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Avoiding collisions, enhancing marine safety – a simplified model for the Aegean Sea

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Abstract

Ship collision is a hazardous event within the chain of maritime transport. Collisions may result in human losses, adverse economic consequences, and environmental damages causing significant impact to local societies and related activities. A major factor in any risk analysis concerning ship collisions is the probability of these collisions occurring. The purpose of this study is to assess the probability of ship-to-ship collision in the Aegean Sea. The basic concept of the developed model is to (statistically) simulate traffic flow in the area of interest and determine the collision candidates; this will be implemented in a pilot study in a segment of the Aegean Sea. The input of this effort is based on values that are extracted from statistical analysis of the international fleet in combination with the study of maps depicting traffic flow in the studied area. Hence, it does not employ detailed AIS data. The obtained results are presented and their agreement with actual incidents is discussed in depth. The paper concludes with interesting insights of the aforementioned tasks.

Introduction

The Aegean seaways are of great importance for international maritime transport constituting a major link between the Black Sea and the rest of the Mediterranean. The northeast boundary of the Aegean Sea is the gate to the Dardanelles Strait, the southeast boundary is a main passage for ships heading to the Suez Canal and the southwest boundary is the main passage to the European ports.

Collisions constitute a significant proportion of the total number of accidents in many areas of interest (Kujala et al., 2009; Mou et al., 2010; Zhang et al., 2013). Concerning collision accidents, the same is true for the area studied within this work (Andritsopoulos, 2011; Chrysavgis, 2011; Tsola, 2011; Nomikos, 2012).

Risk is the combination of the frequency of events and the severity of the consequence (IMO, 2007a). There are different perspectives on this more general definition of risk, many of which are reviewed in the work of Goerlandt and Kujala (2014). In the present study, a model is constructed for the estimation of ship collision probability by predicting the number of collision candidates. The results obtained could be utilized as part of the input in an integrated risk analysis. A schematic of this analysis is shown in Figure 1.

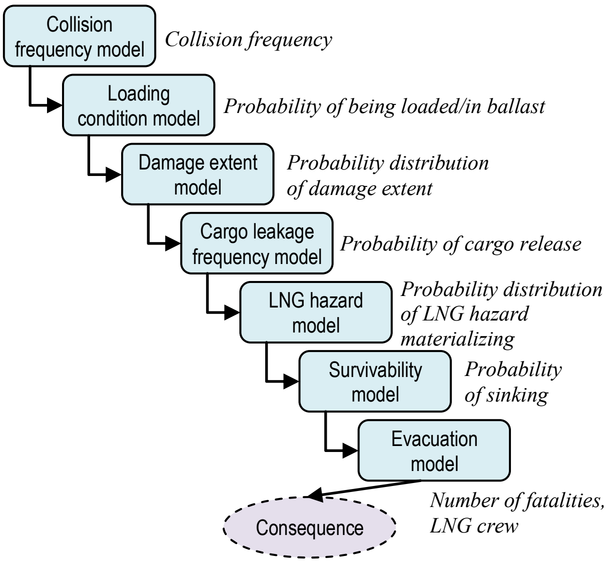

Figure 1. Risk model for collision of LNG carriers (IMO, 2007b)

After a brief literature review, the basic concepts on which the model is based are described where after the results are presented and discussed.

Literature review

To assess collision probability, the prevalent approach used among researchers (Montewka et al., 2010) is based on the concept introduced by Fujii et al. (1970) and MacDuff (1974). In this approach, the number of collisions over the studied time period is estimated using the formula:

$$N_{\mathrm{Coll}} = N_A \cdot P_C \tag{1}$$

where N_A is the number of pairwise ship encounters resulting in a collision and P_C is the causation probability; the probability of failing to avoid collision when on a collision course. In Fujii's approach it is assumed that a collision occurs when two ships reach a distance D_{ij}, known as "collision diameter".

Pedersen (1995) defines D_{ij} as the critical distance in the event of a ship encounter. This distance correlates with the ships' length and width. Pedersen (1995) also distinguishes between crossing, overtaking and head-on collisions. Many studies have incorporated Pedersen's model (Otto et al., 2002; COWI, 2008; Kujala et al., 2009; Klemola et al., 2009).

