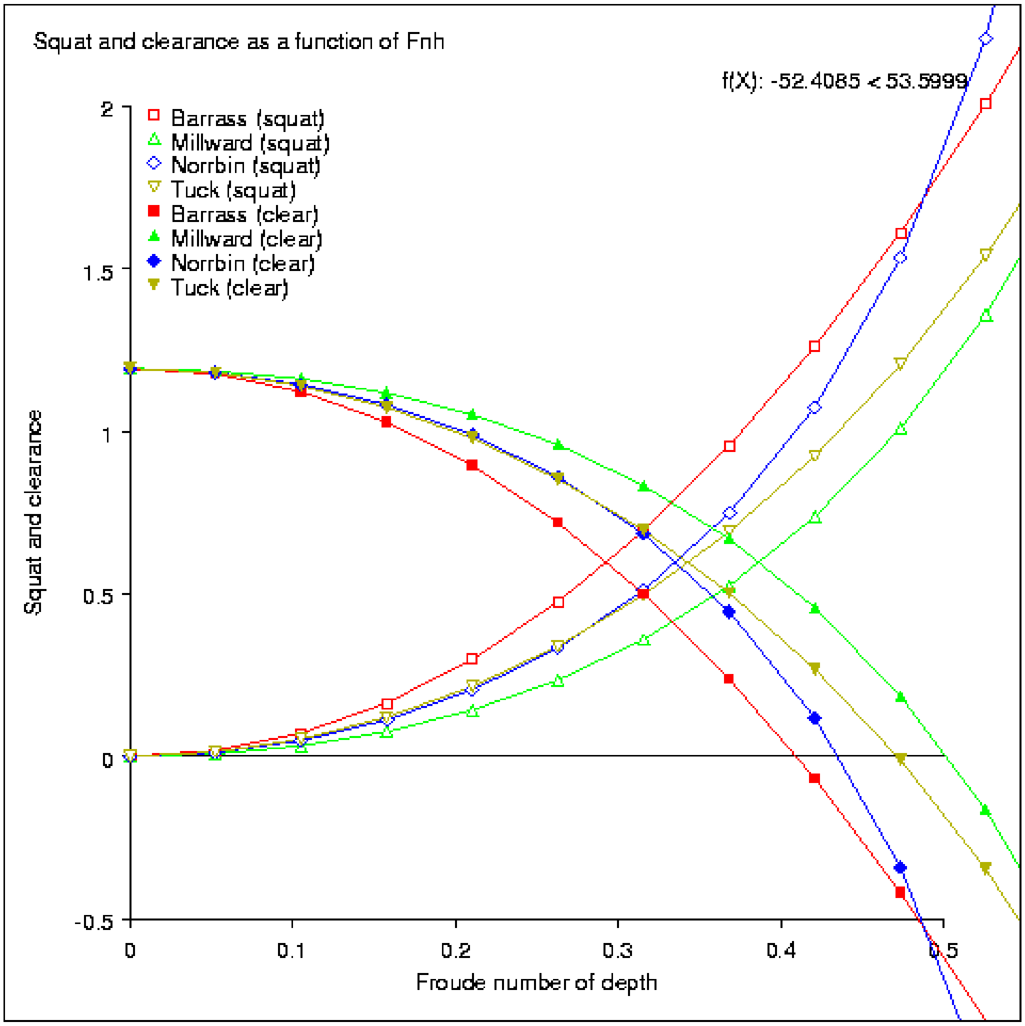

Figure 19: Ship squat as a function of Froude number of depth. (High resolution color version is available at http://deslab.mit.edu/DesignLab/squat/examples.html.)

