HAZARD IDENTIFICATION AND PROBABILISTIC SCENARIO SELECTION FOR SHIP-SHIP COLLISION ACCIDENTS

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SUMMARY

In collision risk-based design frameworks it is necessary to accurately define and select a set of credible scenarios to be used in the quantitative assessment and management of the collision risk between two ships. Prescriptive solutions and empirical knowledge are commonly used in current maritime industries, but are often insufficient for innovation because they can result in unfavourable design loads and may not address all circumstances of accidents involved. In this study, an innovative method using probabilistic approaches is proposed to identify relevant groups of ship-ship collision accident scenarios that collectively represent all possible scenarios. Ship-ship collision accidents and near-misses recently occurred worldwide are collated for the period of 21 years during 1991 to 2012. Collision scenarios are then described using a set of parameters that are treated individually as random variables and analysed by statistical methods to define the ranges and variability to formulate the probability density distribution for each scenario. As the consideration of all scenarios would not be practical, a sampling technique is applied to select a certain number of prospective collision scenarios. Applied examples for different types of vessels are presented to demonstrate the applicability of the method.

NOMENCLATURE

CDF	= Cumulative density function
D	= Ship depth
D_1	= Striking ship depth
D_2	= Struck ship depth
D_n	= Kolmogorov-Smirnov test statistic
d_1	= Striking ship draught at time of accident
d_2	= Struck ship draught at time of accident
$(d_2/D_2)/(d_1/D_1)$	= Relative draught parameter
GT	= Gross tonnage
L_2	= Struck ship length
l_2	= Distance from the foremost point of the struck ship to the impact point
l_2/L_2	= Impact location along the struck ship length
PDF	= Probability density function
V_1	= Striking ship speed at time of accident
V_2	= Struck ship speed at time of accident
V_2/V_1	= Relative speed parameter
Δ_1	= Striking ship displacement
Δ_2	= Struck ship displacement
Δ_2/Δ_1	= Relative displacement parameter
θ	= Collision angle

1. INTRODUCTION

Ships can be subjected to severe accidents during their life cycle that can have serious consequences, such as loss of human life, structural damage and environmental disaster, especially in closed seas. Such accidents also have financial impacts for local communities close to the accident. Ship-ship collisions can also lead to these consequences, particularly where large tankers, toxic products carriers, nuclear powered and wasted cargo ships are involved.

A framework for the quantitative assessment and management of collision risk requires various accident scenarios to be identified. This study proposes an innovative method to select relevant sets of collision scenarios based on random variables to contribute to the hazard identification stage that is the first step in the International Maritime Organization's (IMO) probabilistically based Formal Safety Assessment procedure (FSA).

Figure 1 presents a procedure for quantitative collision risk assessment and management that includes frequency analysis, consequence analysis, risk calculation and risk control options. The results of these investigations will be presented in future papers.

The International Tanker Owners Pollution Federation (ITOPF) has a database of incidences of oil spills from tankers, combined carriers and barges except those resulting from acts of war [1]. Figure 2 shows the incidence of spills greater than 700 tonnes by cause across four periods. The statistics show that grounding and collisions are the most common causes of oil spills. The percentage of oil spills caused by collisions increased in the periods 1970-2004, 1970-2007 and 1970-2009, but decreased a small amount (0.1 %) for the overall period 1970-2012.

This finding indicates that although the majority of oil tankers are safely built to reduce the amount of oil spilled in the event of an accident, oil spills due to collision cannot be prevented. There is thus still a need for more analysis and investigation of all aspects of collision between ships.

In this regard, it is of crucial importance to be able to reduce the probability of accidents, assess their consequences and ultimately minimise or prevent potential damage to ships and to the marine environment [2].

Ship collisions are normally classified into two types: ship-ship collisions and head-on collisions. Ship-ship collisions refer to a situation in which the bow of a striking ship collides with the side structure of another struck (collided) ship. Head-on collisions typically refer to a situation in which the bow of a vessel collides with fixed rigid walls such as piers and bridge abutments [3]. In this study, the focus is on ship-ship collisions.

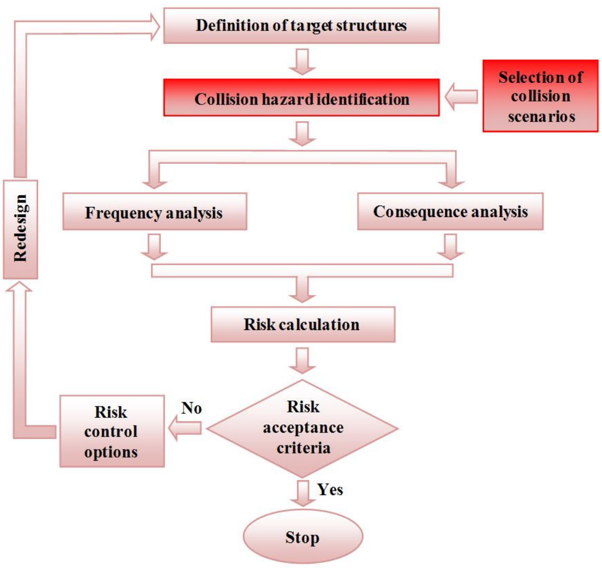

Figure 1: Quantitative collision risk assessment and management procedure considered in the present study

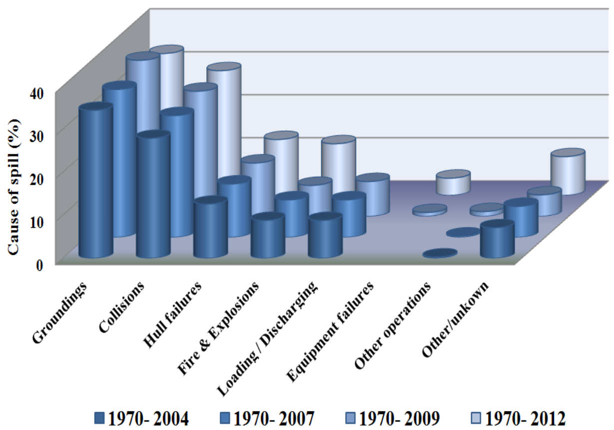

Figure 2: Incidence of oil spills greater than 700 tonnes by cause [1]

1.1 LITERATURE REVIEW

The structural crashworthiness or resistance of a ship, and especially the struck ship structure, to accidental loads plays a very important role and has been highlighted in many recent research and development efforts [4]. Several authors have developed collision scenario models, which can be divided into three groups. The first can be called 'statistical collision models' that are defined based on statistics from historical collision accidents, as suggested by Rawson et al. [5], the National Research Council (NCR) [6], Brown [7] and Tuovinen [8]. The second group is 'encounter collision scenarios' that are determined by applying the concept of the ship domain in relation to the ship traffic flow in cross-traffic lanes taking into consideration an evasive manoeuvring to avoid collision such as changing in speed and course. The most recent studies in this vein use the Automatic Identification System (AIS) to simulate the marine traffic flow to obtain realistic encounter scenarios in specific areas. This type of scenario has been explored by Ståhlberg [9], Montewka et al. [10] and Goerlandt et al. [11]. The third group of models is the 'blind navigator collision models' in which no manoeuvring actions are taken to avoid the collision. These models are used for finding the so-called collision candidates for collision probability evaluation [11], and have been explored by Pedersen [12,13], Van Drop and Merrick [14] and Goerlandt and Kujala [15].

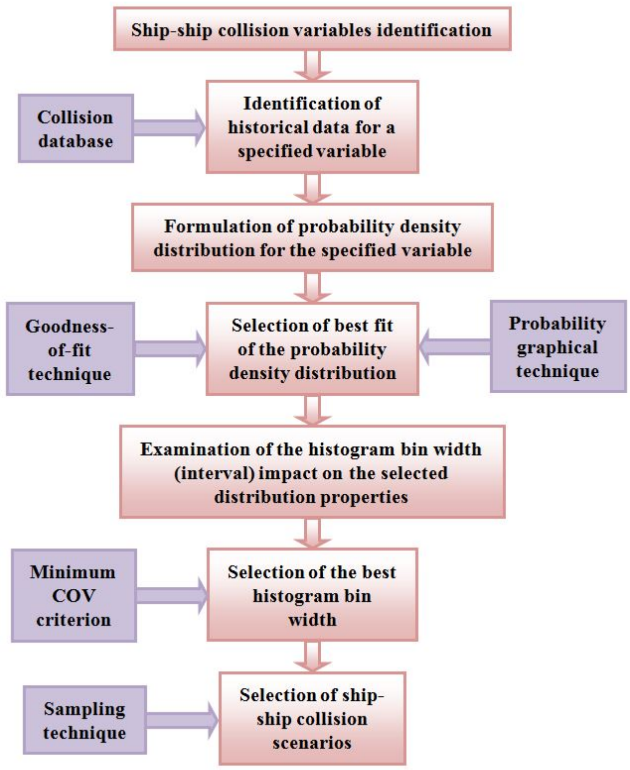

Figure 3: Flow of the proposed method for probabilistic analysis

1.2 GENERAL PROCEDURE OF THE PROPOSED METHOD

Once the updated ship-ship collision accident database has been created, the collision variables can be identified. Each variable must be described by defining its range and variability for use in deriving the probability density distributions. The goodness-of-fit technique is used to select the best probability density function that represents the original data. The probability graphical technique is also applied at a certain confidence interval to assess whether or not the original dataset follows the theoretical distribution.

Once the best fit probability density function has been selected, the effect of the histogram bin width (interval) on the distribution properties can be examined. The minimum coefficient of variation (COV) criterion is then applied to select the best histogram bin width.

Finally, a sampling technique is applied to randomly select a set of scenarios that are defined by the studied collision parameters. Figure 3 shows the general procedure of the proposed method.

2. PROCEDURE OF THE DEVELOPED PROBABILISTIC METHOD

2.1 IDENTIFICATION OF THE SHIP-SHIP COLLISION VARIABLES

An extensive analysis of ship-ship collision accidents is implemented to characterise the scenario parameters (see Figure 4) that can affect the damage pattern in both colliding vessels. These parameters can be listed as follows.

- Striking ship displacement (Δ_1).
- Struck ship displacement (Δ_2).
- Striking ship speed (V_1).
- Struck ship speed (V_2).
- Striking ship draught (d_1).
- Struck ship draught (d_2).
- Striking ship type.
- Striking bow shape.
- Struck ship impact longitudinal location (l_2).
- Collision angle (θ).

The collision angle is assumed to be the angle between the initial directions of motion of the two colliding ships at the moment of impact, as shown in Figure 4. Based on this assumption, the relative angle between zero and 180 degrees is independent from the location of impact. These assumptions were used by Rawson et al. [5].

From the view point of causality avoidance or risk minimisation, the primary considerations for a ship's structure are resistance to accidental load, sufficient residual strength, adequate stability and containment of the cargo from spilling (i.e., when the struck ship cargo hold is breached) [4]. Designers should thus evaluate the crashworthiness and energy absorption capability of the target structure for both colliding structures. In this study, the relative displacement (Δ_2/Δ_1), relative speed (V_2/V_1), relative draught [(d_2/D_2) / (d_1/D_1)], location of impact through the struck ship length (l_2/L_2) and collision angle (θ) parameters are individually dealt with as random variables in the scenario selection stage.

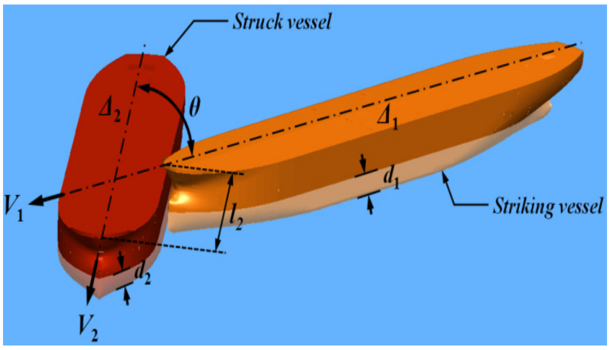

Figure 4: Schematic of a ship-ship collision

2.1 (a) Striking Ship Type Parameter

Because the striking ship type plays an important role in collision accidents, it is important to treat it as a random variable. This is achieved by dividing the striking ship types in the collision database into six categories that are then ordered for formulation as a normal distribution and represented by a range of values. Each category includes several more specific types, as follows.

