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The Effect of Traffic Complexity on the Development of Near Misses on the North Sea

Fulko van Westrenen, Joost Ellerbroek *Member, IEEE*

***Abstract*—Vessel traffic is changing due to changing transport demands, larger ships and new use of sea space, such as windmill parks. This may have an effect on the risks at sea. This study uses ship state information provided by AIS-messages to analyse the traffic on the North Sea. From the ship-state information conflict situations are selected, i.e., situations where the ships need to manoeuvre to avoid collision. In addition, situations of near-miss collisions are calculated. It was found that complex conflicts lead to more near-misses. It was also found that near-misses are not spread evenly over the sea but are concentrated in a number of specific locations. These findings may be important for the design of route structures for ships, as well as for investigations into methods to resolve complex conflict situations.**

***Index Terms*—traffic complexity, maritime traffic, collision risk, solution space, near miss**

I. Introduction

Ships are rapidly becoming larger, and are used more often, due to the ever increasing transport demand between Europe, Asia and America. In addition, the development of transport hubs increases traffic concentration along particular routes. As a further complication, the sea becomes economically ever more important for energy production and mining, reducing the freely navigable area for ships. All of these aspects lead to increased risks in maritime transportation. This article describes a study on vessel traffic safety in the busiest sea area in Europe, the North Sea. It will focus on the risk of collision, in relationship to ship size, navigable area and traffic structure.

Even though the North Sea is one of the busiest sea areas in the world, the number of accidents is considered low [1]. Nevertheless, the number of accidents that do occur is still significant. A well known recent accident is the collision between the Baltic Ace and the Corvus J, on 5 December, 2012. As a result, the Baltic Ace sank 15 minutes after the event, and only 13 of the 24 crew could be saved. Fourteen-hundred factory-new cars were lost, 500m^3 fuel is still on board, and the wreckage is situated in the middle of a very important but shallow traffic lane, making removal imperative.

Although collisions are rare, accidents like these show that collisions at sea can have an enormous impact. The lives of crew and passengers can be lost, the fairway can be blocked, and pollution of the environment can have a devastating effect. In addition, the impact of lost cargo on the economy can be huge. More than 90% of all cargo is transported by ship, where the largest ships carry up to 19,000 standard (twenty foot equivalent, TEU) containers (to put that into perspective: there are 17,121 fashion shops in the Netherlands [2]. Because of such high-impact outcomes, collisions are considered a serious risk[1]. As collisions involve two autonomously navigating ships, they are more difficult to analyse than single-sided accidents, and their risk is more difficult to estimate.

The most common approach to analysing collision risk is to use probabilistic methods such as fault-tree analysis that make aggregate risk assessments. While results from such studies might be useful for global assessments and policy-making, they provide little insight into low-level and situation-specific contributions to risk. The objective of this study, therefore, is not to make a global risk analysis, but to investigate (local) conflict complexity as a contributor to collision risk.

Vessel traffic has all the characteristics of a complex system (e.g. [4], [5]). In this case the system consists of a situation with multiple ships at sea, where each ship is autonomous, and has a navigator responsible for staying clear of all other ships and obstacles in the environment. In addition to operating the technical systems on board, a navigator has a multitude of tasks, all of which are highly interconnected. Keeping the ship in a safe state, keeping her in a safe position, resolving conflicts, selecting a safe track, and planning for time, economy and environment, form the base of the navigator's task. To realise this, the navigator must deal with uncertainties about the state of the ship, the environment and other ships. Consequently, there is often no clear optimal solution for a given situation. In general, there are many acceptable solutions, some of which can be seen as better, depending on the chosen criterion, while others will be considered unacceptable. This, however, makes it impossible to determine beforehand which solution will be chosen.

Analysing safety and risk with complex systems, especially complex systems with humans, is strenuous. Human operators are generally there to make the system work. And they are good at that, otherwise they would be replaced or engineered out of the system. Even though ships are increasingly automated, they remain fully under human control. In terms of safety analysis, however, the human element adds to the complexity of the system.

Several aviation-related studies propose that traffic complexity can be assessed in terms of traffic manoeuvrability, expressed in a *solution space* for each aircraft [6], [7]. This

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[1]Risk in this article refers to "uncertainty and severity of the consequences (or outcomes) of an activity with respect to something that humans value" [3].

paper proposes a similar method for maritime traffic. Based on simple extrapolation of the current traffic situation, conflict resolution constraints can be determined, which together form the solution space of the respective vessel. If the ratio between acceptable and unacceptable solutions within this solution space is high, risk is considered low; if this ratio is low, risk will be high.