Fowler and Sørgård (2000) define as a critical encounter event when two ships reach a distance not greater than 0.5 Nm of each other. This reference distance is independent of the crossing angle.

In the work of Montewka et al. (2010) a minimum distance to collision (MDTC) is defined as the minimum distance between two vessels on collision course that allows them to perform efficient anti-collision maneuvers. The main factors relevant to determine the MDTC value are the vessels' maneuverability, the angle of intersection and the relative bearing of one vessel to the other. In this model, a distinction is made between tankers, container ships, passenger ships and Ro-Ro vessels.

Theory

In risk assessment efforts regarding maritime safety, risk is often defined as the combination of probability and expected consequences (Goerlandt and Kujala, 2011; Zhang et al., 2013):

$$\mathrm{Risk} = P \cdot C \tag{2}$$

where P is the probability of occurrence and C is the severity of the consequences. A more thorough analysis of risk and the link between probability and consequence is given in the work of Montewka et al. (2014). The model developed in the present study focuses on the estimation of probability.

Firstly, the basic concepts incorporated in the model are described. Secondly, traffic is stochastically simulated in the area of interest and, during a fragment of simulated time, the total generated number of ships is compared in a pairwise manner in order to determine the number of collision candidates. Finally, a causation factor is applied and the probability of collision is obtained.

The criterion according to which a collision is detected depends on two factors: i) whether the ships' trajectories intersect and ii) the time of arrival at the intersection point. Conceptually this is similar to the 0.5 Nm criterion (Fowler and Sørgård, 2000).

According to the central limit theorem (Billingsley, 1995), and because the model's random input variables follow multiple known distributions, after a "large" number of iterations, the convergence to a mean output value is achieved. Consequently Monte Carlo simulation is performed. Thus, by multiple repetitions a frequentist approach to probability is attempted.

Traffic-simulation collision model

The studied area

The studied area is the sea route connecting the Dardanelles Strait, located at approximately 40°1'9.14" N 26°9'57.90" E, with the Elafonisos Strait (the area between Elafonisos and Kythira) located at approximately 36°25'9.12" N 22°58' 15.15" E.

Construction of the route plan

The definition of the route's geographical boundaries is based on the traffic density map obtained from MarineTraffic as depicted in Figure 2.

Utilizing Google Earth, the coordinates of the minimum required number of boundary points (16 points) are acquired as depicted in Figure 3. Originally the points from Google Earth are obtained in the World Geodetic System (WGS84). To simplify later work, a transformation of the coordinates from WGS84 to the Hellenic Geodetic Reference System 1987 (or Greek Geodetic Reference System 1987 – GGRS87) is conducted. GGRS87 is a non-geocentric datum that is effectively defined by the coordinates of the key geodetic station at the Dionysos Satellite Observatory near Athens (Delikaroglou, 2008). Essentially, the transformation is the equivalent of the projection to the Cartesian system of reference.