- Tankers: including crude and product tankers, chemical tankers and gas carriers.
- Bulk carriers: including dry bulkers and coal carriers.
- Cargo vessels: including general cargo and refrigerated vessels.
- Container vessels: including containers, car carriers, container/RO-ROs and RO-ROs.
- Passengers: including passenger vessels and ferries.
- Other: including service vessels, fishing vessels, barges, dredgers, factory vessels, heavy lift vessels, pleasure boats and yachts.

2.1 (b) Striking Bow Shape

The bow shape of the striking ship is important because it determines the volume of the structure that is damaged during the collision [5]. Differences in striking ship bow stiffness and bow height and shape have an important influence on the allocation of absorbed energy between the striking and the struck ship and the extent of damage in the struck ship [16]. Refined bow models are more realistic, but are difficult to analyse [17]. The newest seagoing ships have bulbous bows for better hydro-dynamism.

In the literature, a bulbous bow has been modelled as a conical shape with different lengths and spreading angles for use in experimental impact tests [3, 18], and also (the whole forward portion) as an elliptic parabola [19, 20], as shown in Figure 5.

If the bow shape is unknown but the length, breadth and bow height of the striking ship are known, then the bow shape can be estimated from the stem angle (φ), the distance between the bulb tip and the foremost part of the bow (R_D), the bulb length (R_L), the vertical radius of the bulb (R_V) and the horizontal radius of the bulb (R_H) this model explored by Lützen [19] as shown in Figure 5. Pérez [21] suggested a bow mathematical model using a family of curves and surface splines based on a set of defined parameters.

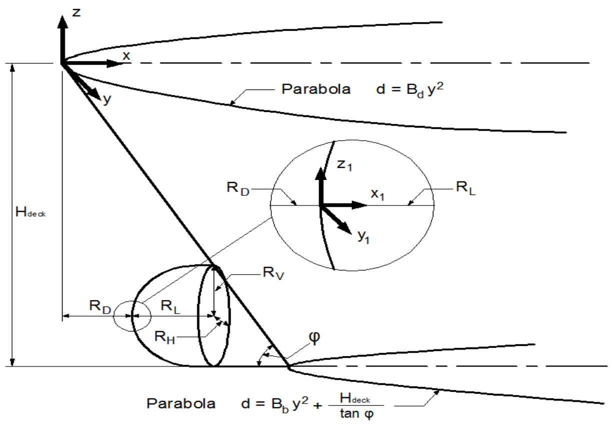

Figure 5: Elliptic parabola shaped bow model [19]

2.2 DATA SOURCES

The available statistics suffer from incompleteness. There is a lack of historical data that can be used to recreate accident scenarios. The conditions surrounding accidents, such as the ship speed, loading condition, environmental conditions and so on are often not clearly recorded. Major efforts are still needed to build up a database of collision and grounding accidents [17].

In this study, ship-ship collision accident data for the 1991 to 2012 period provided by 14 accident investigation boards under the responsibility of the national maritime authorities of different countries are collated. All of these accident investigation boards have a similar target, which is to cover all accidents in national waters and all accidents involving their nationally flagged ships across the world.

It is of interest to report near-misses (i.e., near-collisions) and small accidents in the database to develop a proactive approach rather than a reactive approach that is taken consequent to accidents. The International Maritime Organization (IMO) defines near-misses as a sequence of events or conditions that could have resulted in loss, where the loss was only prevented by a fortuitous break in the chain of events or conditions. The potential loss may be human injury, environmental damage or a negative business impact [22]. A near-collision is a situation in which two ships come within a certain distance of each other. Several near misses are recorded in the database. The data are filtered by omitting insufficient and unconscionable data, leaving 205 cases that may represent the world-wide collision accidents.

Unfortunately, the database contains little information about the displacement of both colliding ships, and so some empirical formulae [23] derived from a huge number of existing ships are used to calculate the displacement in relation to ship type.

2.2 (a) Distribution of Vessel Types in Accidents

The collision database is used to establish the distribution of vessel types involved in accidents. The vessel types are divided into 11 groups, each of which includes several specific types.

- Tankers: including crude and product tankers.
- Chemical tankers: including chemical and other liquid carriers.
- Bulk carriers: including dry bulkers and coal carriers.
- Cargo vessels: including general cargo and refrigerated vessels.
- Container vessels: including containers and container vessels.
- Gas carriers: including LNG and LPG carriers.
- RO/RO vessels: including car carriers, cargo/RO-ROs and RO-ROs.
- Passengers: including passenger vessels and ferries.
- Service vessels: including tugs, supply boats and salvage vessels.
- Fishing vessels: including all types of fishing vessels.
- Other: including barges, dredgers, factory vessels, heavy lift vessels, pleasure boats and yachts.

Figure 6 shows three types of distribution for both colliding vessels, striking vessels and struck vessels involved in accidents.

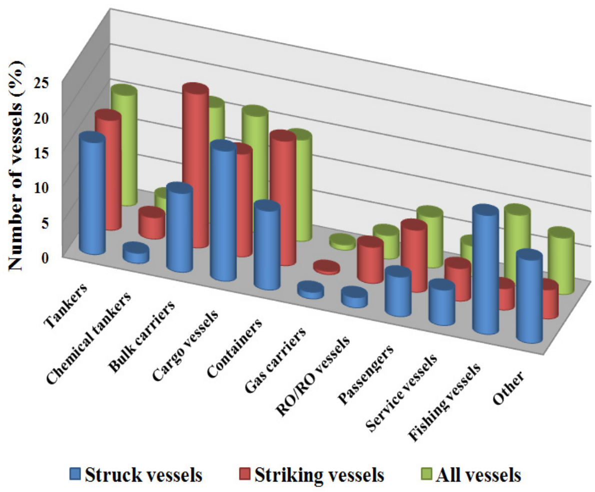

Figure 6: Distribution of vessel types involved in accidents

2.2 (b) Relationship between the Striking and Struck Vessels

Based on the historical collision accident database, the relationships between the length, breadth, depth, draught, gross tonnage and speed at time of accident of the striking and struck vessels are examined, as shown in Figure 7. Ship length, breadth and depth are widely distributed but there is a trend towards small vessels being struck by larger vessels and larger vessels being struck by larger vessels. In addition, few cases are found where large vessels being struck by small vessels such as supporting tugs, fishing vessels and pleasure boats causing minor damage to struck vessels.

Figure 7 also shows the wide distribution of ship draughts, indicating that the loading condition at the moment of impact for both colliding ships has a significant effect on the collision consequence. In terms of ship speed, it is observed that only a small percentage of struck vessels (about 7%) are moored or anchored at the moment of collision, probably because many collision accidents occur when struck vessels are sailing in open seas or in traffic routes such as ports, canals, rivers and narrow passages.

