

Investigation of Potential Risk Factors for Groundings of Commercial Vessels in U.S. Ports

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Abstract

We formulate a Bayesian model to estimate the physical risk of grounding during transits into and out of port as a function of potential risk factors. We assemble and analyze information on factors surrounding groundings in three U.S. ports between 1981 and 1995. Although the data are far from perfect, it is possible to establish associations between grounding risk and changes in factors such as vessel type and size, wind speed, and visibility.

Key Words: risk assessment, vessel groundings, Bayesian statistics

1. Introduction

Groundings of commercial ships account for about one third of all commercial maritime accidents, including some of the most expensive in the United States' history, such as the *Exxon Valdez*. Like other kinds of casualties, groundings represent a risk because they expose vessel owners and operators, as well as the public, to the possibility of losses. These include vessel and cargo damage or loss, injuries and loss of life, environmental damage, and obstruction of the waterway, among others. Strictly speaking, the risk associated with groundings is a product of the probability of the vessel touching bottom and the probability, given that the vessel has grounded, of economic losses (where "economic" is broadly defined). This paper deals only with the physical risk component of grounding risk. We will show that while the historical data on circumstances surrounding groundings in U.S. waters are neither perfect nor complete, they contain information useful to improving our understanding of why groundings may occur. For a more detailed description of this research, see Kite-Powell *et al.* (1996) and Jebsen and Papakonstantinou (1997).

Note that we are investigating the *association* between the circumstances surrounding a transit and the occurrence of groundings, based on historical data. We emphasize the word "association" as distinct from "cause." There is no intent in the present work to prove causal relationships between factors and groundings. 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 only to establish associations, to identify and investigate factors that, on the basis of association and by rational consideration, appear to contribute meaningfully to risk. This approach has the advantage of permitting the inclusion of a range of potential contributing factors. Other methods, such as fault tree analysis (see Amrozowicz (1996)), provide a more detailed view of how groundings are caused but require a great deal of data beyond what is available in the historical record.

2. Model

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

$$p(G|x) = l(x|G) p / (l(x|G) p + l(x|S) (1-p))$$

where p is the unconditional probability of G and where $l(x|G)$ and $l(x|S)$ are the likelihoods of x given G and S , respectively. S denotes the event that the transit is completed safely.

To implement this approach, it is necessary to select a set of explanatory variables that discriminates between G and S (Hand, 1981) and to estimate the unconditional grounding probability p and the likelihoods $l(x|G)$ and $l(x|S)$. The vector of explanatory variables X must capture the attributes of the transit that can be expected reasonably to contribute to the likelihood of a grounding. These attributes might include, among others:

- vessel characteristics (draft, beam, maneuverability)
- topography of the waterway (water depth, channel width, channel length, complexity of turns, traffic density)
- environmental conditions (wind, visibility, currents, waves)
- operators (experience with the vessel, training, local knowledge)
- information available to operators (quality of charts, quality of information about tide levels and currents, VTS guidance, navigation aids)

For each attribute, explanatory variables (x_i) must be extracted from historical data as numerical or categorical indicators.

3. Data

We initially examined five U.S. port areas: San Francisco Bay, Houston/Galveston, Tampa Bay, Port of New York/New Jersey, and Boston Harbor. For three of these — New York/New Jersey, Tampa, and Houston/Galveston — we were able ultimately to gather sufficient data to conduct a meaningful analysis. Data on historical groundings, transits, environmental conditions, and aspects of navigation infrastructure were collected for each study area for the period 1981 to 1995. Sources include national and local units of the Coast Guard and the Army Corps of Engineers; 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.

Grounding 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 replaced the 1991 counts by averages of the four surrounding years for purposes of analysis. From the USCG data we select for inclusion in this study only accidental, navigational groundings, and ignore those identified as intentional or due to mechanical failure or other, clearly non-navigational causes. 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). Table 1 shows the number of groundings of self-propelled vessels in the data for each study port and year.

Transit data are based on ACE Waterborne Commerce Statistics annual summaries, 1981-1994. For our purposes, "transit" is a vessel movement, so that a port call usually consists of two transits: one into and one out of the port. To avoid double counting, we base our transit counts on data for only one "waterway" in each port, as follows:

	<u>waterway code</u>
Port of Boston	0149
New York and New Jersey Channels	0388
Tampa Harbor	2021
Houston Ship Channel	2012
San Francisco Bay Entrance	4320

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.

We examine transit data using the same vessel type and size breakdown as for grounding data. Table 2 shows average annual transits during the study period. The only explicit adjustment we made to ACE annual trip data is in the small dry cargo vessel category for the port of Boston, which includes a large number of very small vessels (local passenger ferries). These have been removed from the data. Barge train transits are estimated using an average number of barges per train for each study port.