The remainder of this paper is structured as follows: After discussing risk in the maritime domain in Section II, conflicts between ships, resolution space and complexity are derived. These are then used to analyse traffic on the North Sea near the Netherlands, using Automatic Identification System (AIS) data. AIS broadcasts ship-state data (position, speed, heading, size, etc) via VHF (Very High Frequency) radio. The results of this analysis are presented in Section VII, followed by a discussion on the findings, and conclusions.

II. Complexity and risk in the maritime domain

Uncertainty and unpredictability are common contributing factors in shipping accidents [8], [9]. Together with the difficulty of ship manoeuvring, these are therefore of particular interest in area's of high traffic density, and have been the focus of several studies. Weng et al., for instance, found collision probability hotspots for various vessel types in the Singapore Strait [10]. Qu et al. presented traffic indices relating to collision risk for Singapore Strait, based on the manoeuvring of ships [11]. Ladan & Hänninen analysed the possible use of various data sources for risk analysis, with particular focus on the Gulf of Finland [12]. Goerlandt & Kujala studied the reliability of various probabilistic risk models using data from the Gulf of Finland. Their conclusion was that the reliability and validity of probabilistic risk assessment is limited [13].

Several other studies have related unpredictability to mental demand. Van Westrenen, for instance, showed a relationship between available manoeuvring space and workload [14]. Similarly, Hockey et al. found a direct relationship between traffic density and workload, and that traffic-rule violations amplify this [15]. In addition, ships can be hard to manoeuvre and the navigator depends on an accurate mental model for ship handling [16]. The current article focusses on how complexity of the local traffic situation has an effect on near-miss collisions. A measure of complexity will be developed based on the resolution space. The hypothesis is that complex situations lead to more near misses.

III. Conflicts and resolution space

To remain safe, ships must maintain a certain minimum distance between them at all times. To realize this, any conflicts that occur need to be detected and resolved. The basic regulations for this process are defined by the International Regulations for Preventing Collisions at Sea (Colregs). The Colregs consider situations between pairs of ships. In conflict situations, both ships are required to avoid collision. However, in most situations one vessel is burdened to "give way" while the other is privileged to "stand on". This is mostly based on angle of approach and vessel type; size and manoeuvrability hardly matter. Applying the Colregs to everyday traffic situations, however, does have a few problems. Chauvin & Lardjane studied decision making and strategies used by ferry crews in the English Channel [17]. They showed that the Colregs are not strictly followed by all vessels: Slower vessels are more reluctant to make evasive manoeuvres, and economy can prevail over rules if safety is not impaired. In addition, the crew can play with the geometry of a conflict to force the other ship to manoeuvre.

Table I
Number of registered collisions on the Dutch part of the North Sea.

year	significant	total
2004	4	11
2005	1	9
2006	1	8
2007	1	7
2008	2	6
2009	2	7
2010	6	13

The Colregs originate from well over a century ago, and need to function in all environments and for all users. As a result they are rather vague, leaving many decisions to the navigator on board. They are better suited for putting blame after a mishap than to prescribe how a conflict should be resolved. For this study this has two complications: conflict definition and conflict asymmetry.

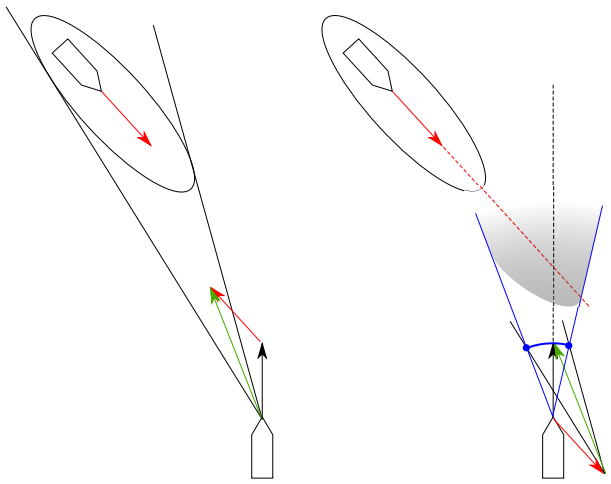
When two ships collide it is clear that there was a conflict. Similarly, when one ship loses directional control due to hydrodynamic interaction there was also a conflict. The Colregs, however, do not specify a minimum safe passing distance, and as a result, a conflict is not unambiguously defined. In addition, collisions during ship voyages are very rare and consequently a poor measure of risk.