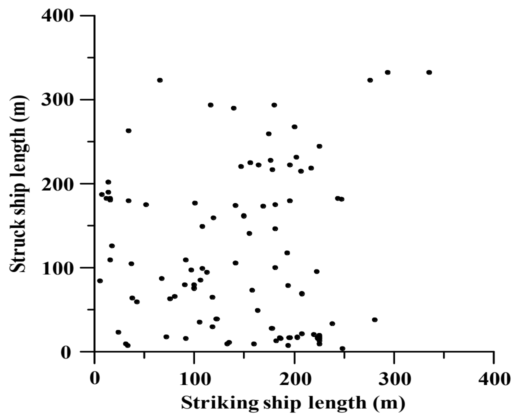

Figure 7(a) Striking ship length versus struck ship length

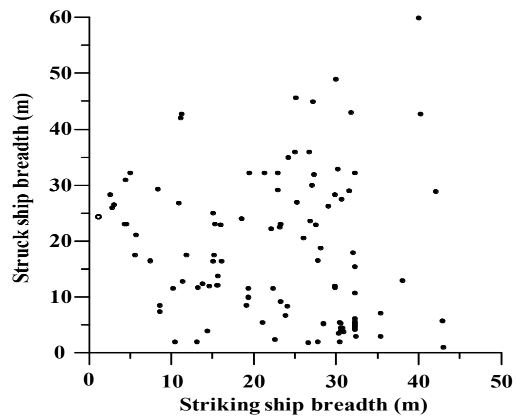

Figure 7 (b) Striking ship breadth versus struck ship breadth

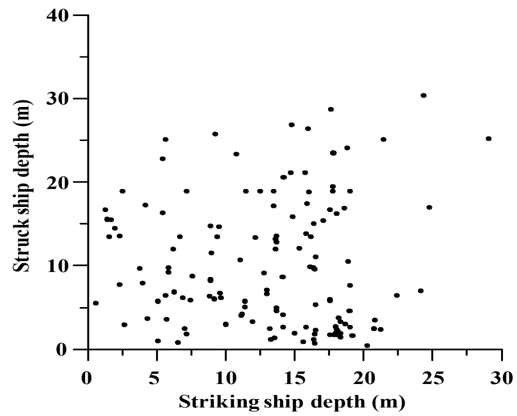

Figure 7 (c) Striking ship depth versus struck ship depth

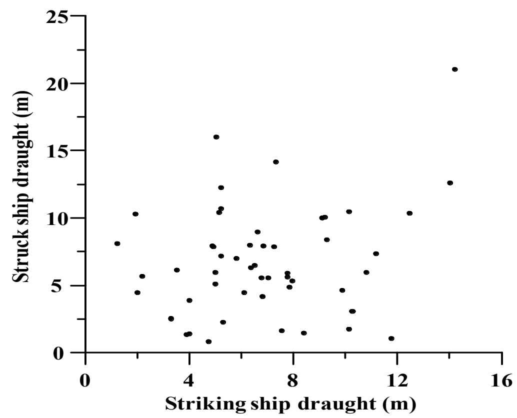

Figure 7 (d) Striking ship draught versus struck ship draught

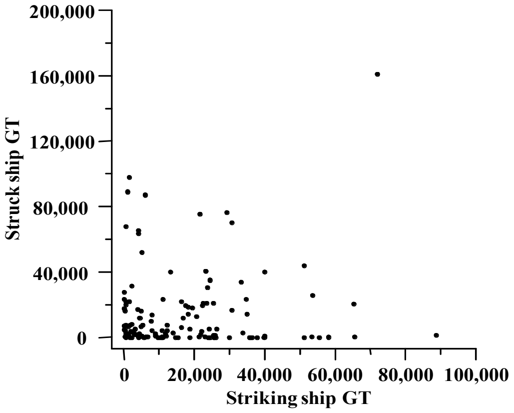

Figure 7 (e) Striking ship GT versus struck ship GT

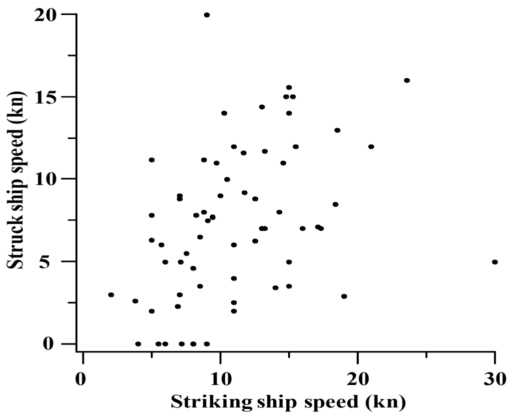

Figure 7 (f) Striking ship speed versus struck ship speed

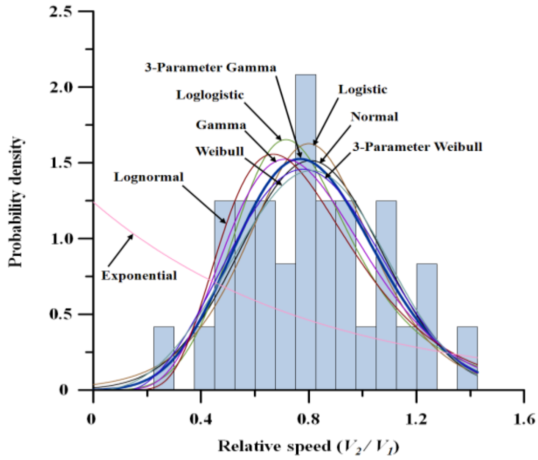

Figure 8(a) Sample of PDF versus relative speed parameter

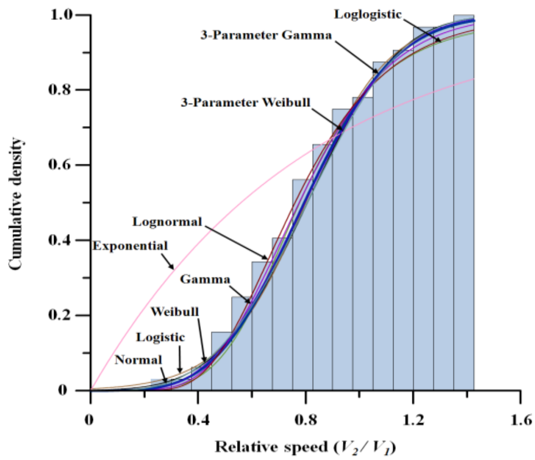

Figure 8(b) Sample of CDF versus relative speed parameter

2.3 FORMULATION OF THE PROBABILITY DENSITY DISTRIBUTIONS

To describe the range and variability of the collision parameters to be used in the ship-ship collision scenario selection, probability density distributions are derived for each of the collision parameters. Nine types of the most commonly used probability density functions (PDFs) are used to fit the historical data. Figure 8 shows some examples of the PDFs and cumulative density functions (CDFs) versus relative speed parameter (V_2/V_1) in which cargo ships are considered to be struck ships.

2.3 (a) Selection of the Best Probability Density Distribution

When it is assumed that data follow a specific distribution, a serious risk is taken. If the assumed distribution is wrong, then the results obtained may be invalid. One way to deal with this problem is to check the distribution assumptions carefully [24].

Goodness-of-fit (GoF) tests can be used to measure the compatibility of historical data with a theoretical PDF. Some of these tests are based on the empirical distribution function (EDF) that measures the differences in cumulative density functions (CDFs).

If this difference is probabilistically accepted, then the data support the assumed distribution. If not, then the distribution assumption is rejected. The most widely used GoF test is the Kolmogorov-Smirnov test (K-S) [25], which uses the maximum absolute difference between the distribution functions of the samples. The K-S test statistic D_n is the largest absolute value of the difference between the empirical CDF $F_n(x)$ for a number (n) of observations (x) and the CDF of the candidate distribution $F(x)$, which must be less than 1. Test statistic D_n can be given by Equation (1),

$$D_n = sup_x \left| F_n(x) - F(x) \right| \qquad (1)$$

where sup_x is the supremum of the set of distances.

Figure 9 shows the graphical meaning of the K-S test. This is an attractive test because it is distribution free, makes use of each individual data point in the samples and is independent of the direction of order of the data [26]. Further, the K-S test tends to be more powerful than other tests when there are many alternative distributions, and is valid (exactly) for any sample size (n). In this study, the K-S test is applied to each of the studied collision parameters to determine the best PDF to represent the historical data. The better the distribution fits the historical data, the smaller the statistic D_n.

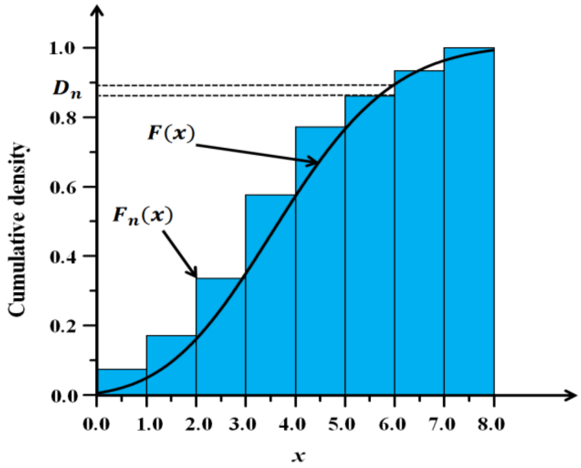

Figure 9: Graphical representation of the Kolmogorov-Smirnov test

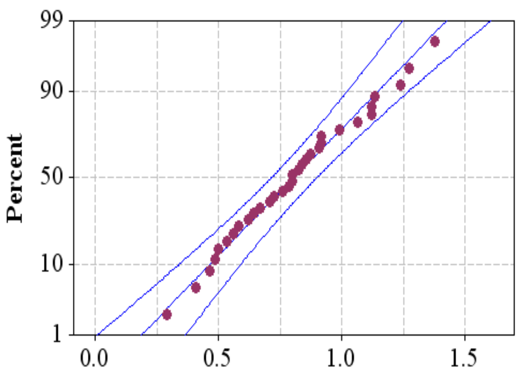

Figure 10: Probability plot for the relative speed parameter at a 95% confidence interval

2.3 (b) Data Fitting Assessment using the Probability Graphical Technique

A probability plot is a graphical technique for assessing whether or not a dataset follows a given distribution at a certain confidence level. It gives a range of numbers containing the most plausible values for a sample (i.e., the margin of error). The confidence interval also reveals that for a given level of certainty, if the scientific model is correct, then the true value in the sample data is likely to be within the range identified [27] and is generally chosen to be 0.9, 0.95 or 0.99. The confidence level is expressed as a percentage of certainty. The most commonly used confidence levels are 95% and 99%.

In probability plots, the original data (i.e., observations) are plotted against a theoretical candidate distribution in such a way that the points form an approximately straight line. Departures from this straight line indicate departures from the specified candidate distribution [28]. Figure 10 shows an example of a probability plot for the relative speed parameter (V_2/V_1) versus a normal distribution.

2.4 IMPACT OF THE HISTOGRAM BIN WIDTH ON THE PDF PARAMETERS

In the statistical analysis of a random variable, the effect of the histogram bin width (or interval) usually has a significant effect on the data distribution properties. Thus, distribution parameters such as the mean and COV are determined for various intervals (histogram bin widths). The minimum COV guarantees that the degree of variation between the probability distribution and the data will be the smallest that can be achieved at the minimum standard deviation (i.e., minimum spreading) and maximum mean values. For these reasons, the bin width that gives the largest mean value and the smallest COV is selected (see Figure 11) based on the minimum COV criterion [29,30]. Sturges' formula [31] and Doane's formula [32] are useful for determining the best bin width value for normally and non-normally distributed data, respectively.

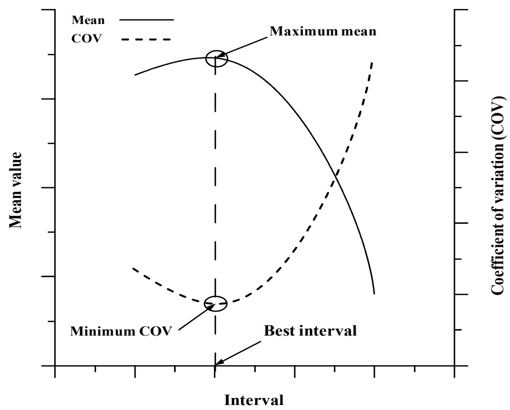

Figure 11: Schematic of the minimum COV criterion

2.5 SELECTION OF COLLISION SCENARIOS

Although a huge number of possible collision scenarios may be relevant, it is not practical to consider all of them. The Latin Hypercube Sampling (LHS) technique [33] is used here to select the probable scenarios. The probability P of each of M samples being generated by the LHS technique for N variables is obtained by Equation (2).

$$P = \left(\frac{1}{M}\right)^N \tag{2}$$

When sampling a function of N variables (i.e., collision parameters) using the LHS technique, the range of each variable is divided into M equally probable strata (intervals), as shown in Figure 12. One sample is chosen from each stratum (e.g., assuming uniform probability over the stratum). The M^{th} column in the N^{th} dimension of the hypercube corresponds to the value from the M^{th} stratum of the N^{th} random variable. Sample points are then placed to satisfy the Latin hypercube requirements, as in Figure 12.

This approach forces the number of divisions M to be equal for each variable. The sampling scheme does not require more samples for more dimensions (variables), which is one of its main advantages.

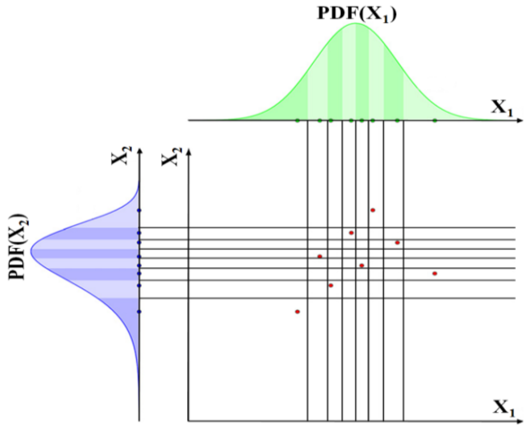

Figure 12: Illustration of the Latin hypercube sampling technique for a case with two variables and eight samples

3. APPLIED EXAMPLES

Different ship categories are used to demonstrate the applicability of the developed method. The first includes all types of ship involved in the collision database, and the second includes specified types of struck ship, such as double hull oil tankers, bulk carriers, containers and cargo ships.

3.1 ALL TYPES OF SHIP CATEGORIES

In this section, the proposed probabilistic method (see Figure 3) is applied individually to each of the studied all types of ship categories, as discussed. Figure 13 shows the formulated PDFs and CDFs versus the collision parameters. The K-S test is then applied to determine the best PDF to represent the original data. The test statistic D_n is presented in Table A.1 for each collision parameter versus several types of PDFs. The distribution function that has the smaller D_n is the best fit to represent the historical database for each of the individual collision parameters, as discussed in Section 2.3 (a).