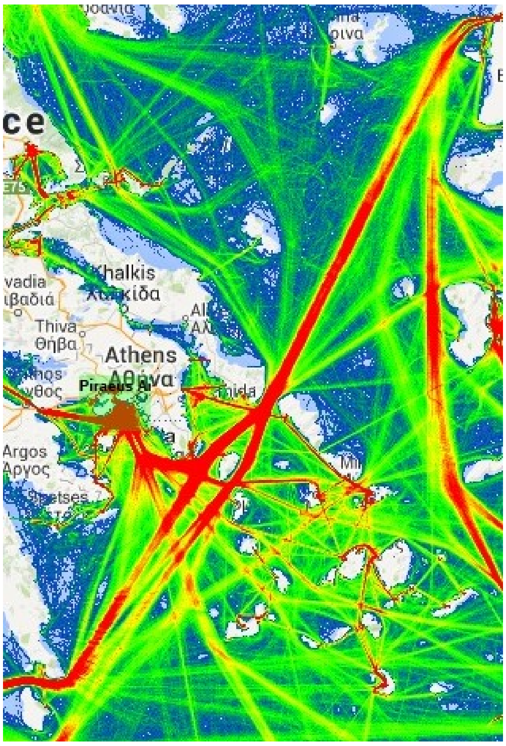

Figure 2. Traffic density map

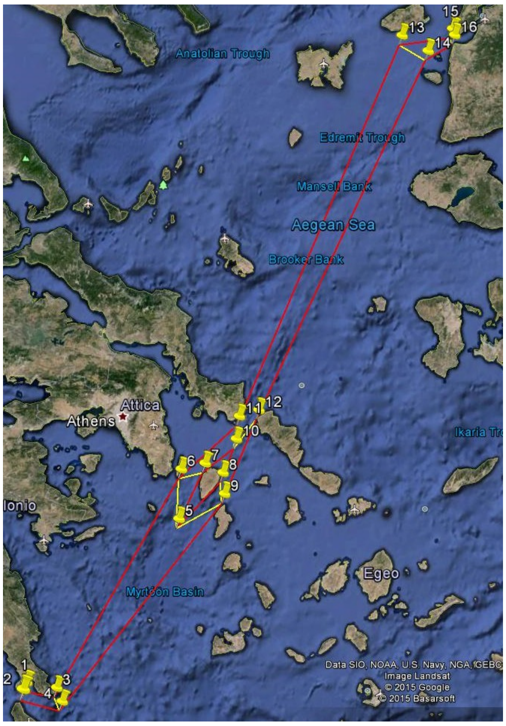

Figure 3. Density map approximation by coordinates

With respect to accuracy loss due to this transformation, the indicative measurement of the east boundary of the route (defined by points 2, 4, 9, 12, 14 and 16) in Figure 3 is considered. The value obtained from Google Earth is 512584 m and the value computed using the points projected on GGRS87 is 512460 m. The maximum accuracy loss is thus approximately 0.024% which, within the scope of this study, is considered insignificant.

After the boundary waypoints are obtained, the nodes that each ship passes through in order to reach her destination are defined. The space interval of each node is divided in equal intervals of 100 m length.

The points at the end of each 100 m long interval constitute the total number of waypoints in each node. Every ship that arrives at the extreme nodes (named gates: gate1_2 and gate15_16) chooses randomly from a uniform distribution one waypoint from the respective node (gate) and then, using the same procedure, one waypoint from each subsequent node. The straight lines connecting all the randomly selected waypoints constitute the ship's exact path.

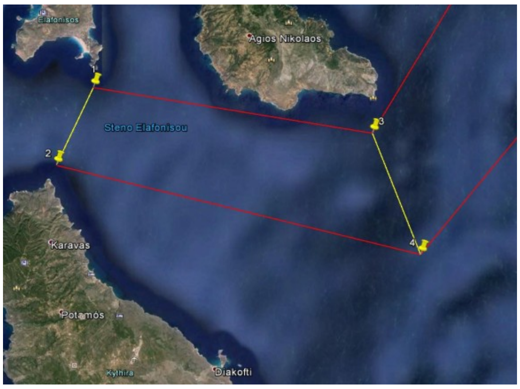

Figure 4. Visualization of gate1_2 and node3_4

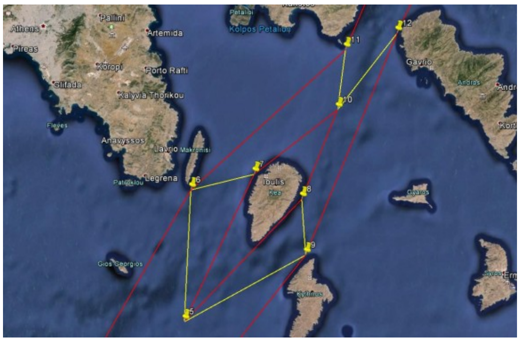

Figure 5. Visualization of node5_6, node5_9, node6_7, node8_9, node10_11 and node10_12

For example, when a ship arrives at gate1_2 it randomly chooses one waypoint from gate1_2, then one from node3_4 (Figure 4). It then chooses how the detour of Kea Island is conducted using a binomial distribution with equal probabilities for each outcome. Thus, waypoints are chosen either from node5_6, node6_7 and node10_11 or from node5_9, node8_9 and node10_12 (Figure 5). Finally, one waypoint from each of node13_14 and gate15_16 is chosen (Figure 6).