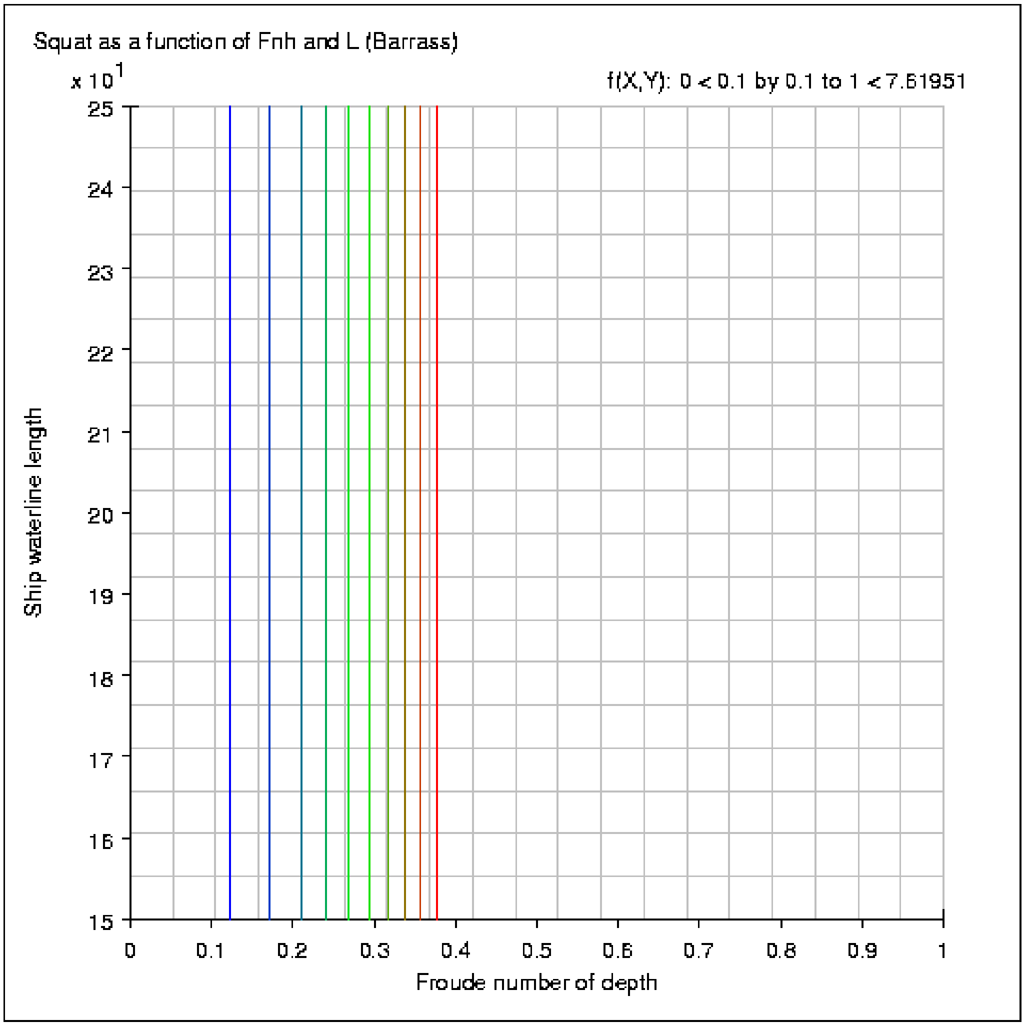

Figure 20: Ship squat as a function of Froude number and length, Barrass model.
(High resolution color version is available at
http://deslab.mit.edu/DesignLab/squat/examples.html.)

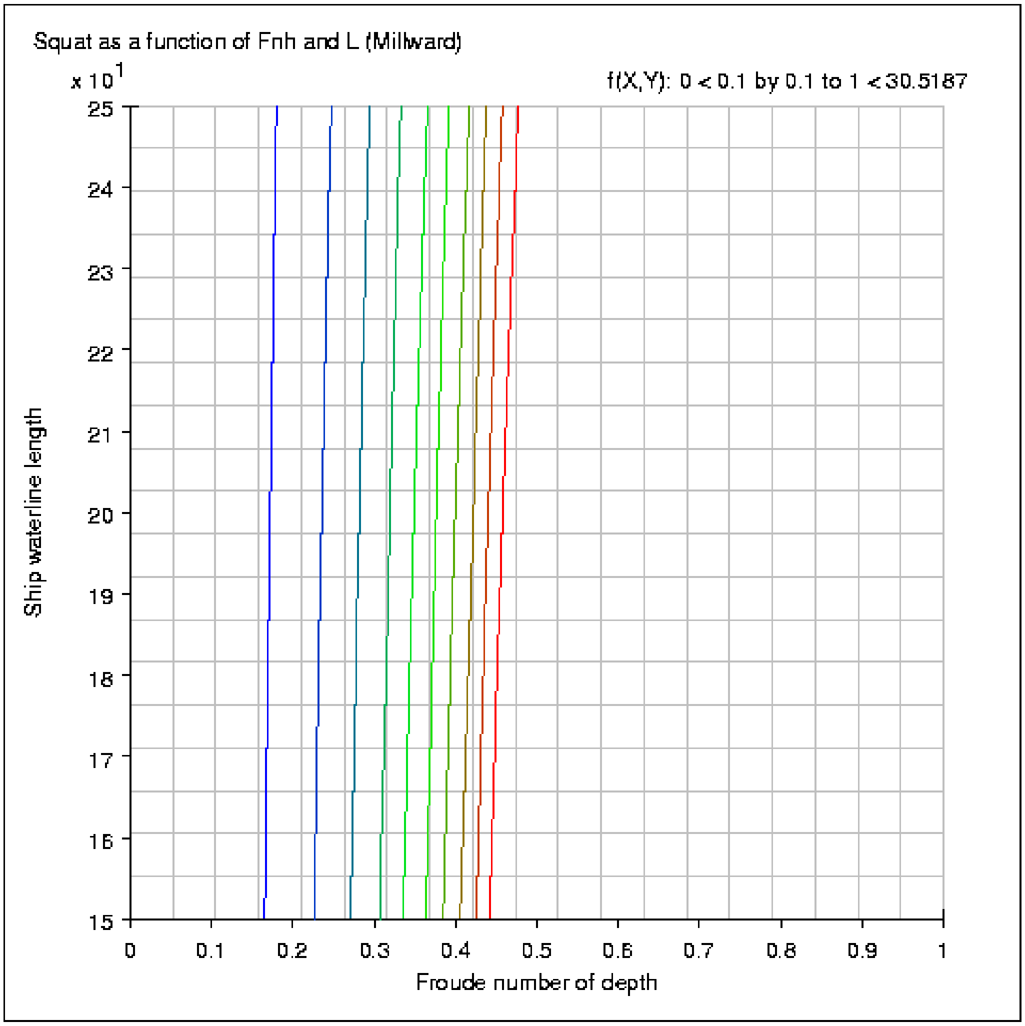

Figure 21: Ship squat as a function of Froude number and length, Millward model.
(High resolution color version is available at
http://deslab.mit.edu/DesignLab/squat/examples.html.)