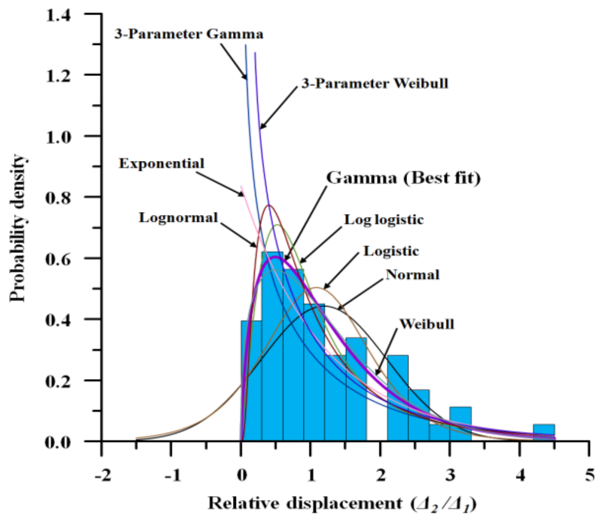

Figure 13(a) PDF versus relative displacement parameter

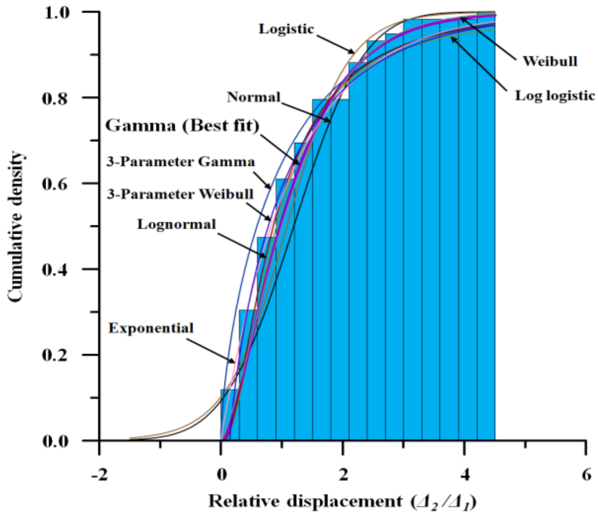

Figure 13(b) CDF versus relative displacement parameter

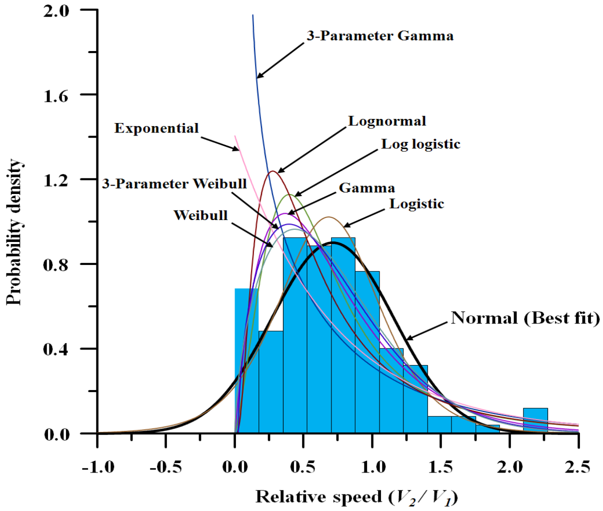

Figure 13(c) PDF versus relative speed parameter

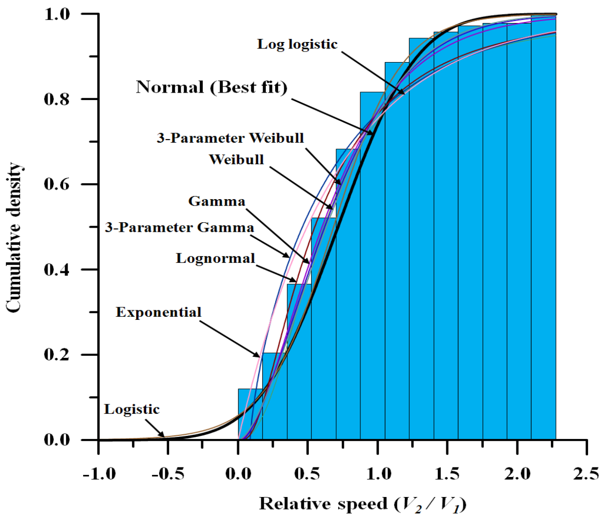

Figure 13(d) CDF versus relative speed parameter

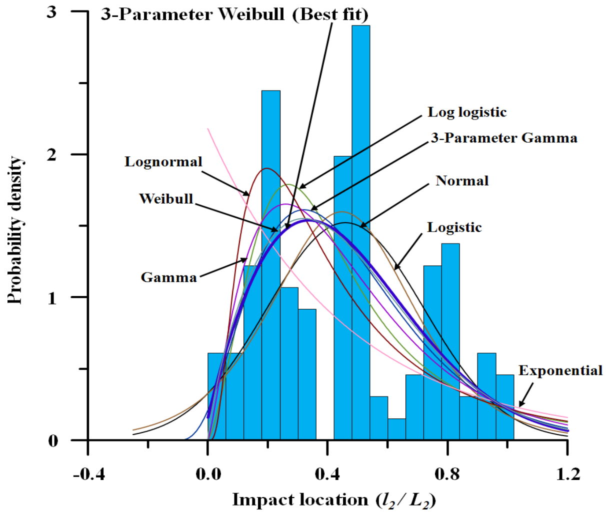

Figure 13(g) PDF versus impact location parameter

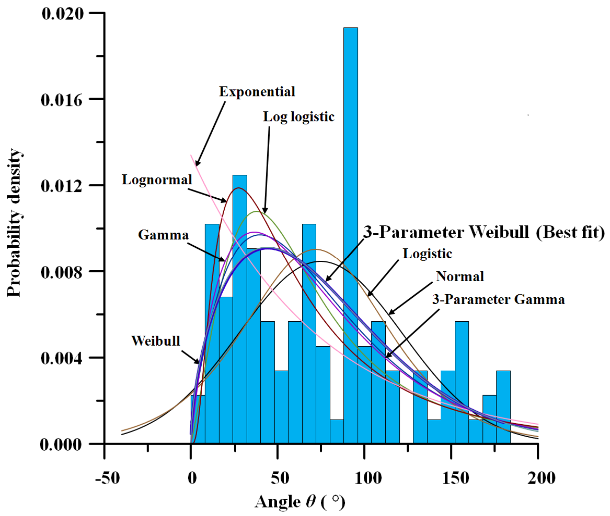

Figure 13(e) PDF versus collision angle parameter

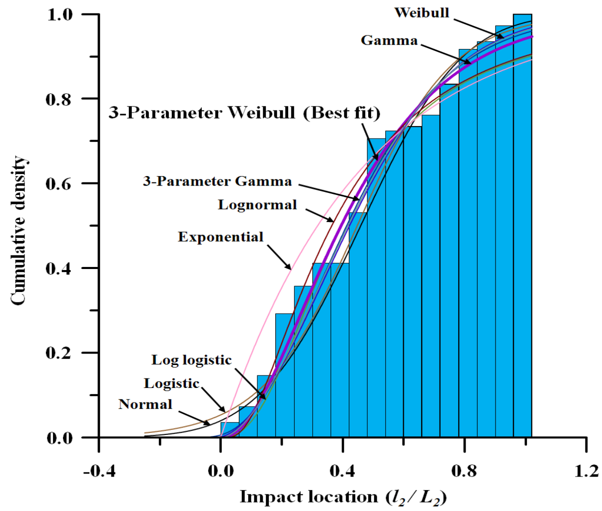

Figure 13(h) CDF versus impact location parameter

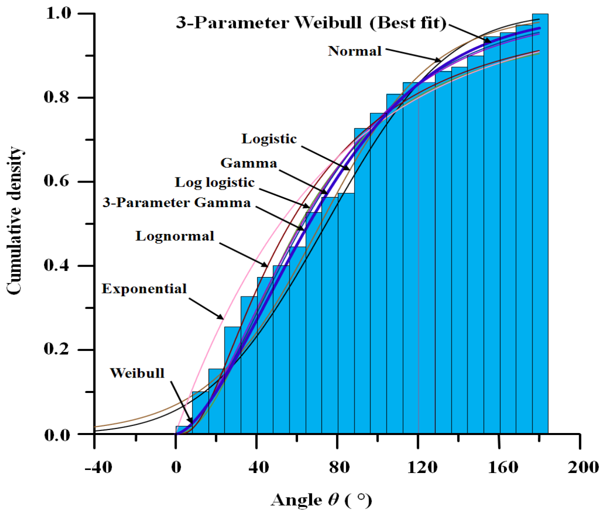

Figure 13(f) CDF versus collision angle parameter

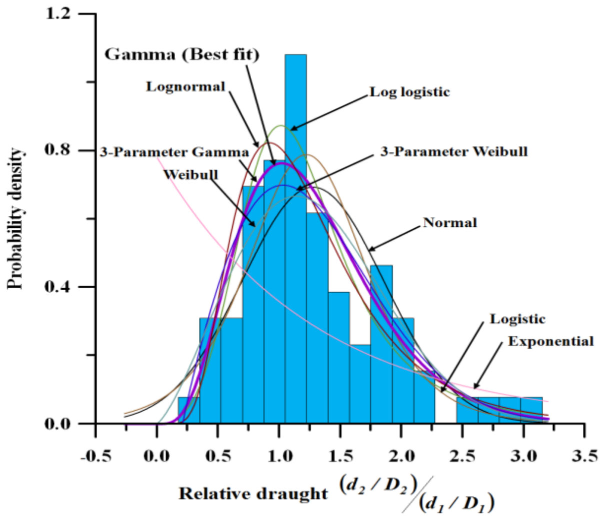

Figure 13(i) PDF versus relative draught parameter

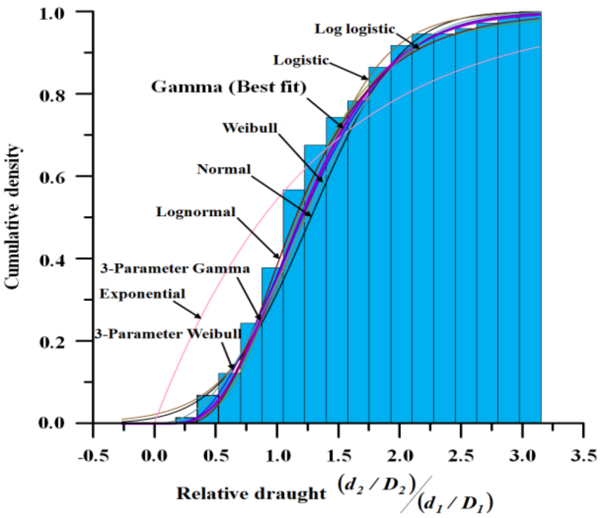

Figure 13(j) CDF versus relative draught parameter

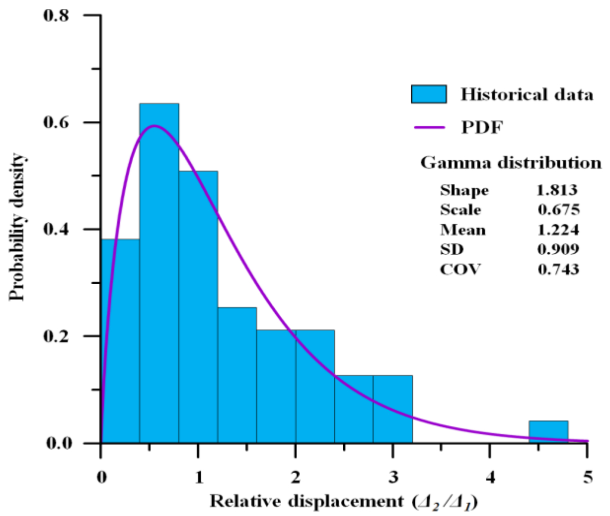

Figure 14(a) Selected PDF for relative displacement parameter

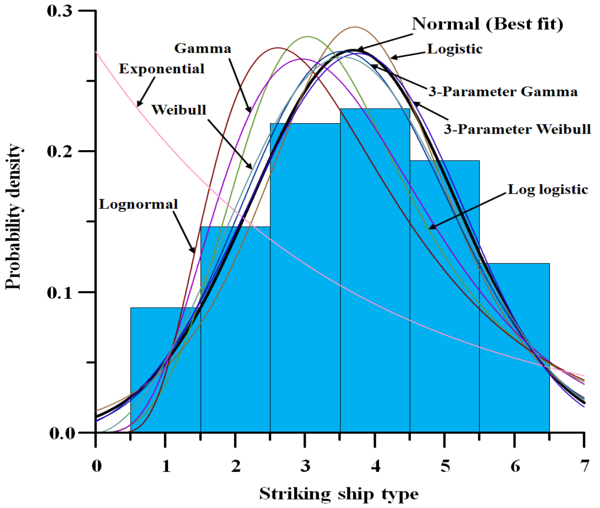

Figure 13(k) PDF versus striking ship type parameter

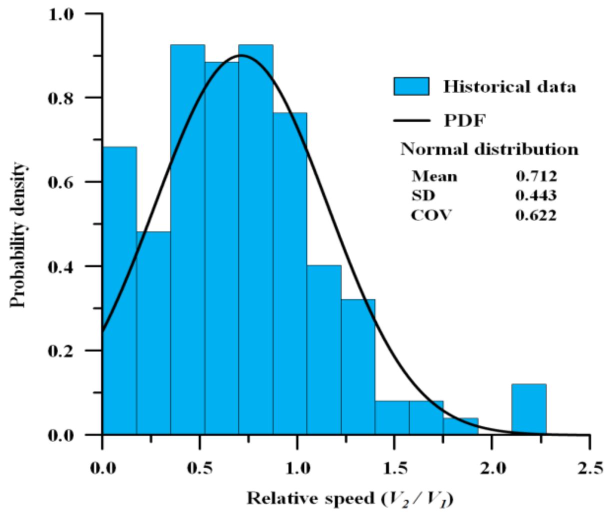

Figure 14(b) Selected PDF for relative speed parameter

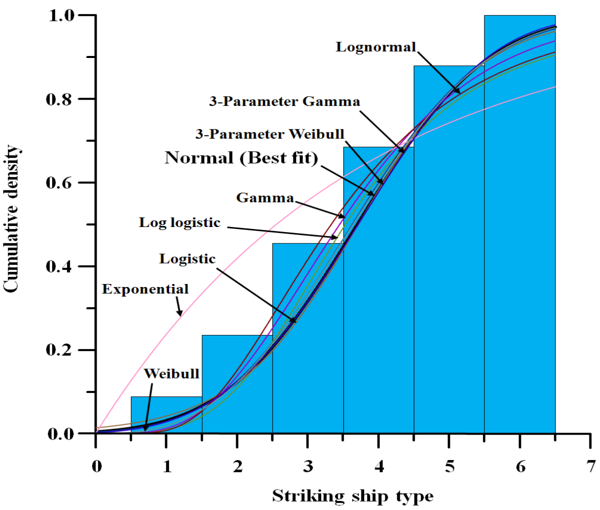

Figure 13(l) CDF versus striking ship type parameter

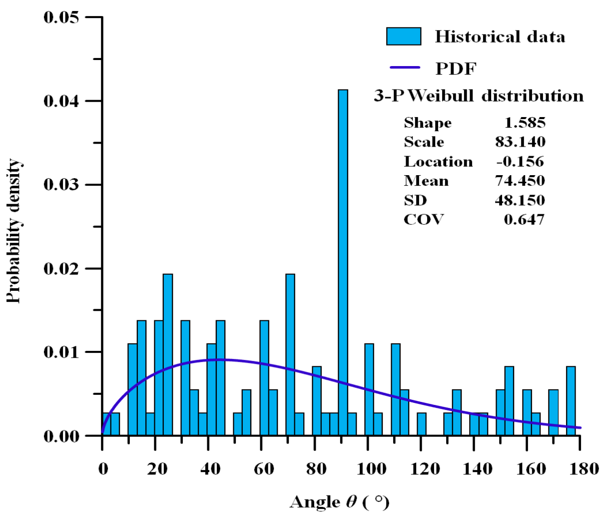

Figure 14(c) Selected PDF for collision angle parameter

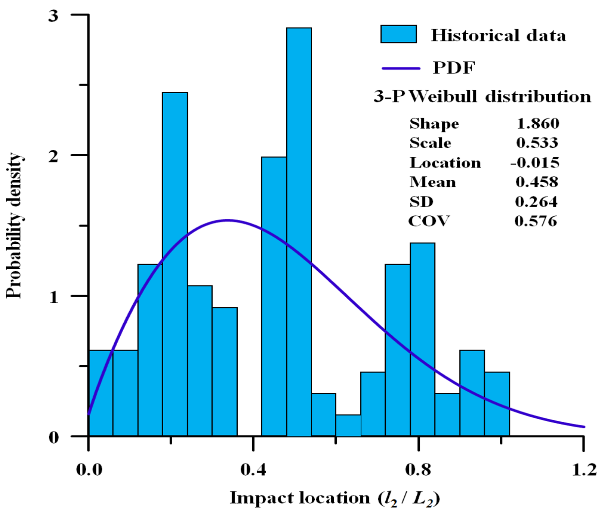

Figure 14(d) Selected PDF for impact location parameter

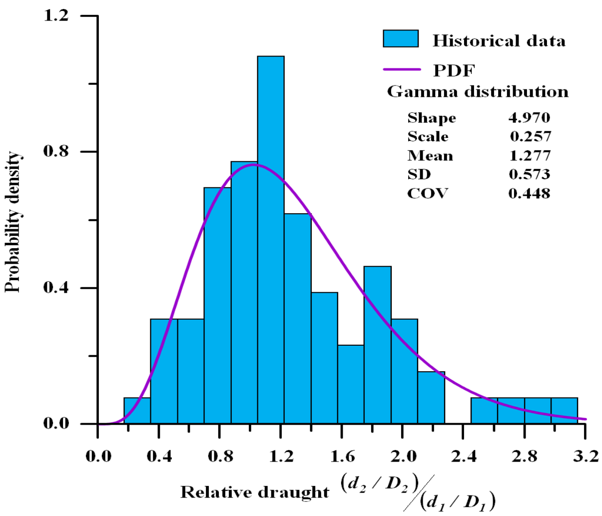

Figure 14(e) Selected PDF for relative draught parameter

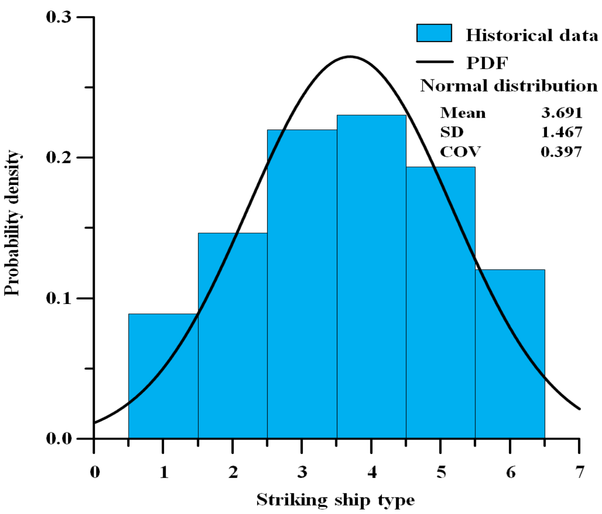

Figure 14(f) Selected PDF for striking ship type parameter

At a 95% confidence interval (see Section 2.3 (b)), probability graphs are plotted for each collision parameter versus PDFs. Figure A.1 shows the probability plots for the relative draught versus PDFs, where each value is plotted against the percentage of values in the sample that are less than or equal to it along a fitted distribution line (middle blue line), and where the two curved blue lines represent the approximate 95% confidence for the percentiles.

This plot indicates that 95 % of the intervals of the probability will be accepted to represent the data (i.e., any above that percentage will be rejected). The distribution function at which the red points are closest to the middle fitted line is selected.

The effect of the histogram bin width (interval) on the distribution parameters such as the mean and COV are examined for the selected PDFs for each collision random variable, as shown in Figure A.2. The bin width that gives the largest mean and the lowest COV is selected (see Section 2.4).