Figure 6. Visualization of node13_14 and gate15_16

The route is constructed such that ships travel in straight lines between the nodes. Each ship is considered to travel with a constant speed attributed to her upon arrival at either of the gates, according to her type. All transient phenomena at each waypoint are ignored and the ships are considered to turn instantly. The ships take no evasive actions according to the concept of blind navigation. Meteorological conditions are not taken into account.

Traffic volume estimation

The number of ships arriving at each gate during the minimum simulation time is approximated using a homogenous Poisson process. Characteristic of the process is the expected number of arrivals per unit time, λ. Although other models (Pedersen, 1995; Gucma, 2003; Przywarty, 2008; Montewka et al., 2010) implement it, Goerlandt and Kujala (2011) found this to be an inadequate estimation method. This inadequacy is addressed in the present study not by using a thinning process for λ but by evaluating λ in a stochastic manner for each iteration of the algorithm, as described below.

The minimum simulation time is the time needed by the slowest ship, from the available ship speed databases, to travel from gate to gate. It is calculated to be 2768 minutes. Thus, the number of iterations required to simulate the period of one year is 190 (specifically one year and 5.35 hours).

The live map from MarineTraffic has been utilized in order to make observations regarding a) the total number of ships detected within the boundaries of the route, b) their direction (northward or southward), and c) their basic type-classification which according to MarineTraffic is "Tanker", "Cargo" and "Passenger". Essentially the discrimination made is between ships that carry liquid cargo, dry cargo and passengers. A record of 20 days at random moments in each day has been kept.

There are eight ship speed databases, obtained from IHS Sea-web. Speed distributions are integrated in the model according to ship type: Tanker (5276 ships), Gas Carrier (1463 ships), Bulk Carrier (9371 ships), Containership (4869 ships), General Cargo (8404 ships), Reefer (678 ships), Ro-Ro Cargo (1526 ships) and Cruise Ship (320 ships).

Thus if the observation indicates "Tanker" the multinomial distribution (specifically binomial) for the exact ship type is derived, with probability of each outcome (ship type):

$$P_{\text{Tanker}} = 0.7829 \tag{3}$$

$$P_{\text{GasCarrier}} = 0.2171 \tag{4}$$

If the observation indicates "Cargo" the multinomial distribution for the exact ship type is derived, with probability of each outcome:

$$P_{\text{BulkCarrier}} = 0.3771 \tag{5}$$

$$P_{\text{Containership}} = 0.1959 \tag{6}$$

$$P_{\text{GeneralCargo}} = 0.3382 \tag{7}$$

$$P_{\text{Reefer}} = 0.0273 \tag{8}$$

$$P_{\text{RoRoCargo}} = 0.0615 \tag{9}$$

If the observation indicates "Passenger" the exact ship type is Cruise Ship since there is no active passenger line on the route. Hence:

$$P_{\text{CruiseShip}} = 1 \tag{10}$$

Initially, based on these observations, two Poisson distributions are extracted: one for the number of ships with northward direction and one for the number of ships with southward direction. Furthermore, two trinomial distributions are extracted regarding the discrimination of ships to "Tanker", "Cargo" and "Passenger", for each direction.

In each iteration, the algorithm generates a random value, according to the extracted distributions, in the following sequence: a) the number of ships observed within the route, b) the number of ships that classify as "Tanker", "Cargo", "Passenger", c) the number of ships that classify as Tankers, Gas Carriers, Bulk Carriers, Container Ships, General Cargo, RoRo Cargo, Reefers and Cruise Ships, and d) the speed of each ship according to her exact type. This procedure is performed separately for the northward and southward directions.

In this way, an average speed is calculated and, accordingly, the mean time required for each ship to travel the entire route. The assumption is made that all ships travel with this speed and that they are equidistant along the route's length. We estimate the total number of ships arriving during the minimum simulation time by dividing the required traveling time with the number of time intervals between the observed ships (which are equal since the ships are considered equidistant) and then the minimum simulation time with the acquired quotient. This estimation is also performed separately for each direction.

Integrating all the extracted distributions, a new value for λ is obtained for each iteration and a number of ships is generated by a homogenous Poisson process. Each ship is then attributed a traveling speed according to her exact type from the corresponding ship speed distribution.

Collision candidate detection

In the next step, the algorithm detects which of the ships' trajectories intersect using a pairwise evaluation. It distinguishes between Head-on, Crossing and Overtaking encounters according to COLREG (IMO, 2002).