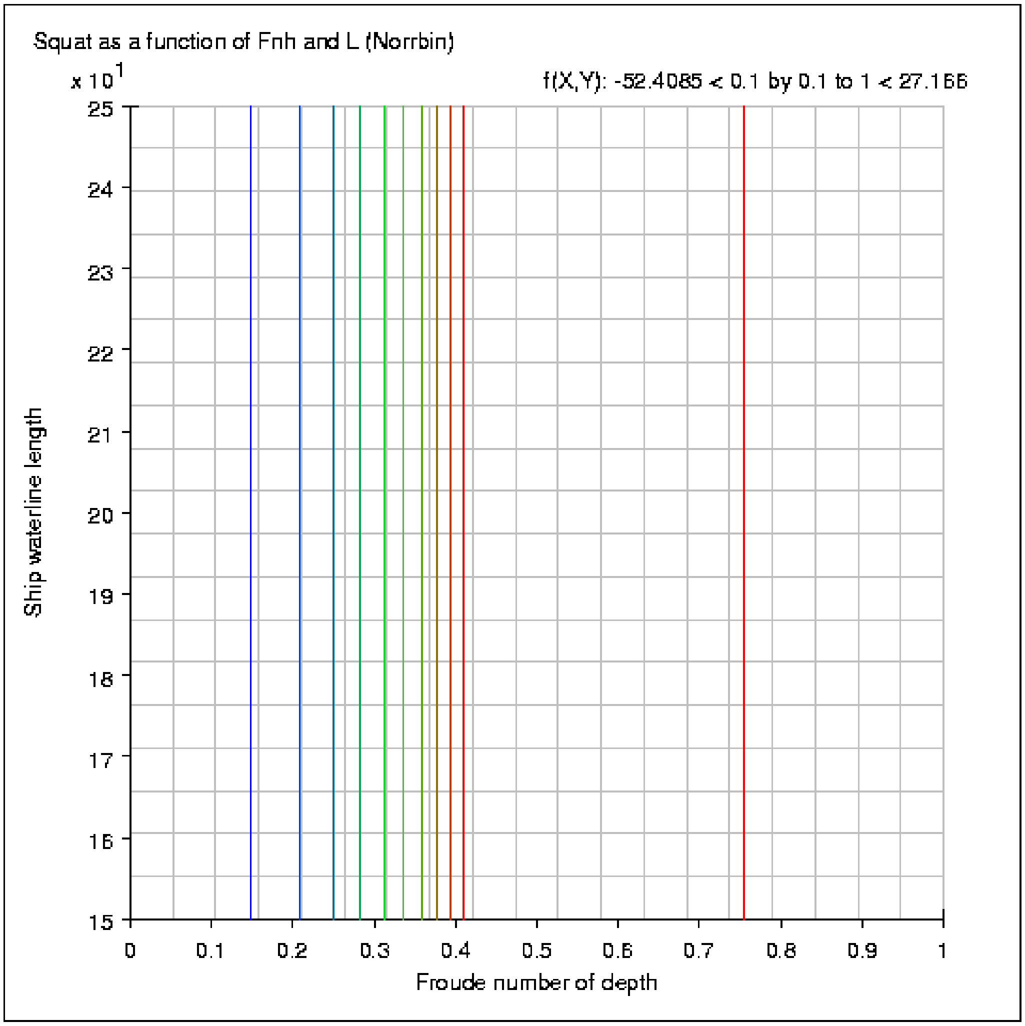

Figure 22: Ship squat as a function of Froude number and length, Norrbin model.
(High resolution color version is available at
http://deslab.mit.edu/DesignLab/squat/examples.html.)