Figure 14 shows the selected PDFs for each collision variable that best represent the historical data based on the results of the K-S test, the probability plots and the impact of the histogram bin width.

The LHS technique is then used to randomly select 50 collision scenarios, as indicated in Table A.2. The probability density distribution for each of the collision parameters is divided into 50 ranges, with the interval of each range determined to ensure that the area below the curve between the probability density versus the collision parameter is equal. Figure A.3 shows a comparison of the selected PDFs that fit the historical data and the PDFs of the selected 50 scenarios for each collision parameter. Figure A.4 shows the PDFs of the selected 50 scenarios for each collision parameter.

In Table A.2, the data for each of the collision parameters are randomly selected within a specified range based on the gathered historical data to cover all possible collision scenarios. If the struck ship particulars (i.e., the target structure) are known, then the striking ship displacement, speed and draught at time of accident as well as the initial kinetic energies for the colliding ships can be obtained for the 50 collision cases using Table A.2. Also the striking ship bow shape can be determined for each case using the bow shape model (see Figure 5) that explored by Lützen [19].

For the striking ship type parameter, the LHS technique randomly produces 50 values, each of which represents a certain type of ship, as discussed in Section 2.1 (a).

3.2 VARIOUS TYPES OF STRUCK SHIPS

In this section, the developed method is applied to the other ship categories in the collision accident database as struck ships, that is, oil tankers, bulk carriers, containers and cargo ships, to demonstrate the applicability of the developed method. Table A.3 shows the selected PDFs and characteristics for the studied collision parameters versus the ship categories. Figure 15 shows the data presented in Table 2 in graphical form.

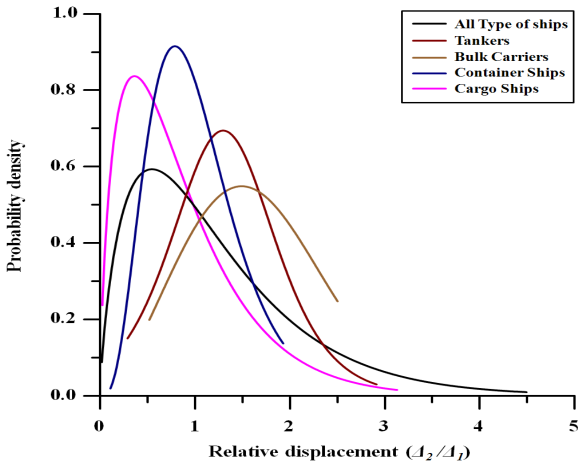

Figure 15(a) PDFs of relative displacement parameter versus struck ship categories

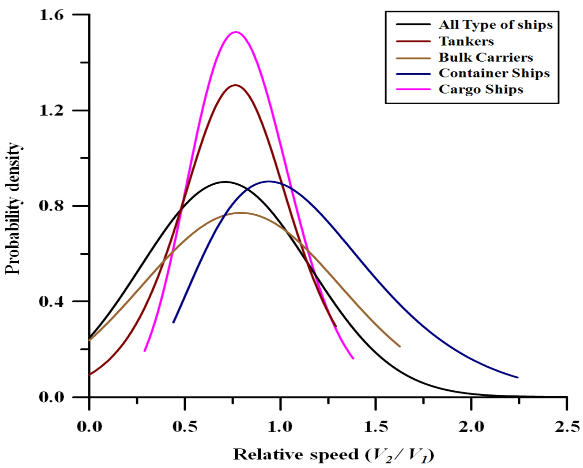

Figure 15(b) PDFs of relative speed parameter versus struck ship categories

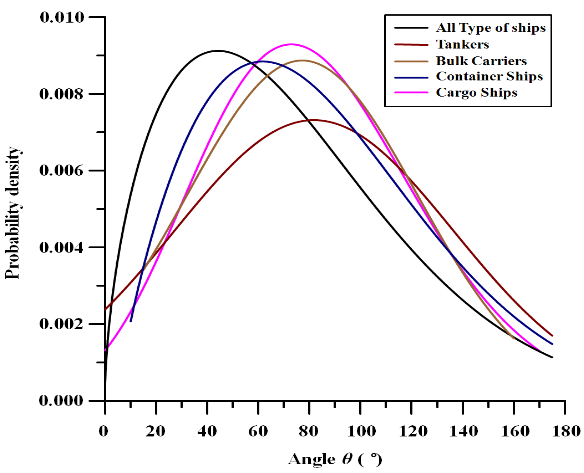

Figure 15(c) PDFs of relative collision angle parameter versus struck ship categories

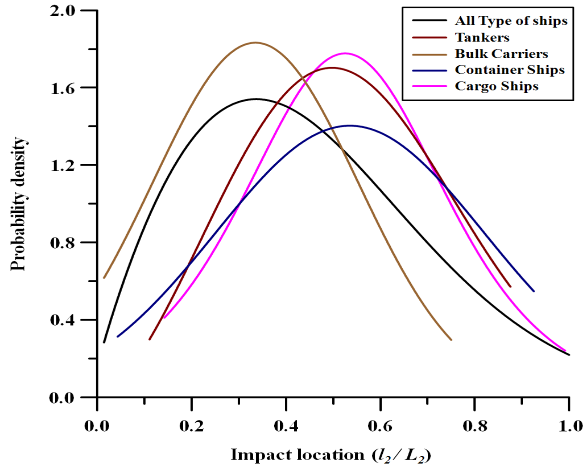

Figure 15(d) PDFs of relative impact location parameter versus struck ship categories