Whenever an intersection is detected, the algorithm calculates the exact coordinates of the intersection point and checks whether these coordinates fall within the geographical boundaries of the route. When the coordinates are found within the boundaries, the exact time at which each ship arrives at the intersection point is calculated. If the ships following the intersecting trajectories are found to arrive at the intersection point within a time window of 60 seconds they are considered collision candidates. Considering an average speed of 15 knots translates to a mean distance of about 463 meters. The collision angle is calculated and the type of colliding ships is stored. This step is executed in three stages; a) for the ships with northward direction, b) for the ships with southward direction, and c) for the ships with both northward and southward direction. At the end of the algorithm, the Monte Carlo technique is applied and the acquired variables are cumulatively stored in a matrix.

Causation probability

Causation probability can be estimated in two ways; by the scenario approach or by the synthesis approach (Kujala et al., 2009). In the scenario approach the probability estimation is based on historic accident data. According to Pedersen (1995) causation probability can be estimated from accident data collected at various locations and then transformed to the analyzed area. In the synthesis approach specific error situations are attributed a probability to occur. If they occur during a critical situation they may cause an accident. Probability of error situations is estimated by application of Bayesian Belief networks or fault trees analysis (see, for example, Martins and Maturana, 2013).

The causation factor is dependent on many variables, according to the way each model is perceived. Some estimations of the causation factor address more specialized needs, for example, Montewka et al. (2011) assess a causation factor for application in a MDTC model.

To the authors' knowledge, no study has elaborated the particularities of the Aegean Sea or provided a value for the causation probability of collision. In order to apply the most appropriate causation factors to the collision candidates obtained from the model, a literature review of causation factors has been conducted.

Results and discussion

The algorithm is scripted in Matlab and the mean number of collision candidates per year is obtained after 100 iterations. The 95%-confidence interval for the mean value is calculated as follows:

$$\overline{X}_{(n)} \pm z_{95\%}\sqrt{\frac{S^{2}_{(n)}}{n}} \qquad (11)$$

where $\overline{X}_{(n)}$ is the mean over n iterations, $z_{95\%}$ is the upper 95% critical point for a random variable from a normal distribution, and $S^{2}_{(n)}$ is the variance over n iterations.

The output values of the algorithm are presented in Table 1. The values of the causation factors derived from Pedersen (1995) and Goerlandt and Kujala (2011) applied to the output of the algorithm are presented in Tables 2 and 3 respectively. After the application of the respective causation factors, the expected number of accidents per year is presented in Tables 4 and 5. For comparison, the expected number of accidents per year, with application of causation factors from COWI (2008) and Friis-Hansen and Simonsen (2002), are presented in Table 6.

Table 1. Output of the algorithm over 100 iterations, with a critical time window of 60 seconds

Number of collision candidates						
Total	Head-on	Crossing	Over-taking	At least one Tanker involved	At least one Cargo involved	At least one Passenger involved
949.65	7.7	0.39	941.56	369.57	570.47	9.61
±42.533	±0.1717	±0.0067	±41.2723	±12.1563	±20.9518	±0.222

Table 2. Causation factors applied by Pedersen (1995)

	Head-on	Crossing	Overtaking
Causation Factor	1.01E-05	2.56E-04	5.62E-05

Table 3. Causation factors applied by Goerlandt and Kujala (2011)

Situation	P_C for Crossing encounter	P_C for Head-on and Overtaking encounter
At least one Tanker involved	5.60E-04	5.60E-04
At least one Passenger involved, good visibility	6.83E-05	4.90E-05
At least one Passenger involved, poor visibility	4.64E-04	4.90E-05
All other ships	1.30E-04	4.90E-05

Table 4. Expected number of collisions per year with application of causation factors by Pedersen (1995)

	Head-on	Crossing	Overtaking	Total
Number of accidents	7.78E-05	9.98E-05	5.29E-02	5.31E-02
	±1.73E-06	±1.73E-06	±2.32E-03	±2.32E-03

Table 5. Expected number of collisions per year with application of causation factors by Goerlandt and Kujala (2011)