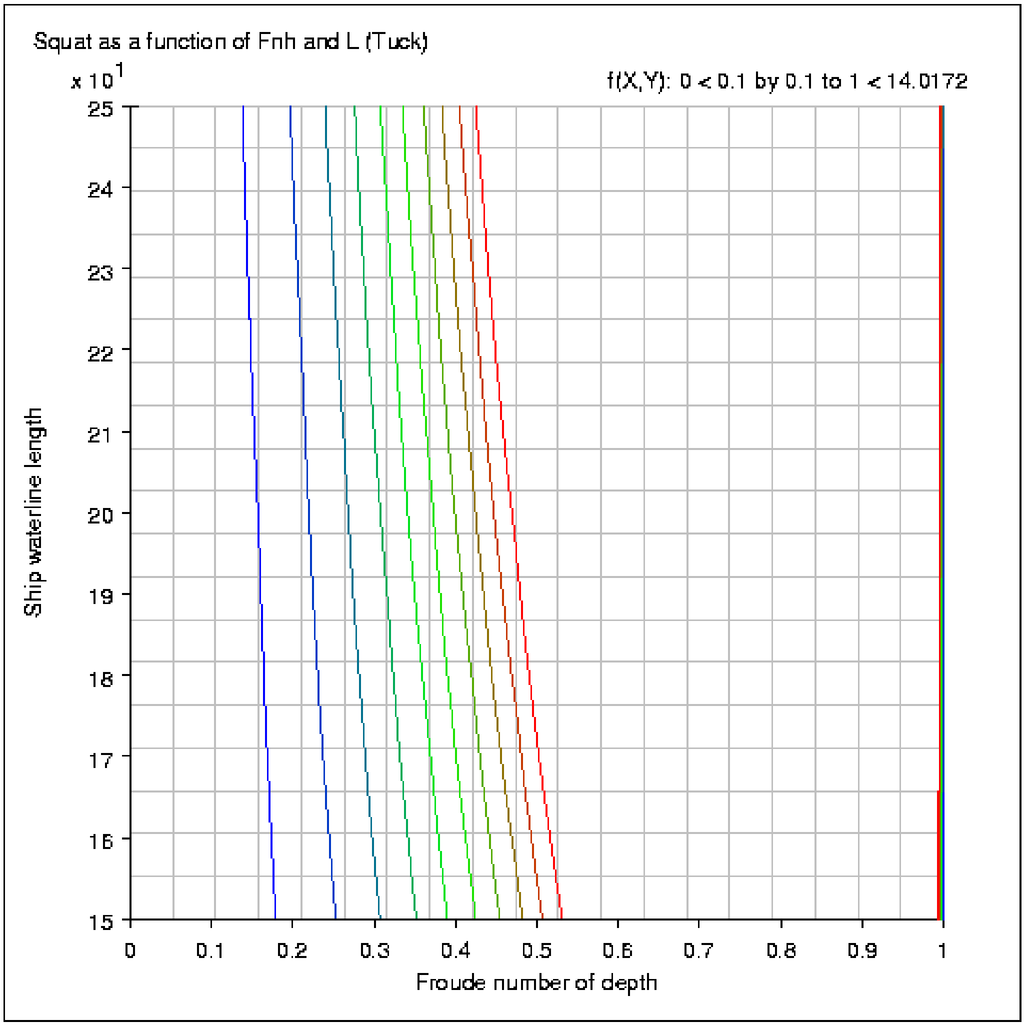

Figure 23: Ship squat as a function of Froude number and length, Tuck model.
(High resolution color version is available at
http://deslab.mit.edu/DesignLab/squat/examples.html.)

Squat can also be plotted as a trivariate function. An example for the Millward model with Froude number (varying from 0 to 1), ship length (150 to 250m), and ship beam (25 to 40m): SQUAT(Fn_h, L, B) = c_i, displayed as a VRML (Pesce 1995) world is web-accessible at

http://deslab.mit.edu/DesignLab/squat/tri-millward.wrl

Because of its three-dimensional nature, this plot is not reproduced here.

6. Conclusions

We have illustrated the use of a simple Bayesian model of the risk of groundings and collisions, using historical data on casualties, safe transits, and environmental conditions for four U.S. ports. Our analysis suggests that factors such as vessel type and size, and visibility conditions, appear to affect the risk of accidents, and that historical data on these and other parameters, while far from perfect, can be used to develop models of accident risk.

Specifically, the project determined that, based on historical data on navigational accidents involving commercial vessels in U.S. port approaches:

- one commercial ship grounds in a U.S. port approach roughly every 1300 transits, and one collision occurs roughly every 1200 transits;
- barge train accident rates are slightly higher than those for ships, and large ships have higher accident rates than small ships;
- high wind speed appears to increase the risk of accidents only slightly, whereas poor visibility appears to increase accident risk by one to two orders of magnitude;
- U.S. flag vessels appear to be involved in a disproportionately large number of accidents;
- Water level forecast errors do not appear to contribute to accident risk; and
- Due to data limitations, it is unclear whether uncertainty in water depth information resulting from older surveys contributes to grounding risk in U.S. port approaches.

Implications of these findings for transit risk management include possible benefits from greater emphasis on navigational aids and transit regulations for poor visibility conditions. Since visibility and absence of daylight are among the most significant environmental risk factors we identified, they are logical starting places for an effort to reduce the risk of groundings and collisions. The availability of improved navigation systems, such as electronic charts, GPS receivers, and VTS, may help mitigate visibility-induced risks. However, it must be noted that the response of vessel operators to such changes is likely to be complicated and that reductions in accident rates are difficult to predict. It may be, for example, that operators are comfortable with the present overall level of risk, and will take advantage of improved navigation capabilities in part to improve transit efficiency (e.g., moving the vessel more aggressively in poor visibility conditions).

The analysis conducted here for the four study ports can be applied readily to any other port or body of water for which sufficient data are available. Improving the collection of maritime accident data will assist future analyses of this kind. Two general observations can be made about historical data on maritime accidents in U.S. waters: (1) the data are incomplete, thereby limiting the type and depth of analysis that can be conducted, and (2) the data are inconsistent, making it difficult to compare accident rates across ports or over time. The project has resulted in the following suggestions for improved data collection on maritime accidents in the future:

U.S. Coast Guard casualty databases:

- establish and use consistent criteria for all ports for entering incidents into the database
- establish and use consistent criteria for obtaining information such as wind speed and direction, visibility, water level, current speed and direction, etc.
- eliminate/correct erroneous and duplicate entries (e.g. location information)
- record data on actual draft and trim, presence and use of tugs, presence of pilots

U.S. Army Corps of Engineers (and port authority) transit databases:

- report separately dry cargo and passenger vessel movements
- report "barge train" movements as well as individual barges
- improve temporal resolution (transits by day or hour)

The available data limited the number and type of factors we could evaluate explicitly in the present study. Ultimately, this work should lead to a comprehensive model of transit risk that includes additional factors such as traffic type and density, navigational aid configuration, and channel design. We would like to have included these factors in our analysis, but were not able to find sufficient data in the historical record to support their inclusion. Because of the limitations imposed by historical data, more comprehensive models of transit risk will have to rely on the integration of simulation results and expert judgement with the sort of historical data analysis presented here.