	<i>Boston</i>	<i>NY/NJ</i>	<i>Tampa</i>	<i>Houston/ Galveston</i>	<i>San Francisco</i>
1981	2	12	5	13	2
1982	1	2	1	5	5
1983	0	3	2	18	7
1984	0	6	9	13	3
1985	0	17	8	3	5
1986	0	8	3	2	5
1987	0	7	6	9	7
1988	0	6	15	13	4
1989	2	16	8	7	7
1990	1	8	3	9	6
1991*	0	2	0	1	1
1992	1	9	6	10	4
1993	0	7	3	5	5
1994	1	3	4	15	9
1995	1	1	1	11	6
1981-95	9	107	74	134	76

*1991 data are clearly incomplete

Table 1: Groundings of Ships, 1981-95, based on USCG data

	<i>ships</i>	<i>barge trains</i>
Boston	1,870	1,736
New York	10,193	30,050
Tampa	3,735	2,988
Houston	9,930	18,643
San Francisco	7,773	382

Table 2: Average Annual Transits, Ships and Barge Trains, 1981-95, based on ACE data

The distribution of explanatory factors associated with grounding events, $l(x|G)$, is derived primarily from the USCG data on groundings. 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 used NOAA's National Climatic Data Center (NCDC) hourly average wind speed and visibility data. If the time of the grounding is not reported in the USCG data, a daily average was 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. Data on hydrographic surveys in grounding locations were obtained from NOAA's National Geophysical Data Center (NGDC). Grounding locations are provided in the USCG casualty data.

The distribution of explanatory factors associated with safe transits, $I(x|S)$, was derived from a variety of data sources. Vessel type and size counts were 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 was derived from NOAA/NCDC data for "safe" days, when no groundings 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. Data on hydrographic surveys for safe transit regions were obtained from NOAA/NGDC.

4. Results

Grounding rates are calculated by dividing annual groundings by transits for each port. Average grounding rates are shown in Table 3. 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 grounding rates).

	groundings per 1000 transits	
	<i>ships</i>	<i>barge trains</i>
Boston	0.32	0.37
New York	0.72	0.18
Tampa	1.32	1.84
Houston	0.89	1.28
San Francisco	0.65	2.28

Table 3: Average Grounding Rates, Ships and Barge Trains, 1981-95

Given these caveats, it appears that the time-averaged grounding rate for ships is highest in Tampa, lowest in Boston, and clustered in between (around 0.75 groundings per 1000 transits, or one grounding in 1300 transits) for New York, Houston, and San Francisco. 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. In the other ports, they remain largely constant over the study period.

Grounding rates for barge trains appear to be lower in Boston and New York than in other ports. The Houston barge train grounding 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.

These underlying historical grounding rates form the basis for an estimate of p , the unconditional (underlying) probability of grounding, in the physical risk model. The underlying probability of grounding (p) for commercial vessels in the ports of New York/New Jersey, Tampa, and Houston/Galveston during the study period was 0.000353, 0.001636, and 0.00115, or 3.5, 16.4, and 11.5 groundings per 10,000 transits, respectively. Tables 4, 5, and 6 show the model results for the three ports for various vessels types, sizes, and registries, and two regimes for wind speed and visibility.

	probability of grounding, Port of New York/New Jersey					
	<i>good vis.</i> ($\geq 2km$)	<i>poor vis.</i> ($< 2km$)	<i>change w/ poor vis.</i>	<i>low wind</i> ($<10m/s$)	<i>high wind</i> ($\geq 10m/s$)	<i>change w/ high wind</i>
small ships (draft < 30 ft)						
U.S. flag	0.0019	0.0070	+270%	0.0020	0.0020	0
non-U.S. flag	0.0002	0.0014	+540%	0.0002	0.0008	+300%
large ships (draft ≥ 30 ft)						
U.S. flag	0.0045	0.0937	+1960%	0.0066	0.0050	-20%
non-U.S. flag	0.0015	0.0139	+820%	0.0018	0.0010	-40%
barge trains	0.0002	0.0015	+660%	0.0002	0.0002	0

Table 4: Grounding Risk in New York/New Jersey

	probability of grounding, Tampa Bay					
	<i>good vis.</i> ($\geq 2km$)	<i>poor vis.</i> ($< 2km$)	<i>change w/ poor vis.</i>	<i>low wind</i> ($<10m/s$)	<i>high wind</i> ($\geq 10m/s$)	<i>change w/ high wind</i>
small ships (draft < 30 ft)						
U.S. flag	0.0023	0.0125	+450%	0.0024	[no data]--	
non-U.S. flag	0.0008	0.0072	+750%	0.0009	[no data]--	
large ships (draft ≥ 30 ft)						
U.S. flag	0.0048	0.0407	+750%	0.0053	[no data]--	
non-U.S. flag	0.0016	0.0160	+880%	0.0018	[no data]--	
barge trains	0.0017	0.0170	+890%	0.0019	0.0048	+160%