Situation	Number of accidents for Head-on encounter	Number of accidents for Crossing encounter	Number of accidents for Overtaking encounter
At least one Tanker involved	1.68E-03	8.50E-05	2.05E-01
	±5.52E-05	±2.80E-06	±6.75E-03
At least one Passenger involved, good visibility	1.33E-06	2.70E-07	4.67E-04
	±8.82E-08	±6.23E-09	±1.08E-05
At least one Passenger involved, poor visibility	1.33E-06	1.83E-06	4.67E-04
	±8.82E-08	±4.23E-08	±1.08E-05
All other ships	2.27E-04	3.05E-05	2.77E-02
	±8.32E-06	±1.12E-06	±1.02E-03
Total number of accidents	2.35E-01		
	±7.85E-03		

Table 6. Comparison of the obtained results with the results obtained after application of causation factors found in COWI (2008) and Friis-Hansen and Simonsen (2002)

	COWI	GRACAT
Causation factor	3.00E-04	9.00E-05
Total number of accidents	2.85E-01	8.55E-02
	±1.28E-02	±3.83E-03

Table 7. Output of the algorithm over 100 iterations, with a critical time window of 120 seconds

Number of collision candidates						
Total	Head-on	Crossing	Over-taking	At least one Tanker involved	At least one Cargo involved	At least one Passenger involved
1881.52	7.7	0.78	1873.04	732.4	1129.91	19.21
±108.874	±0.1717	±0.01345	±106.657	±28.4356	±50.443	±0.4879

For better evaluation of the conflict criterion, another set of 100 iterations is performed where the time window is extended to 120 seconds, which translates to a distance closer to the 0.5 Nm criterion (Fowler and Sørgård, 2000). The output is presented in Table 7 and the results after applying the different causation factors are presented in Tables 8 and 9.

Table 8. Expected number of collisions per year with application of causation factors by Pedersen (1995) using the values from Table 7

	Head-on	Crossing	Overtaking	Total
Number of accidents	7.78E-05	2.00E-04	1.05E-01	1.06E-01
	±1.73E-06	±3.45E-06	±5.99E-03	±6.00E-03

Table 9. Expected number of collisions per year with application of causation factors by Goerlandt and Kujala (2011) using the values from Table 7

Situation	Number of accidents for Head-on encounter	Number of accidents for Crossing encounter	Number of accidents for Overtaking encounter
At least one Tanker involved	1.68E-03	1.70E-04	4.08E-01
	±6.52E-05	±6.60E-06	±1.59E-02
At least one Passenger involved, good visibility	9.94E-07	5.44E-07	9.37E-04
	±9.79E-08	±1.38E-08	±2.38E-05
At least one Passenger involved, poor visibility	9.94E-07	3.70E-06	9.37E-04
	±9.79E-08	±9.39E-08	±2.38E-05
All other ships	2.27E-04	6.09E-05	5.51E-02
	±1.01E-05	±2.72E-06	±2.46E-03
Total number of accidents	4.66E-01		
	±1.84E-02		

To explore the model's behavior further, two more sets, of 100 iterations each, are performed. In the first case, the time window is kept to 60 seconds and an artificial increase of 10% in traffic volume is implemented. The results obtained are presented in Tables 10, 11 and 12. In the other case, the time window is extended to 120 seconds also with a 10% artificial increase in traffic volume. These results are presented in Tables 13, 14 and 15.

Table 10. Output of the algorithm over 100 iterations, with a critical time window of 60 seconds and an artificial increase of 10% implemented on traffic volume

Number of collision candidates						
Total	Head-on	Crossing	Over-taking	At least one Tanker involved	At least one Cargo involved	At least one Passenger involved
1151.6	9.92	0.45	1141.23	451.72	688.01	11.87
±49.189	±0.2219	±0.0065	±47.863	±15.1048	±22.451	±0.2259

Table 11. Expected number of collisions per year with application of causation factors by Pedersen (1995) using the values from Table 10

	Head-on	Crossing	Overtaking	Total
Number of accidents	1.00E-04	1.15E-04	6.41E-02	6.44E-02
	±2.24E-06	±1.68E-06	±2.69E-03	±2.69E-03

Table 12. Expected number of collisions per year with application of causation factors by Goerlandt and Kujala (2011) using the values from Table 10