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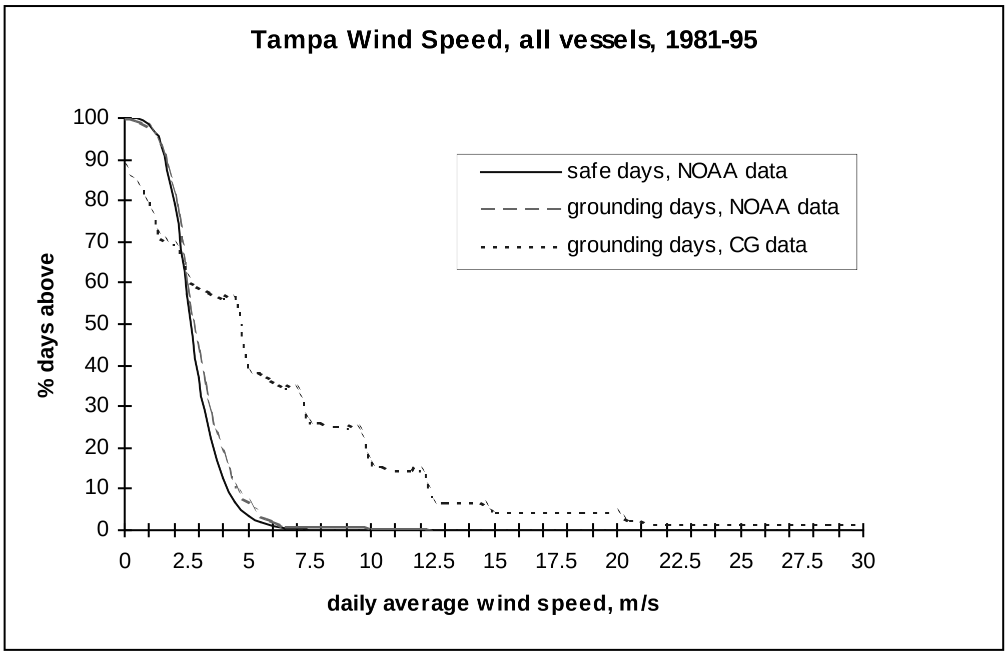
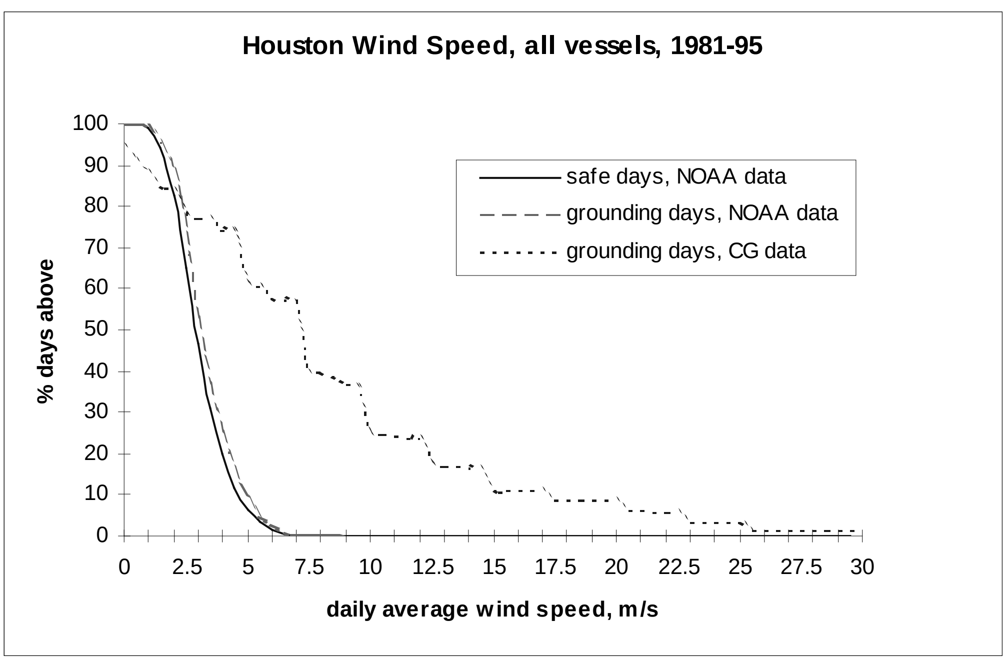
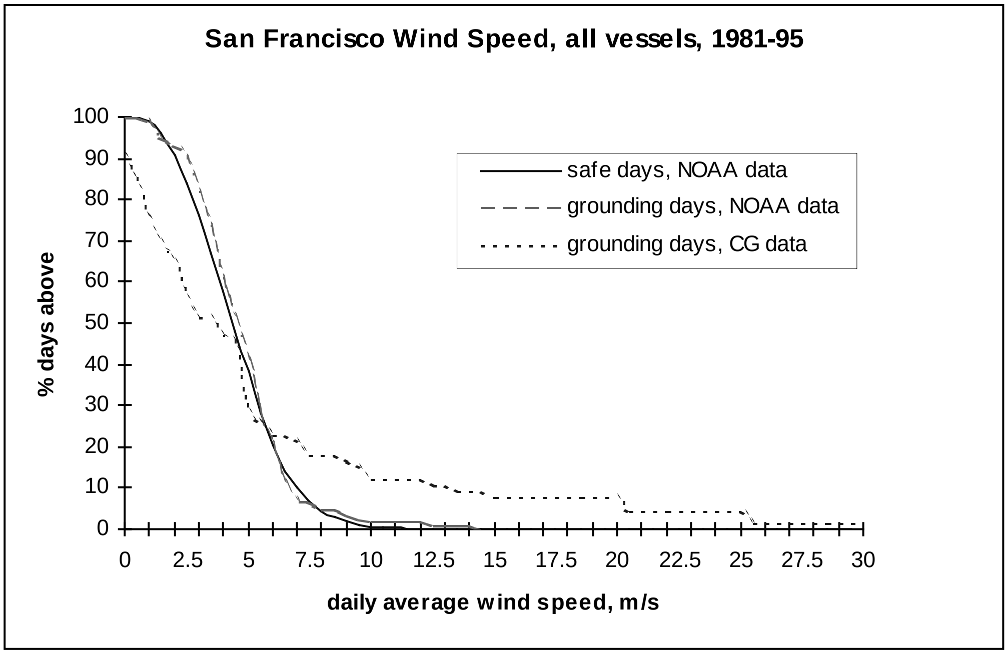
Appendices

Appendix 1: Wind Speed Distributions

See section 2.4.1 for discussion.