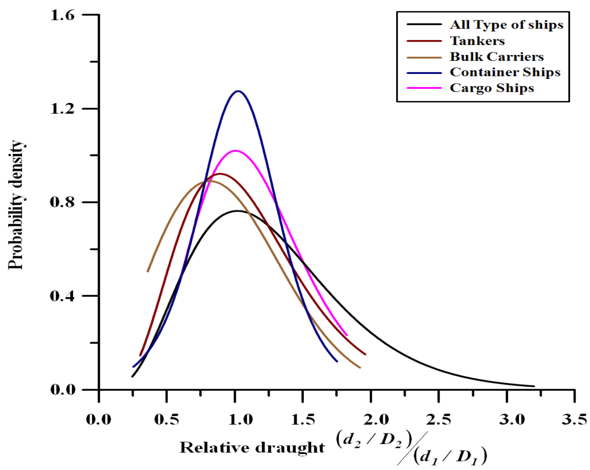

Figure 15(e) PDFs of relative draught parameter versus struck ship categories

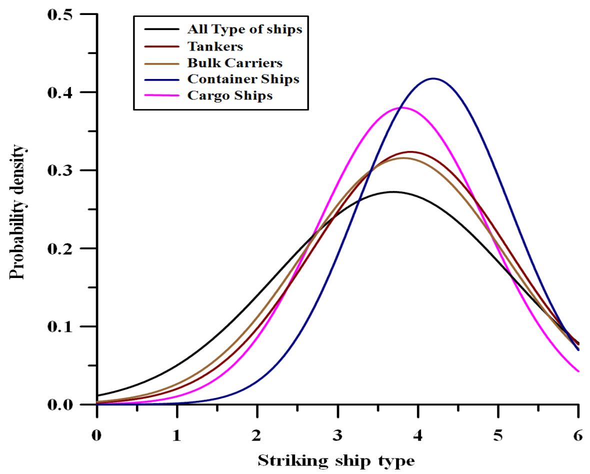

Figure 15(f) PDFs of relative striking ship type parameter versus struck ship categories

4. CONCLUSIONS

This study introduces an innovative method using probabilistic approaches to select possible ship-ship collision accident scenarios that cover all possible scenarios on the basis of random variables. The developed method contributes to step 1, 'Hazard Identification', in the International Maritime Organization's (IMO) probabilistically based Formal Safety Assessment procedure (FSA) or quantitative risk assessment and management.

A historical database of worldwide ship-ship collision accidents and near-misses for the period of 21 year during 1991 to 2012 has been collated from different sources. Each collision parameter is treated as a random variable and is analysed by statistical methods to accurately characterise its range and variability to formulate the probability density distributions.

The histogram bin width (i.e., interval) significantly affects the mean and COV values of each variable. Thus, the best histogram interval that gives the maximum mean and minimum COV value is selected.

A sampling technique is applied to select reasonable collision scenarios as defined by the selected PDFs for the studied collision parameters. If the struck structure in an accident is required to withstand accidental collision, then the developed method can be used to examine different striking ship characteristics (i.e., displacement, speed and draught) at the time of impact in a set of scenarios.

The distributions of the vessel types involved in accidents are significantly different and the proposed method should thus be applied individually for each type. Here, the developed method is applied to various struck ship categories to demonstrate its applicability.

The 50 ship-ship collision scenarios selected in the present paper as those shown in Table A.2 can be used for risk calculations of ship-ship collision accidents which are now on-going by the team of the present study.

Collision frequency and consequence analyses of a target ship are being carried out. In future work, the risk will then be calculated and assessed by comparison with the acceptance criteria. Finally, a complete quantitative collision risk assessment and management study is also on-going (see Figure 1).

5. ACKNOWLEDGEMENTS

This research was jointly supported by the Lloyd's Register and the Basic Science Research Program, the latter being through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (Grant no.: K20903002030-12E0100-04610). The study was undertaken at the Lloyd's Register Foundation Research Centre of Excellence at Pusan National University, Korea. The Lloyd's Register Foundation supports the advancement of engineering-related education, and funds research and development that enhances safety of life at sea, on land and in the air.

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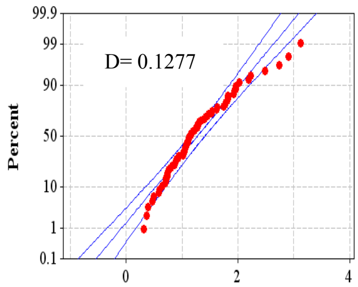
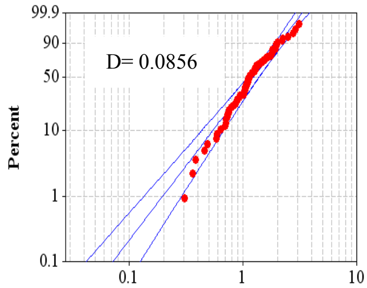
APPENDIX

Table A.1: Goodness of fit test (Kolmogorov-Smirnov) statistics for various PDFs

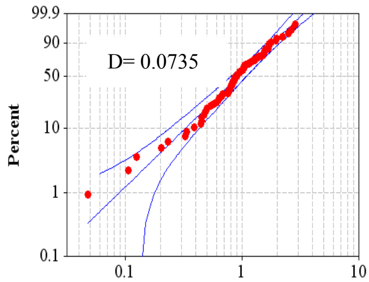
Distribution function	PDF test statistics D_n for the collision parameters					
	Δ_2/Δ_1	V_2/V_1	$(d_2/D_2)/(d_1/D_1)$	l_2/L_2	θ	Striking ship type
2-Parameter Weibull	0.0764	0.0971	0.0856	0.1207	0.1099	0.2029
3-Parameter Weibull	0.0551	0.0915	0.0735	0.1071	0.0963	0.2643
Exponential	0.1420	0.2106	0.3139	0.1956	0.1543	0.2686
Normal	0.1421	0.0645	0.1277	0.1140	0.1040	0.1220
Lognormal	0.0650	0.1266	0.0892	0.1775	0.1328	0.1840
2-Parameter Gamma	0.0500	0.1169	0.0668	0.1295	0.1136	0.1674
3-Parameter Gamma	0.0576	0.0916	0.0669	0.1234	0.1202	0.5239
Logistic	0.1464	0.0782	0.1249	0.1364	0.1265	0.1440
Log-Logistic	0.0827	0.0916	0.0948	0.1829	0.1443	0.2333



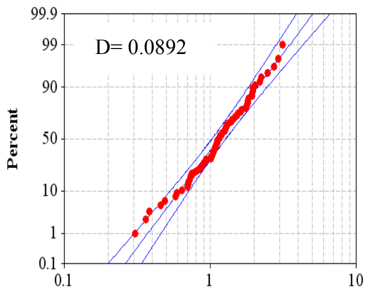
(a) Normal distribution - 95% confidence interval



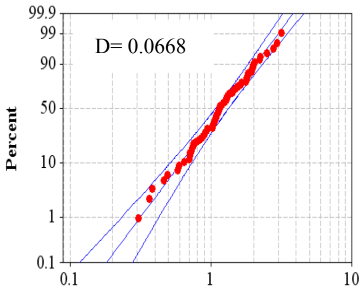
(b) 2-parameter Weibull distribution - 95% confidence interval



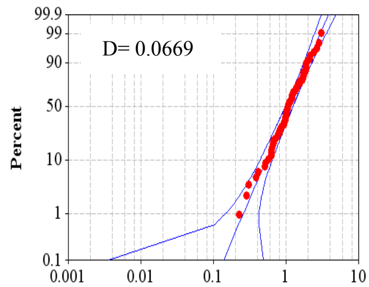
(c) 3-parameter Weibull distribution - 95% confidence interval



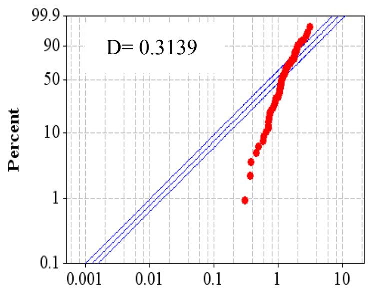
(d) Lognormal distribution - 95% confidence interval



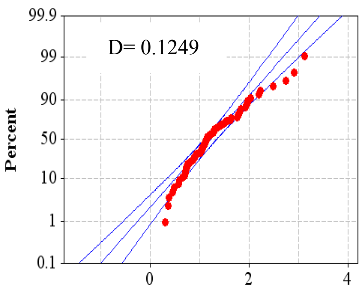
(e) 2-parameter Gamma distribution - 95% confidence interval



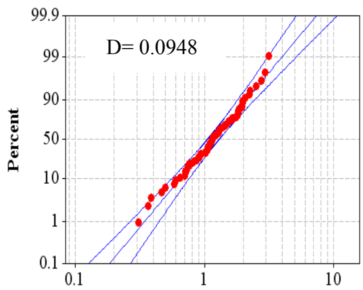
(f) 3-parameter Gamma distribution - 95% confidence interval



(g) Exponential distribution - 95% confidence interval

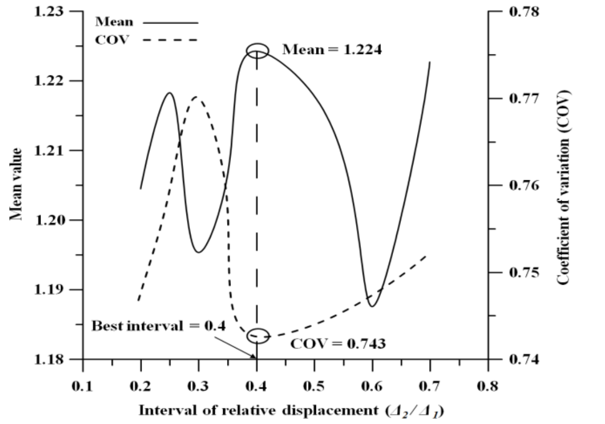


(h) Logistic distribution - 95% confidence interval

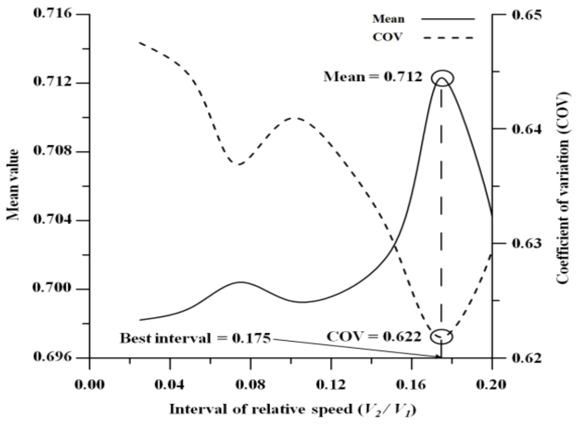


(i) Log logistic distribution - 95% confidence interval

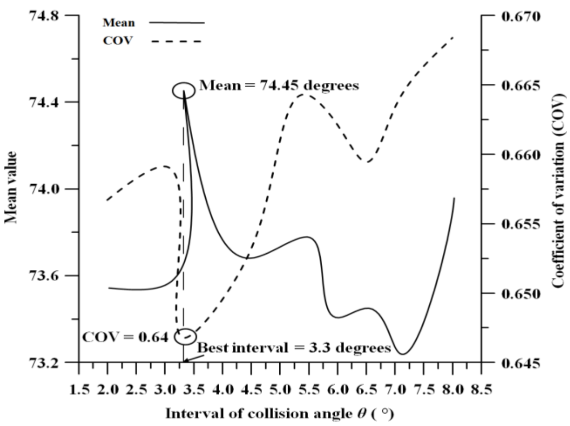
Figure A.1: Probability plots for the relative draught parameter at a 95% confidence interval