Situation	Number of accidents for Head-on encounter	Number of accidents for Crossing encounter	Number of accidents for Overtaking encounter
At least one Tanker involved	2.18E-03	9.88E-05	2.51E-01
	±7.29E-05	±3.31E-06	±8.38E-03
At least one Passenger involved, good visibility	1.42E-06	3.17E-07	5.76E-04
	±9.54E-08	±6.03E-09	±1.10E-05
At least one Passenger involved, poor visibility	1.42E-06	2.15E-06	5.76E-04
	±9.54E-08	±4.10E-08	±1.10E-05
All other ships	2.90E-04	3.50E-05	3.34E-02
	±9.48E-06	±1.14E-06	±1.09E-03
Total number of accidents	2.87E-01		
	±9.57E-03		

Table 13. Output of the algorithm over 100 iterations, with critical time window of 120 seconds and an artificial increase of 10% implemented on traffic volume

Number of collision candidates						
Total	Head-on	Crossing	Over-taking	At least one Tanker involved	At least one Cargo involved	At least one Passenger involved
2296.07	10.43	0.76	2284.88	898.58	1374.8	22.68
±138.235	±0.2077	±0.01607	±137.900	±42.592	±5.314	±0.444

Table 14. Expected number of collisions per year with application of causation factors by Pedersen (1995) using the values from Table 13

	Head-on	Crossing	Overtaking	Total
Number of accidents	1.05E-04	1.95E-04	1.28E-01	1.29E-01
	±2.10E-06	±4.12E-06	±7.75E-03	±7.76E-03

Although drawing inferences about the validity of the model is highly uncertain due to the limited number of collision events (Goerlandt and Kujala, 2011), a comparison with available data from the literature is attempted.

Andritsopoulos (2011) conducted a statistical analysis of maritime accidents in the Aegean Sea based on historical data over the period 1999–2009. During this 11-year period, 21 accidents were found in the Dardanelles–Adriatic area. Of these, 6% were collision accidents. This is equivalent to 0.1145 collisions per year. In the model presented in Tables 4 and 5 the average number of expected collisions per year is 0.1441 ± 5.09E-03. However, it should be noted that interactions with traffic volume from other routes and the studied route are not taken into account here. This means that a ship involved in a recorded collision might have originated from another route, which slightly reduces the expected number of collisions. Thus our background knowledge regarding actual collisions found within the studied route is incomplete. Nonetheless the obtained results show a strong convergence with the recorded number of collisions.

Table 15. Expected number of collisions per year with application of causation factors by Goerlandt and Kujala (2011) using the values from Table 13

Situation	Number of accidents for Head-on encounter	Number of accidents for Crossing encounter	Number of accidents for Overtaking encounter
At least one Tanker involved	2.29E-03	1.67E-04	5.01E-01
	±1.08E-04	±7.89E-06	±2.37E-02
At least one Passenger involved, good visibility	1.05E-06	5.13E-07	1.11E-03
	±9.90E-08	±1.01E-08	±2.17E-05
At least one Passenger involved, poor visibility	1.05E-06	3.48E-06	1.11E-03
	±9.90E-08	±6.83E-08	±2.17E-05
All other ships	3.06E-04	5.92E-05	6.70E-02
	±1.23E-05	±2.38E-06	±2.70E-03
Total number of accidents	5.72E-01		
	±2.66E-02		

A comparison with other existing models would be unrealistic because they implement different parameters especially concerning local characteristics and traffic volume. However, at least in view of the order of magnitude of major variables, a reasonable agreement is found with the work of Goerlandt and Kujala (2011).

The low number of crossing encounters detected by the model is due to the way the route has been constructed. It consists mostly of long straight paths; this trend is not equally strong around Kea Island where crossing encounters are found since angles between these paths can be wider. The very low numbers of passenger ships found to be collision candidates are due to the fact that there is no active passenger line on the route. The considered passenger ships are solely cruise ships, which constitute a minor proportion of the total traffic volume. The other parameters seem to follow the general trend.

Conclusions

The model seems to provide reasonable output, compared to available historical data, in spite of the assumptions that have been made. The need for further improvement of the output elaboration arises, most importantly, with respect to the aspect of the appropriateness of the causation factors applied. Further attention should also be given to the collision criterion by which the most realistic approach would be ensured.

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