The number of officially recorded collisions in the Dutch part of the North Sea that is categorised as "significant" is shown in Table I ([1], p 47). An accident is "significant" if there is damage to the hull, making it no longer seaworthy. In addition, the total number of collisions is presented. The number of collisions is too low to determine locations or situations of high risk. At the same time, although officially considered low, these collisions do represent a serious risk.

For various reasons one can assume that near misses are far more common than collisions. Near misses could therefore be used to analyse situations of high risk. However, near misses are not defined for the same reason conflicts are not defined. A method to consistently define conflicts and near-misses could be to use a ship's domain: an area around each ship that must not be occupied by another ship at any time [18]. Several of these domain shapes have been developed, depending on the the specific objective of the risk analysis. There are, however, no officially or even generally accepted domains. Shapes that have been proposed are circles, ellipses, fuzzy and sector-domains [18]–[21], each of which has its strengths and weaknesses.

In this analysis, ship domains represent uncertainty, not risk. For this a simple elliptical domain will suffice, based

on the domain by Fujii [19]. Since the bow of a ship is considered critical, the ellipse will be centered around the bow, partly mitigating the critique on symmetrical domains. In restricted waters, such as channels, the Fujii-domain may not be appropriate [22]. The area under analysis in this study, however, is in open sea, with few restrictions for most ships. Also, the ellipsis works reasonably well in situations where ships sail in streams. Of particular benefit in the current study is the fact that an elliptical domain is mathematically well defined. Thich simplifies analysis, as the dimensions of the domain depend only on the size of the ship.



(a) Conflicting set of courses in terms of relative velocity.

(b) Translating the set of conflicting courses reveals a conflict set in terms of absolute velocity.

Figure 1. Derivation of the set of courses that lead to an intrusion, and the resulting conflict area.

For a given domain and geometry of two conflicting ships, one can calculate if the two ships enter each other's domain for a series of courses. Here, all ships in the area represent potential conflicts. Figure 1 shows how a set of conflicting courses can be determined for each proximate ship. First, Figure 1a shows that two ships are in conflict, when the relative velocity of one ship with respect to the other is pointed towards the domain of the other ship. In other words, a conflict occurs when the relative velocity vector (the green vector in Figure 1a) lies between the two lines tangent to the domain of the other ship. Figure 1b subsequently shows that when this area is translated with the velocity of the other ship (the red vector in Figure 1b), a set of conflicting courses can be determined for the observed ship (the thick blue line in Figure 1b)[2]. An absolute conflict area can be created for this set of courses, using the time of first domain intrusion, shown by the shaded area in Figure 1b. Figure 2b shows how these areas from multiple surrounding ships (see Figure 2a) can be combined to divide the surrounds into areas of conflicting trajectories, and conflict-free areas. The boundary is based on constant speed and instantaneous heading changes. The remaining space will be defined as the resolution space. This space is not involved in potential conflicts, and therefore provides a resource for conflict-free manoeuvring. When conflicts occupy more space, the resolution space decreases, and consequently there are fewer opportunities to resolve conflicts, increasing complexity.

Conflicts will be categorised using two properties of the resolution space; the size of the current conflict, and the complexity of the entire situation. Both properties are considered only within a certain time range T_{range} (e.g. 600s), and within a course range [-π/2, π/2]. The resulting semi-circular area under consideration is illustrated in Figure 2. The first property, conflict size, is determined using the area resulting from the conflict courses corresponding to the current conflict:

$$\text{Size } s = \int_{-\pi/2}^{\pi/2} (T_{range} - T(\alpha)) d\alpha$$

This corresponds to the intersection of a semi-circular area that is delimited by the time range T_{range}, and a conflict area for the current conflict, as defined in Figure 1b. The second property, complexity, corresponds to the the area covered by the conflict courses of all nearby ships combined, as illustrated in Figure 2b. This area is equal to, or larger than the conflict size (i.e., it is the same if there are no ships nearby, other than the conflicting ship, but can be larger when more ships are nearby). Since the estimation of conflict-courses depends on the extrapolation of all ships, complexity depends on the number of ships. It is assumed that for experienced navigators, complexity increases less than linearly, in this study this factor is represented as n^a, with $a \leq 1$. This choice is motivated by the fact that experienced navigators can, up to a point, apply certain strategies that reduce the perceived complexity of a situation. For instance, if all ships have independent courses, complexity would increase linearly with their number. However, in most situations ships can be mentally grouped due to the structuring of traffic, thereby reducing complexity for the navigator.