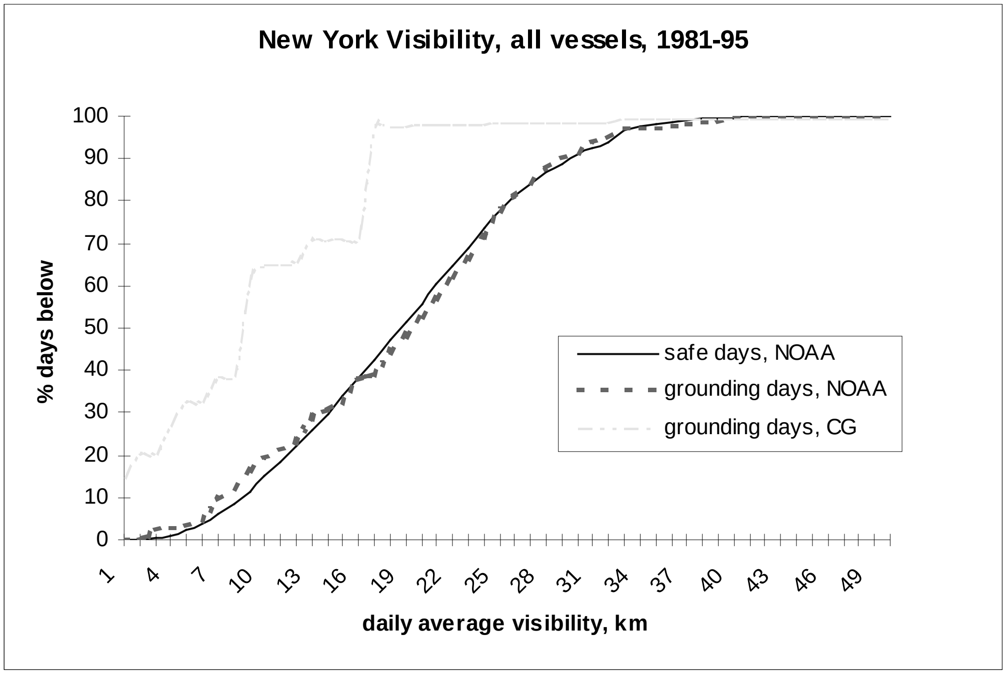


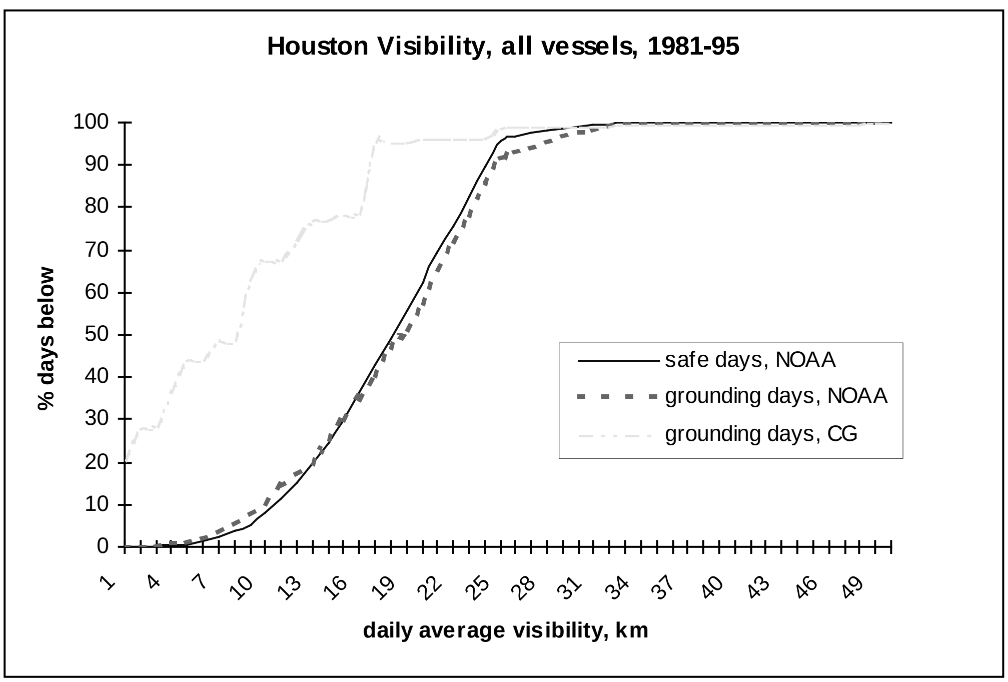


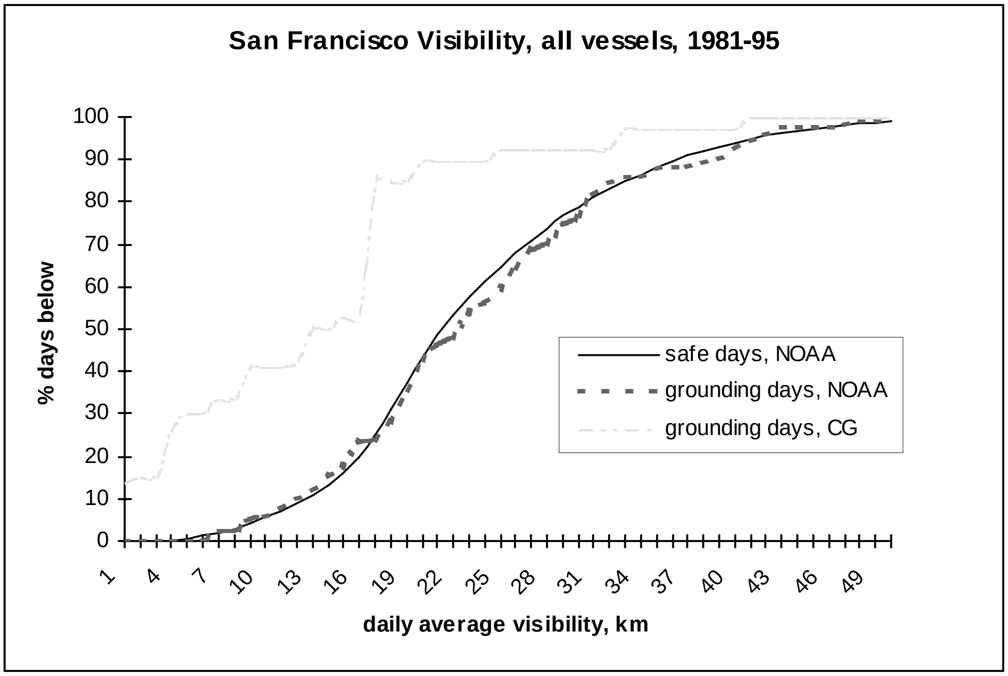

San Francisco Wind Speed, all vessels, 1981-95
% days above
100
90
80
70
60
50
40
30
20
10
0
0
2.5
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
daily average wind speed, m/s
safe days, NOAA data
grounding days, NOAA data
grounding days, CG data

Appendix 2: Visibility Distributions

See section 2.4.2 for discussion.