Table 5: Grounding Risk in Tampa Bay

	probability of grounding, Houston/Galveston					
	<i>good vis.</i> ($\geq 2km$)	<i>poor vis.</i> ($< 2km$)	<i>change w/ poor vis.</i>	<i>low wind</i> ($< 10m/s$)	<i>high wind</i> ($\geq 10m/s$)	<i>change w/ high wind</i>
small ships (draft < 30 ft)						
U.S. flag	0.0014	0.0139	+910%	0.0016	[no data]--	
non-U.S. flag	0.0003	0.0026	+670%	0.0004	[no data]--	
large ships (draft ≥ 30 ft)						
U.S. flag	0.0051	0.0429	+750%	0.0057	0.0745	+1220%
non-U.S. flag	0.0009	0.0013	+50%	0.0009	[no data]--	
barge trains	0.0012	0.0100	+740%	0.0014	0.0041	+200%

Table 6: Grounding Risk in Houston/Galveston

The risk factors included in this analysis were limited by the available data. We will discuss each of these risk factors in turn.

Vessel Type and Size Other things equal, a more maneuverable vessel may be expected to have a lower probability of grounding 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 size.

Our data suggest that, in most cases, barge trains are more likely to ground than ships (see also Table 3). This is consistent with our expectations about maneuverability: barge trains are, in general, likely to be less maneuverable than ships. As illustrated in Tables 4 through 6, our data also suggest that larger 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.

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

The model results on the effect of wind speed are mixed, but do indicate significant increases in grounding risk in high wind conditions for small non-U.S. flag ships in New York/New Jersey (Table 4), for barge trains in Tampa (Table 5), and for large U.S. flag ships and barge trains in Houston/Galveston (Table 6). High wind conditions are relatively rare along the Gulf Coast, and lead to "gaps" (zeros) in grounding data for high wind conditions for Tampa and Houston/Galveston.

To improve the assessment of the effect of wind speed, it may be useful to truncate the safe wind speed distributions on the high end to reflect port closures (no safe transits) at times when winds are very high. It may be appropriate to use different high-wind cutoffs for ships and

for barges. This refinement would only amplify existing differences in the safe and grounding wind speed distributions.

Visibility Poor visibility might be expected to increase the risk of grounding. This is borne out consistently across all vessel types and all three study ports, as shown in Tables 4 through 6. The increase in grounding risk due to poor visibility is more consistent and more significant than the change associated with high wind.

As with the wind data, the analysis of visibility effects may be improved by truncating the safe distributions on the low end to reflect port closures on days when visibility is very low, possibly using different cutoffs for ships and for barges. Again, this refinement would only amplify differences in the visibility distributions.

Operator Skill/Flag of Registry Other things equal, more highly skilled or seasoned operators, and those with better local knowledge, may be expected to experience a lower risk of grounding. 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
New York	17	52
Tampa	16	36
Houston*	13	43
San Francisco	67	29

*based on incomplete data

Table 7: U.S. Flag Share of Ship Transits and Groundings

The relationship between registry and grounding risk is illustrated in Tables 4 through 6, and summarized again in Table 7. The data suggest that during the study period, U.S.-registered ships were involved in groundings relatively more frequently than foreign-flag ships in New York, Tampa, and Houston; the reverse is true in San Francisco. Data for the safe transit flag distribution in Boston were not available, but U.S. flag ships accounted for 11 percent of groundings in Boston during the study period.

While there appears to be a signal in these data, the "flag" factor embodies many variables other than operator skill, and requires further exploration before it can be endorsed fully for the development of the physical risk model. 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 incidence of groundings.

One factor we have not analyzed explicitly, but about which the data from Tampa may provide an interesting hint, 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 was not. Our data show that grounding rates in Tampa have 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.

5. Uncertainty in Nautical Chart Surveys

We conducted a separate analysis of groundings to determine whether uncertainties in nautical charts, arising from incomplete (point) surveys, contributed in measurable ways to grounding risk. 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 greater accuracy, and were constructed with better instruments, than those available to the average mariner. Today, GPS users can position themselves with more accuracy than the surveyors who collected the data on which most existing charts are based. This may have eroded some of the safety margin previously incorporated into the charts. It is conceivable that uncertainty in paper charts based on older surveys has contributed to the incidence of groundings in U.S. ports. To investigate this, we analyzed hydrographic data for uncertainty using Hydrostat software (Kielland *et al.*, 1992) and combined the results with grounding location data to check for correlation between cartographic uncertainty and historical groundings.