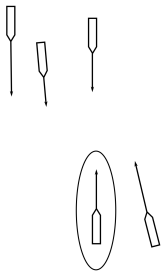
As a consequence of this definition, in single ship conflicts, size and complexity are the same. These conflicts are considered simple. In multiple-ship situations, complexity is always larger than conflict size. To distinguish between non-complex and complex conflicts, complex conflicts are defined as those exceeding a complexity boundary expressed as:

$$b > \frac{c_p}{s} + s$$

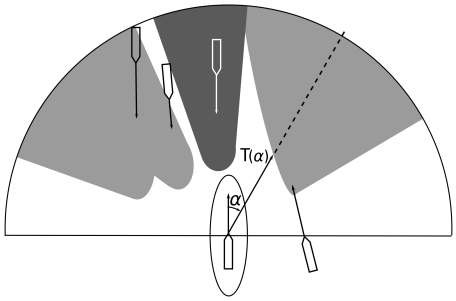
Here, b is the boundary separating simple and complex conflicts, s is the conflict size, and c_p a complexity parameter. Figure 3 shows a graphical representation of this classification.

Between the involved ships, conflicts can not be assumed symmetrical. This becomes clear when comparing a very large ship (with a correspondingly large domain) with a small ship (and small domain): The small ship can be in the large-ship's domain, while the reverse is not the case, making the conflict undefined. In such situations, when the ship that must give way is not in conflict, the conflict is defined by transferring the variables to ship that must give way. Another approach would be to detect the overlap of domains, but this is mathematically more complex. In addition, traffic analysis in this article is essentially ship-based. If domain size would vary with cargo

[2] A more extensive version of this derivation is described by Ellerbroek in [23].



(a) Complex conflict with one ship is shown with her domain, allowing for near-miss and complexity calculations.



(b) Graphical representation of the conflict size of figure 2a, in grey. The boundary of conflicting ship is in dark grey, boundary of all other ships in light grey. The angle α is relative to the own heading. The situation is not to scale.

Figure 2. A complex conflict.

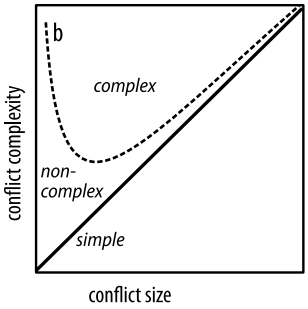


Figure 3. Classification of simple, non-complex and complex conflicts. Single-ship conflicts (simple) are on the x=y axis.

risk and ship manoeuvrability, the required data exchange would hinder any on-board implementation.

The conflict and resolution space as described above relate complexity to the tractability of the traffic situation, from the perspective of the individual navigator. Complexity is based on linear extrapolation, using the current orientation of a group of ships, relative to each other; it does not rely on traffic patterns or location. This is motivated by the fact that when at open sea, ships minimise manoeuvring for economical and safety reasons. This allows for the calculation of the resolution space by linear extrapolation of the ship's trajectory, enabling continuous complexity prediction.

Although relevant, the current definition does not include manoeuvring characteristics of the ship being navigated. The fact that a (human) navigator is involved, implies that a complexity measure must include a cognitive component (in this study n^a) [24]. Simple conflicts, conflicts with only one other ship and few courses that lead to conflicts, can be resolved easily by the navigator. If conflicts become more complex, this changes. Other ships will limit the safe courses, limiting the resolution space, and thus adding to the complexity. When the resolution space decreases, complexity increases, and the risk of ships coming too close together increases. In this study it is therefore hypothesized that situations of high complexity lead to more near-misses.

IV. Area

This study analysed maritime traffic in the Dutch part of the North Sea, which is one of the busiest sea areas in the world. Major ports like Antwerp, Rotterdam, Amsterdam, Hamburg and Felixstowe all connect to this part of the North Sea. It also holds the entrance to the Baltic Sea. The North Sea has rich fishing grounds, and situated under it are significant amounts of gas and oil. It is also a shallow sea, which makes it difficult for ships to navigate. For this reason, traffic in the North sea is highly structured by Traffic Separation Schemes (TSS), creating virtual highways.

Traffic at sea is regulated by traffic rules and TSS's with mandatory sailing direction, separating traffic sailing in different directions. Because of the high traffic density, and the shallowness of the North Sea, which restricts ship-size, there are several of those scheme's. Figure 4 shows the TSS's of the Dutch part of the North Sea. The selected route will depend on a ship's destination and its draught.