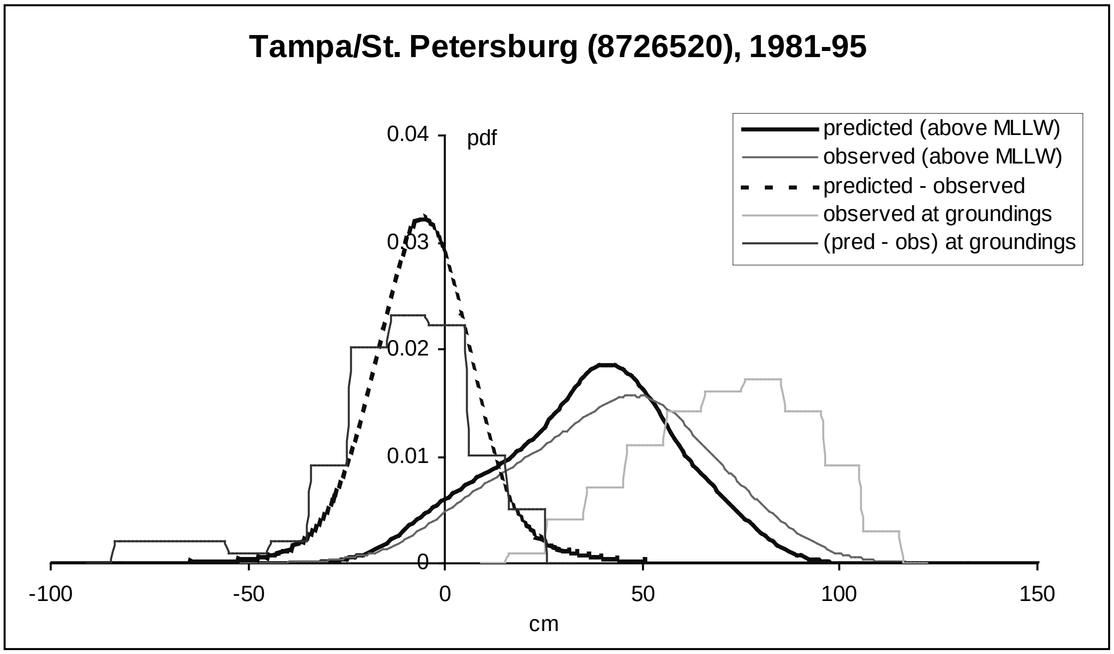


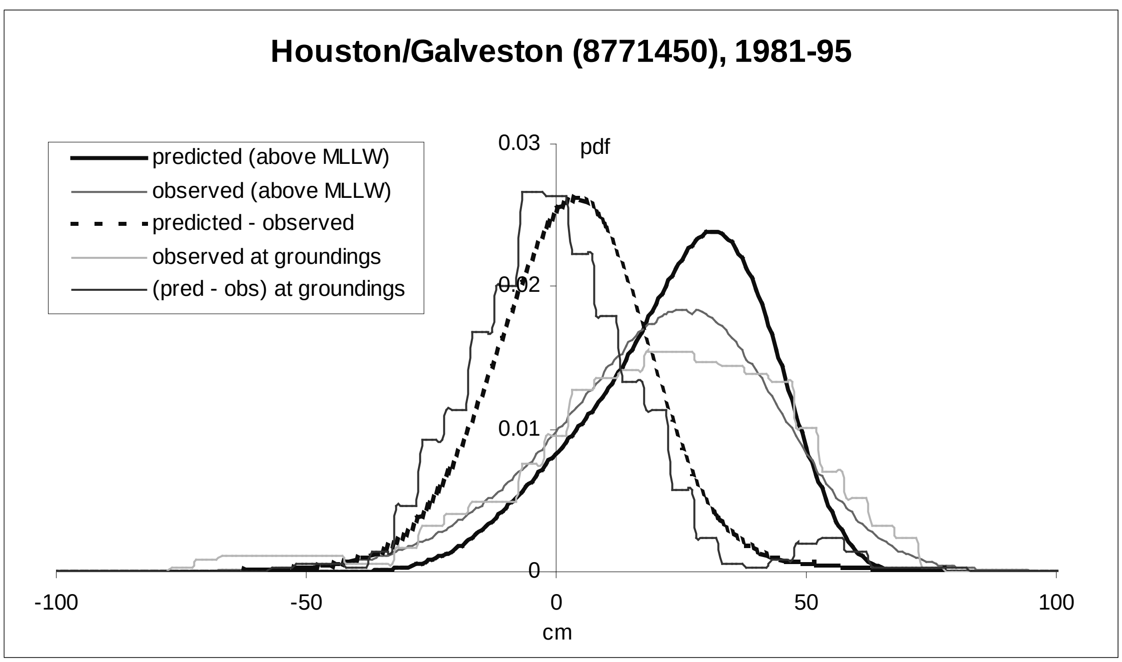


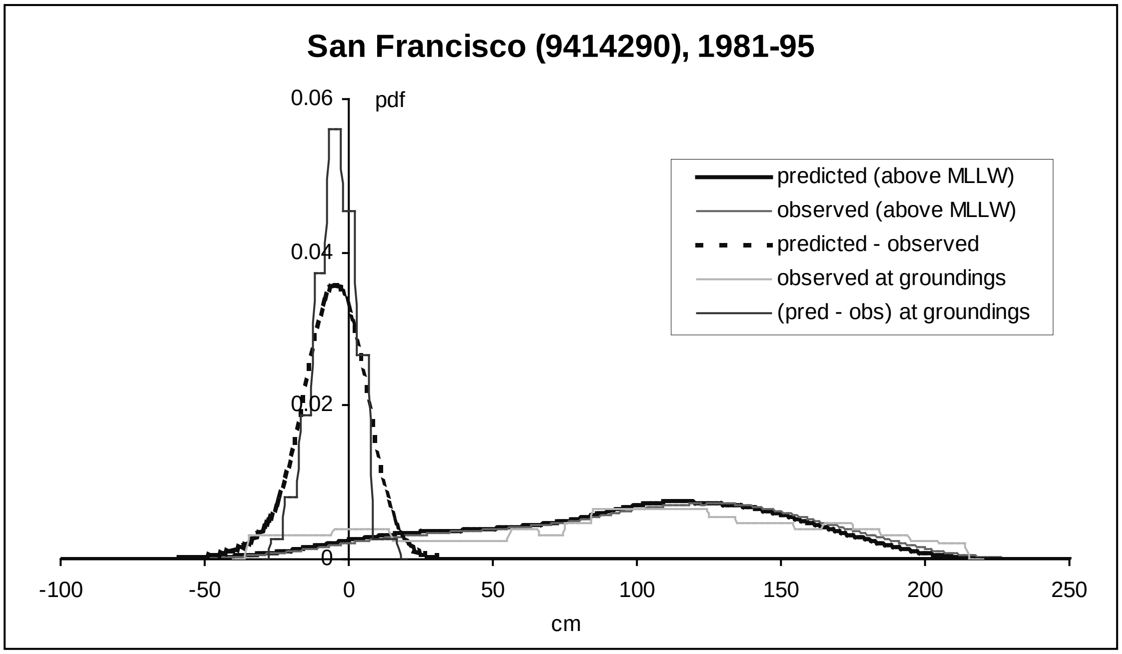

San Francisco Visibility, all vessels, 1981-95
% days below
100
90
80
70
60
50
40
30
20
10
0
1
4
7
10
13
16
19
22
25
28
31
34
37
40
43
46
49
daily average visibility, km
safe days, NOAA
grounding days, NOAA
grounding days, CG

Appendix 3: Water Level and Forecast Distributions

See sections 2.4.3 and 3.3.2 for discussion.






San Francisco (9414290), 1981-95
0.06
0.04
0.02
0
pdf
predicted (above MLLW)
observed (above MLLW)
predicted - observed
observed at groundings
(pred - obs) at groundings
-100
-50
0
50
100
150
200
250
cm

Appendix 4: Publications and Reports

The following list includes all publications and reports produced by the Transit Risk Project in addition to this final report. The list is alphabetical by author.

Jebsen, J. and V. Papakonstantinou. 1997. Evaluation of the physical risk of grounding. Master's degree thesis, Ocean Engineering Department, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Kite-Powell, H.L. 1998. Transit risk analysis for commercial ships in port approaches. *Marine Policy and the Korean Economy: Key Issues and Opportunities.* Proceedings of the First Annual Korea-U.S. Marine Policy Forum. Korea Maritime Institute, Seoul.