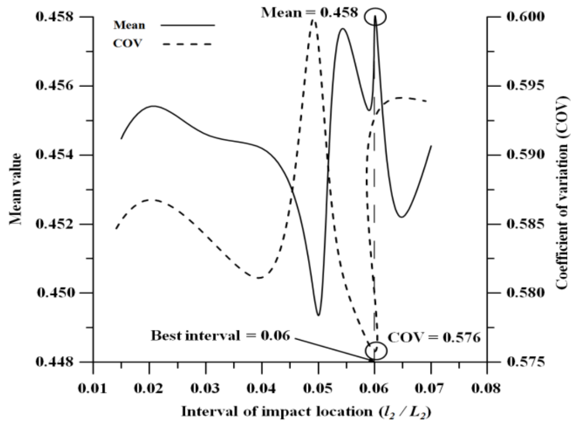
(a) Relative displacement parameter



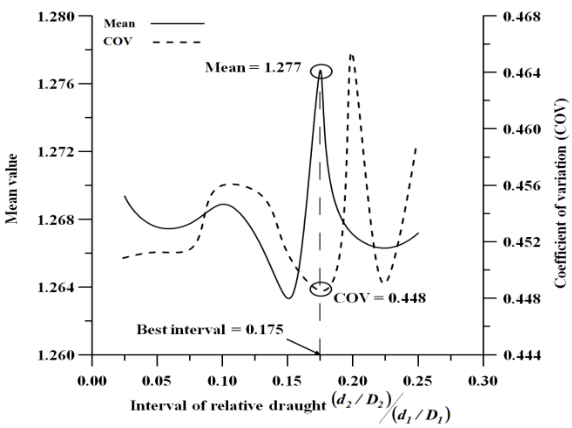
(b) Relative speed parameter



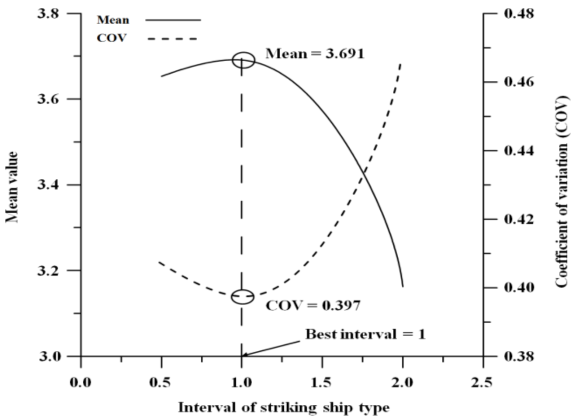
(c) Collision angle parameter



(d) Impact location parameter



(e) Relative draught parameter

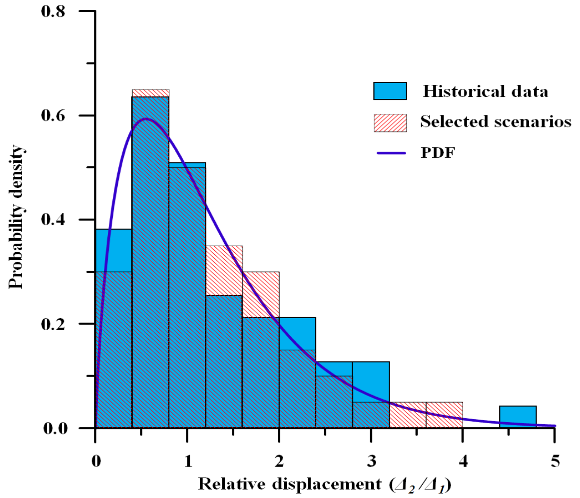


(f) Striking ship type parameter

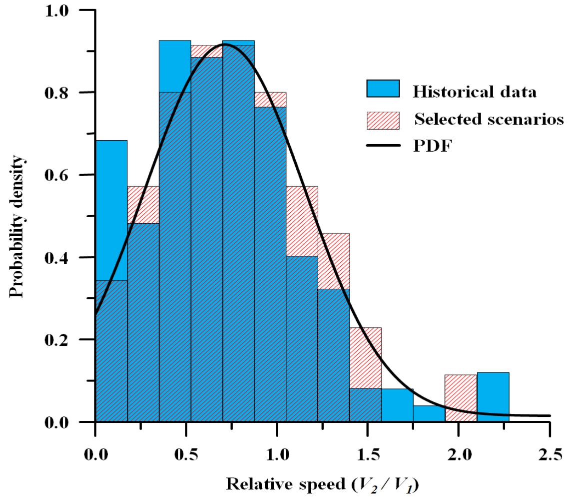
Figure A.2: Effect of histogram bin width (interval) on the mean and COV for the collision parameters

Table A.2: Fifty ship-ship collision scenarios selected as an illustrative example

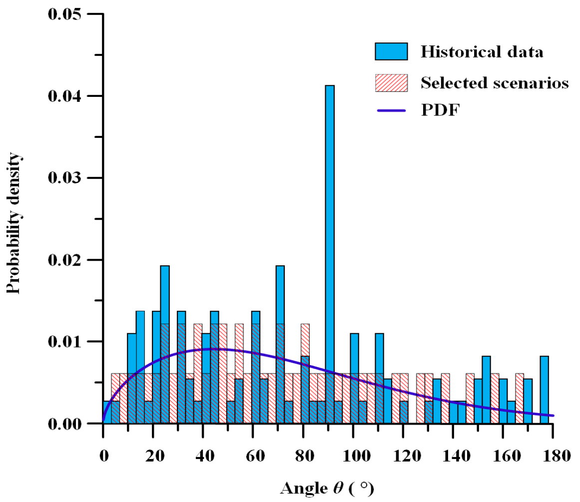
Scenario	Striking ship type	Δ_2 / Δ_1	V_2 / V_1	$(d_2 / D_2) / (d_1 / D_1)$	l_2/L_2	θ [°]
1	Passenger	0.177	0.034	0.364	0.036	3.4
2	Passenger	0.221	0.095	0.458	0.071	8.7
3	Passenger	0.261	0.147	0.520	0.095	12.2
4	Cargo vessel	0.299	0.191	0.569	0.117	15.3
5	Cargo vessel	0.335	0.231	0.612	0.135	18.1
6	Cargo vessel	0.369	0.268	0.650	0.153	20.7
7	Cargo vessel	0.403	0.301	0.686	0.169	23.2
8	Cargo vessel	0.436	0.332	0.719	0.184	25.6
9	Cargo vessel	0.469	0.362	0.750	0.199	27.9
10	Cargo vessel	0.502	0.390	0.780	0.213	30.1
11	Bulk carrier	0.534	0.417	0.809	0.227	32.3
12	Bulk carrier	0.566	0.442	0.837	0.241	34.5
13	Bulk carrier	0.598	0.467	0.865	0.254	36.7
14	Bulk carrier	0.631	0.491	0.892	0.267	38.8
15	Bulk carrier	0.664	0.515	0.918	0.280	40.9
16	Bulk carrier	0.696	0.538	0.945	0.292	43.0
17	Bulk carrier	0.730	0.560	0.971	0.305	45.1
18	Bulk carrier	0.763	0.582	0.997	0.317	47.2
19	Bulk carrier	0.798	0.604	1.023	0.330	49.4
20	Bulk carrier	0.832	0.626	1.048	0.342	51.5
21	Bulk carrier	0.868	0.647	1.074	0.355	53.6
22	Bulk carrier	0.904	0.668	1.100	0.367	55.8
23	Bulk carrier	0.940	0.689	1.127	0.380	58.0
24	Container vessel	0.978	0.710	1.153	0.393	60.2
25	Container vessel	1.017	0.731	1.180	0.405	62.4
26	Container vessel	1.056	0.752	1.207	0.418	64.7
27	Container vessel	1.097	0.774	1.235	0.431	67.0
28	Container vessel	1.139	0.795	1.263	0.445	69.3
29	Container vessel	1.182	0.816	1.292	0.458	71.7
30	Container vessel	1.227	0.838	1.321	0.472	74.2
31	Container vessel	1.274	0.860	1.352	0.486	76.7
32	Container vessel	1.323	0.883	1.383	0.500	79.3
33	Container vessel	1.374	0.905	1.415	0.515	82.0
34	Container vessel	1.427	0.929	1.448	0.530	84.7
35	Container vessel	1.483	0.953	1.483	0.545	87.6
36	Container vessel	1.542	0.978	1.519	0.561	90.6
37	Tanker	1.604	1.003	1.557	0.578	93.6
38	Tanker	1.671	1.030	1.597	0.595	96.9
39	Tanker	1.742	1.058	1.640	0.613	100.3
40	Tanker	1.819	1.087	1.685	0.632	103.9
41	Tanker	1.902	1.118	1.734	0.653	107.7
42	Tanker	1.994	1.151	1.787	0.674	111.7
43	Tanker	2.096	1.187	1.845	0.697	116.1
44	Tanker	2.210	1.226	1.909	0.722	120.8
45	Tanker	2.341	1.270	1.982	0.749	126.1
46	Tanker	2.496	1.320	2.067	0.779	131.9
47	Other	2.685	1.379	2.170	0.813	138.5
48	Other	2.930	1.455	2.301	0.853	146.3
49	Other	3.284	1.563	2.487	0.902	155.7
50	Other	3.995	1.935	2.859	0.964	168.0