V. AIS messages and ships analysed

In this study, traffic will be analysed using AIS data. Almost all commercial ships are required to have AIS. It is a ship-borne system that periodically broadcasts ship state information such as position, heading, and speed, using data from GPS, the gyrocompass, and the speed log. The broadcast uses a VHF transmitter, which effectively limits the range to line-of-sight. Transmission intervals range from 2-180s, depending on the speed of the transmitting vessel. In addition to the state, static voyage information such as ship name, type, size, and destination, are broadcast every 6 minutes.

AIS information can be incorrect due to various technical shortcomings: Problems that have been observed include ship-positions jumping back-and-forth, ships pivoting while moving in a straight line, and courses jumping left-and-right. For this reason AIS data needs to be checked and repaired. Not all messages will arrive, due to message collision (ships broadcasting simultaneously) and transmitters that move out of range. When no data is available for more than 10 minutes the data is considered unavailable. For shorter periods it is interpolated.

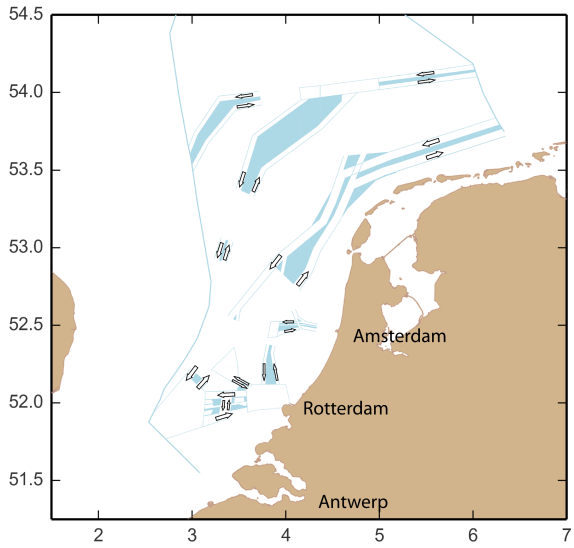


Figure 4. Traffic organisation at the Dutch part of the North Sea by means of Traffic Separation Schemes.

Each data-point is checked for position, heading, speed and course. Using a very simple ship model, the forces needed to realise each state are calculated for the data points. A datapoint is replaced by an extrapolated point when the forces are unreasonably large (>20 times normal). After this correction, a Kalman-filter is applied for the track reconstruction.

This study uses AIS data of the Dutch part of the North Sea, Spring 2014. This area includes the Dutch territorial waters and exclusive economic zone, a 200 nautical mile (NM) sea area stretching out from the baseline (i.e., the coastline). AIS data is collected with land-based stations, and at sea with receivers on installations such as oil-rigs. Although the AIS data cover an area larger than the Dutch area, no data were removed from the analysis. In total, $1.2{\cdot}10^9$ AIS messages were available for the analysis.

All major Dutch ports provide Vessel Traffic Service (VTS); a marine traffic monitoring and information system for the ships in and around the port. This service may have an effect on the autonomous behaviour of the ships. UNCLOS (United Nations Convention on the Law of the Sea) limits VTS service to territorial waters, the first 12NM from the baseline. For this reason, all data within territorial waters is excluded from the analysis. However, because the TSS north of the Netherlands is partly inside territorial waters, the territorial line is replaced there to preserve that TSS for analysis.

The analysis includes all ships with an MMSI (Maritime Mobile Service Identity, a unique numerical identifier) with a first digit between 0-8. This excludes all small yachts. Anchored, drifting and grounded ships are also not included in the analysis. Oil and gas rigs, wind mills, buoys and other constructions at sea are not considered.

VI. Ship conflicts, domain intrusions and near misses

Conflicts are analysed by applying the Colregs: When two ships are in conflict, the calculation is made for the ship that must give way. If both ships must manoeuvre, the calculation is made for the largest ship. The work of fishing vessels, pilot vessels and tugs requires close manoeuvring. Conflicts with these ships are therefore ignored, but their presence is included in the calculation of complexity for conflicts that are considered (i.e., the reduction of the resolution space caused by their presence).