Kite-Powell, H.L., J. Jebsen, V. Papakonstantinou, D. Jin, and N.M. Patrikalakis. 1997. A port-level model of grounding risk and implications for navigation technologies. Proceedings of the *ION National Technical Meeting*, Santa Monica.

Kite-Powell, H.L., D. Jin, J. Jebsen, V. Papakonstantinou, and N.M. Patrikalakis. In press. Investigation of potential risk factors for groundings of commercial vessels in U.S. ports. *International Journal of Offshore and Polar Engineering* .

Kite-Powell, H.L., D. Jin, J. Jebsen, V. Papakonstantinou, and N.M. Patrikalakis. 1997. Toward a port-level model of the physical risk of grounding. Proceedings of the 1997 ISOPE Conference, Hawaii.

Kite-Powell, H.L., D. Jin, J. Jebsen, V. Papakonstantinou, and N.M. Patrikalakis. 1997. Assessing the physical risk of grounding from historical data. Proceedings of the conference on *Marine Risk Assessment*, The Institute of Marine Engineers, London.

Kite-Powell, H.L., D. Jin, S. Lin, and N.M. Patrikalakis. 1998. Risk factors for groundings and collisions in U.S. port approaches. *Proceedings of MTS Ocean Community Conference '98.*

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Lin, Shu-chiang, H.L. Kite-Powell, and N.M. Patrikalakis. Physical risk analysis of ship groundings. Draft paper to be submitted to the Institute of Navigation for the 55th Annual Meeting: *Navigational Technology for the 21st Century*.