Three main types of error arise when charts are designed from survey data: instrumental errors, interpolation errors, and design errors. Instrumental errors consist of positioning errors and depth measurement errors, and are assumed to be constant over the survey. The approximate size of these errors depends on the survey, but they are usually smaller than interpolation errors. Design errors arise from document handling and safety bias when data are transferred to navigational documents. Since both design errors and instrumental errors are well known and usually noted on 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, 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, and 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 this stochastic surface to check for correlation between cartographic uncertainty and historical groundings.

Within the five study areas, for the period 1981-90 and 1992-95, we identified about 1000 navigational groundings. Of these, more than 100 records (primarily from the CASMAIN database, 1981-90) provide no latitude/longitude location information; others include an obviously faulty entry for location (they plot in marsh areas or on dry land). Of the remaining groundings, more than 80 percent occurred around dredged channels. Groundings around dredged channels generally are not due to the sort of bathymetric uncertainty that arises from sparse hydrographic surveys; and we eliminated them for the purpose of our survey investigation.

Unfortunately, not all of the remaining accidents are reported with sufficient accuracy to be useful for this analysis. Accident locations are reported in the USCG data (in theory) to an accuracy of +/-0.1 minutes latitude/longitude, or +/-150 to 200 meters in our study areas. 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 for an analysis of chart/survey uncertainty. This leaves us with 71 useful groundings for this part of the evaluation. Although we would prefer to have more data available, this is still a statistically useful sample.

NOAA's hydrographic survey data include 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 differ greatly in age, quality, and density of data.

We examined charted depth uncertainty in detail for the ports of New York/New Jersey and Houston/Galveston. We compared the overall distribution of interpolated errors in estimated depth for the transit areas of each survey to the distribution of interpolated errors in the depth estimates at locations where accidents occurred. For all surveys examined in the New York and Houston regions, the results suggest that, at a first level of analysis, there appear to be no compelling evidence that "open water" groundings tend to happen in high uncertainty areas. 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.

6. Data Issues

In the course of assembling and analyzing the historical data, we have identified certain deficiencies and limitations. We describe these briefly for each major data source.

USCG Vessel Casualty Data The USCG vessel casualty databases, CASMAIN and MSIS, are the most comprehensive source of commercial vessel casualty information for U.S. waters. However, these databases (particularly the older CASMAIN data) are occasionally

difficult to work with because of missing data, duplicate entries, and inaccuracies. Also, some information useful for the analysis of casualties is not collected in these datasets at all.

The locations of groundings (and other accidents) are reported in theory to tenths of minutes latitude/longitude. In practice, 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 of grounding; and it is difficult to reconstruct actual water depth at the time of the accident from the environmental data. No data are collected on the speed of the vessel at the time of the accident (making squat calculations impossible), or on wave states. Further, the presence and use of escort tugs is not quantified in the data, and the new 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 improved further 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, visibility, water level at time of the accident, etc.).

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, requiring adjustments based on approximations. 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.

NOAA Environmental Data Wind and visibility are available from NOAA as hourly averages. However, these are measured at airports located near each study port, and do not necessarily reflect conditions on the water. Historical water level (tidal and meteorological forcing) and current information is not always available with the same detail and consistency as wind and visibility, and water level and current conditions during historical groundings therefore cannot be reconstructed. This will change as real-time oceanographic data systems, such as PORTS in Tampa, become more common in U.S. harbors.

Port-Specific Traffic Data More detailed information about safe transits would be useful for several aspects of our investigation. Ideally, monthly (or even daily) counts by flag, vessel type, and vessel size, with tug escort and piloting information, could be used. Such data are only rarely available in usable, digital form from port offices or marine exchanges.

7. Conclusions

We have illustrated the use of a simple Bayesian model of the risk of grounding, using historical data on casualties, safe transits, and environmental conditions for three U.S. ports. Our analysis suggests that factors such as vessel type and size, and wind and visibility conditions, appear to affect the risk of grounding, and that historical data on these and other parameters, while far from perfect, can be used to develop models of grounding risk. In particular, low visibility (less than 2km) is associated with an increase of about one order of magnitude in the risk of grounding. Wind speed appears to have a less significant effect. In most cases, large vessels and barge trains are associated with higher risk of grounding. U.S. flag vessels appear to account for a disproportionate fraction of groundings in U.S. ports. 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.

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