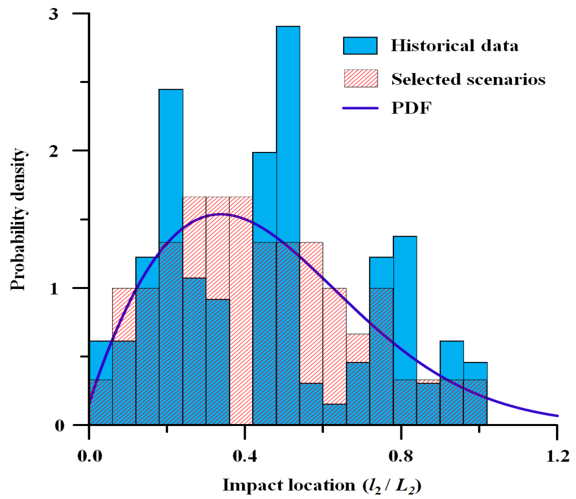
(a) Relative displacement parameter



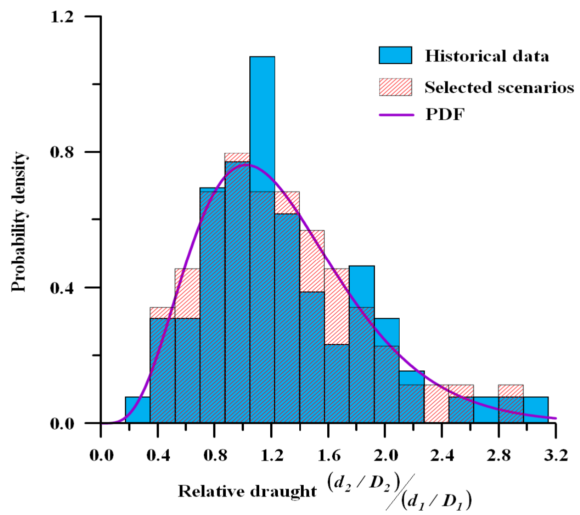
(b) Relative speed parameter



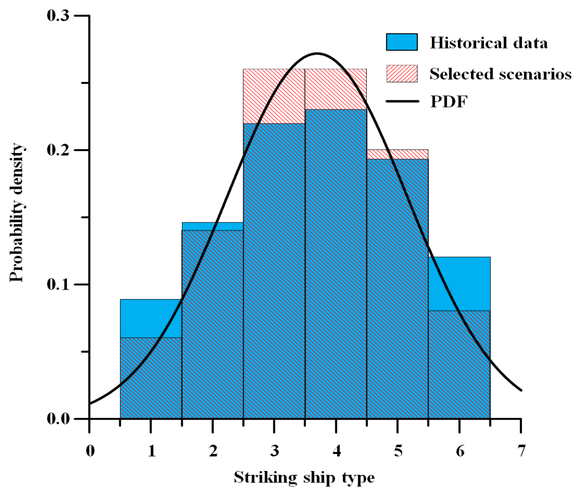
(c) Collision angle parameter



(d) Impact location parameter

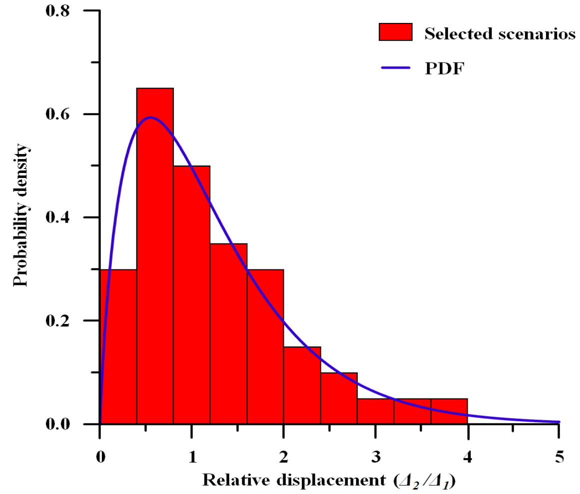


(e) Relative draught parameter

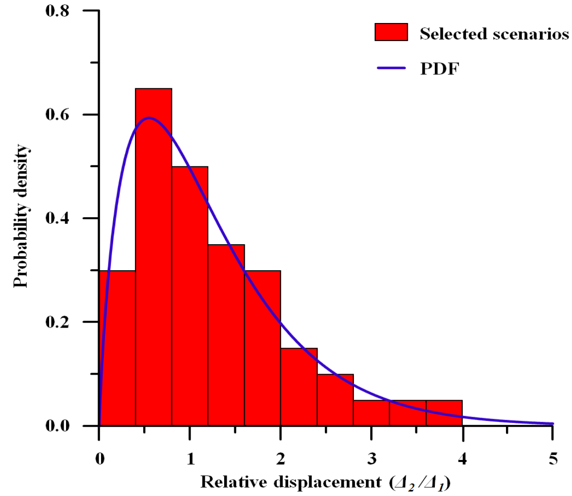


(f) Striking ship type parameter

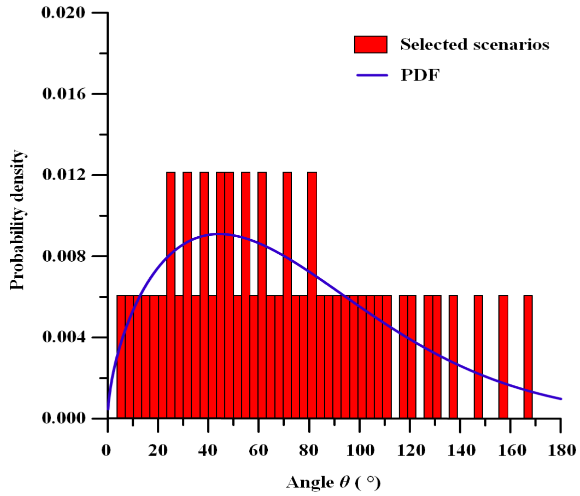
Figure A.3: Comparison of the probability density functions (PDFs) of the historical data and the PDFs of the selected scenarios versus the collision parameters



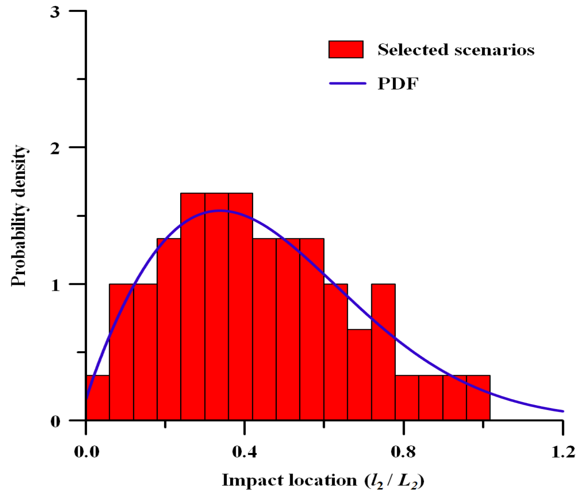
(a) Relative displacement parameter



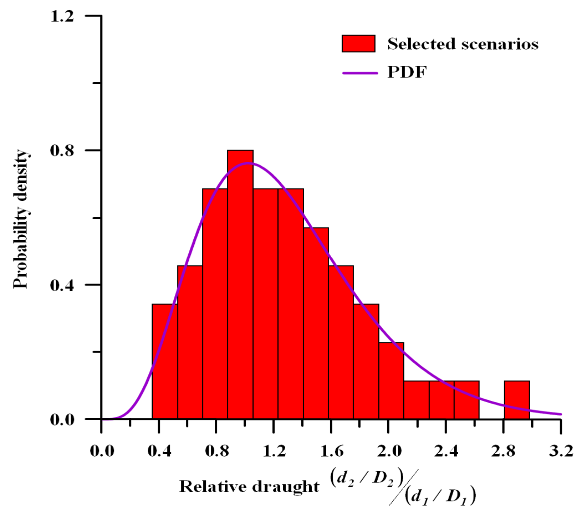
(b) Relative speed parameter



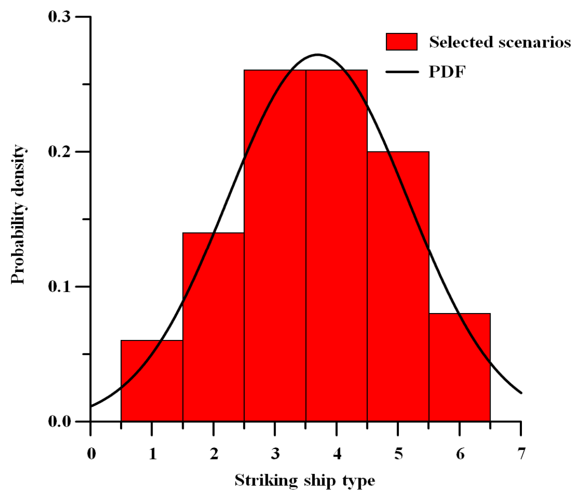
(c) Collision angle parameter



(d) Impact location parameter



(e) Relative draught parameter



(f) Striking ship type parameter

Figure A.4: Probability density distributions of the selected 50 scenarios of collision parameters

Table A.3: Summary of the selected PDFs for the collision parameters for various struck ship categories

Struck ship Category	**Collision parameters**											
	Striking ship type		Δ_2 / Δ_1		V_2 / V_1		$(d_2 / D_2) / (d_1 / D_1)$		l_2 / L_2		θ [°]	
All types	Normal distribution		Gamma distribution		Normal distribution		Gamma distribution		3-P Weibull distribution		3-P Weibull distribution	
	N(3.691, 1.467)		*Γ(1.813,0.675)*		*N(0.712, 0.443)*		*Γ(4.97,0.257)*		*W(0.533,1.86,-0.015)*		*W(83.14,1.585,-0.156)*	
	Max	6	Max	4.491	Max	2.500	Max	3.119	Max	1.000	Max	175.0
	Min	0	Min	0.024	Min	0.000	Min	0.255	Min	0.014	Min	0.0
	Interval	1	Interval	0.400	Interval	0.175	Interval	0.175	Interval	0.060	Interval	3.3
	Mean	3.691	Mean	1.224	Mean	0.712	Mean	1.277	Mean	0.458	Mean	74.45
	SD	1.467	SD	0.909	SD	0.443	SD	0.573	SD	0.264	SD	48.15
	COV	0.397	COV	0.734	COV	0.622	COV	0.448	COV	0.576	COV	0.647
Tankers	Normal distribution		Logistic distribution		Logistic distribution		Gamma distribution		Weibull distribution		Normal distribution	
	N(3.91, 1.234)		*L(1.296,0.36)*		*L(0.764,0.192)*		*Γ(5.42,0.202)*		*W(0.604,2.556)*		*N(81.74, 54.53)*	
	Max	6	Max	2.910	Max	1.288	Max	1.960	Max	0.875	Max	175
	Min	0	Min	0.290	Min	0.000	Min	0.305	Min	0.111	Min	0.0
	Interval	1	Interval	0.450	Interval	0.180	Interval	0.300	Interval	0.095	Interval	9.5
	Mean	3.910	Mean	1.296	Mean	0.764	Mean	1.095	Mean	0.536	Mean	81.74
	SD	1.234	SD	0.653	SD	0.347	SD	0.471	SD	0.225	SD	54.53
	COV	0.316	COV	0.504	COV	0.455	COV	0.429	COV	0.419	COV	0.667
Bulk carriers	Normal distribution		Weibull distribution		Normal distribution		Weibull distribution		Normal distribution		Normal distribution	
	N(3.819, 1.265)		*W(1.834,2.487)*		*N(0.793, 0.517)*		*W(1.054,2.272)*		*N(0.335, 0.218)*		*N(77.14, 44.97)*	
	Max	6	Max	2.500	Max	1.625	Max	1.920	Max	0.750	Max	160
	Min	0	Min	0.522	Min	0.000	Min	0.363	Min	0.014	Min	15
	Interval	1	Interval	0.750	Interval	0.230	Interval	0.175	Interval	0.090	Interval	9.5
	Mean	3.819	Mean	1.627	Mean	0.793	Mean	0.934	Mean	0.335	Mean	77.14
	SD	1.265	SD	0.699	SD	0.517	SD	0.435	SD	0.218	SD	44.97
	COV	0.331	COV	0.43	COV	0.651	COV	0.466	COV	0.649	COV	0.583
Container ships	Normal distribution		Gamma distribution		Gamma distribution		Logistic distribution		Normal distribution		3-P Weibull distribution	
	N(4.192, 0.956)		*Γ(4.445,0.229)*		*Γ(5.675,0.201)*		*L(1.024,0.196)*		*N(0.535, 0.284)*		*W(90.36,1.778,4.959)*	
	Max	6	Max	1.929	Max	2.240	Max	1.750	Max	0.925	Max	175
	Min	0	Min	0.114	Min	0.444	Min	0.255	Min	0.043	Min	10
	Interval	1	Interval	0.500	Interval	0.200	Interval	0.225	Interval	0.060	Interval	9.5
	Mean	4.192	Mean	1.019	Mean	1.141	Mean	1.024	Mean	0.535	Mean	85.365
	SD	0.956	SD	0.483	SD	0.479	SD	0.356	SD	0.284	SD	46.741
	COV	0.228	COV	0.474	COV	0.419	COV	0.347	COV	0.531	COV	0.547
Cargo ships	Normal distribution		Gamma distribution		3-P Gamma distribution		Gamma distribution		Logistic distribution		3-P Gamma distribution	
	N(3.805, 1.049)		*Γ(1.722,0.502)*		*Γ (43.87,0.04,-0.941)*		*Γ(7.755,0.149)*		*L(0.525,0.141)*		*Γ (22.59,9.199,-125.7)*	
	Max	6	Max	3.130	Max	1.378	Max	1.825	Max	0.991	Max	170
	Min	1	Min	0.024	Min	0.290	Min	0.593	Min	0.142	Min	0
	Interval	1	Interval	0.650	Interval	0.075	Interval	0.180	Interval	0.090	Interval	9
	Mean	3.805	Mean	0.865	Mean	0.806	Mean	1.154	Mean	0.525	Mean	82.105
	SD	1.049	SD	0.659	SD	0.264	SD	0.414	SD	0.255	SD	43.722
	COV	0.276	COV	0.762	COV	0.327	COV	0.359	COV	0.486	COV	00.532