Safety is based on the application of domains. This study employs an elliptical domain, as described by Fujii & Tanaka [19], with the same size, but centred around the bow. The minor axis (A) of the ellipse is equal to 1.6 times the ships length over all (LOA), $A = 1.6 * LOA$, its major axis (B) equals $B = 4 * LOA$. The domain size therefore depends on the size of the own ship. A conflict is defined as a projected intrusion of the domain within T seconds, with $T = 450s$. Three training experts were consulted and they considered the initiation of conflict avoidance at 300s too late and at 600s acceptable, so for this analysis a critical value of 450s was chosen. In such situations, with a domain intrusion within 450s, evasive manoeuvres must be made, and minor adjustments in heading and/or speed no longer suffice. Ships outside 600s are not considered critical. A domain intrusion (DI) is defined as a state where any part of a ship enters the domain of another ship. This can be compared to a "loss of separation" in aviation. A near-miss is defined as a state where the intruding ship reduced the free domain by more than N%, with $N = 50$ and $A/B = 1.6/4$.

Conflict detection is done at 60-second intervals. Once a conflict is detected, conflict development is analysed at 2-second intervals. These times were chosen as an acceptable compromise between accuracy and computation time.

Collisions and other accidents were not analysed separately. Distinguishing between near-misses and collisions using AIS data is complicated and therefore not pursued. Furthermore, while accidents are recorded, they are not publicised by government agencies. Accidents outside territorial waters are not investigated unless requested by the owner, flag state, or because of a considerable national concern. Since most collisions are not investigated this cannot be used for additional analysis.

VII. Results

A. Traffic analysis

Figure 5 shows the traffic density, based on the AIS data. The traffic shown corresponds only to "commercial" vessels (categories passenger/cargo/tanker/other) that are under way. Yachts, fishing vessels, service vessels, anchored, drifting and grounded ships are not included.

An average number of 645 ships/day passed the area. A breakdown of the various types and sizes is provided in table II. Again, this only includes travelling (commercial) ships.

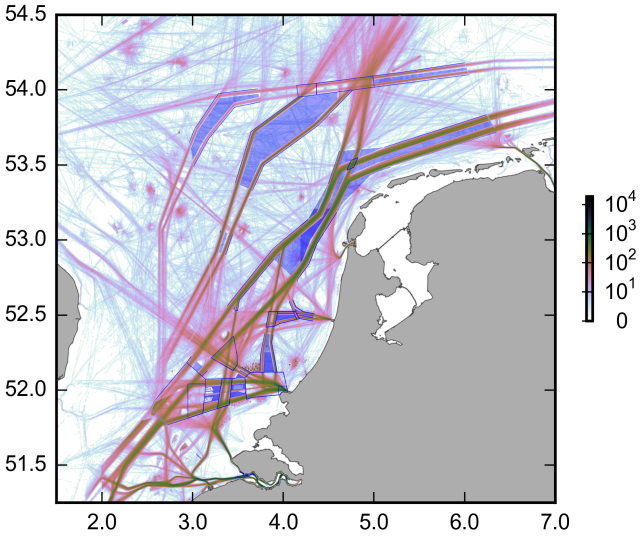


Figure 5. Traffic density in the North Sea area using pseudo-colors. The scale is logarithmic to support the large range. The TSS's are added for reference. The major traffic lanes appear clearly in green-like colours. Latitude and longitude are in degrees.

Table II
THE NUMBER OF SHIPS PER DAY IN THE AREA UNDER ANALYSIS. THE CATEGORY IS TAKEN FROM AIS (MESSAGE TYPE 5).

ship type	AIS code	number/day
passenger	6x	13.5
cargo	7x	373.6
tanker	8x	145.5
other	9x	22.5
fishing/tug/pilot	1x-5x	89.7

Figure 6 shows the number of ships per day, divided by ship length. Here, ship length is calculated from the AIS type 5 message.

B. Conflicts

Outside territorial waters, the computed average rate of conflicts is 100.3/day, the rate of domain intrusions is 9.28/day, and the rate of near-misses is 2.41/day. In the period of analysis there was one reported collision between two large cargo ships.

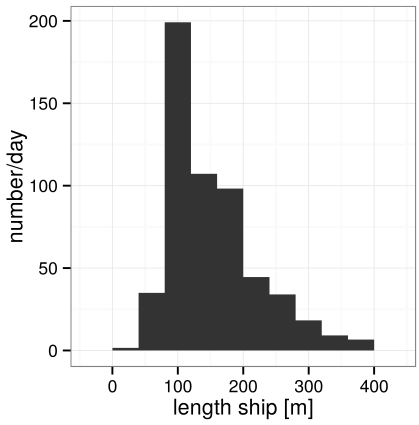


Figure 6. The number of ships per day divided by ship-length.

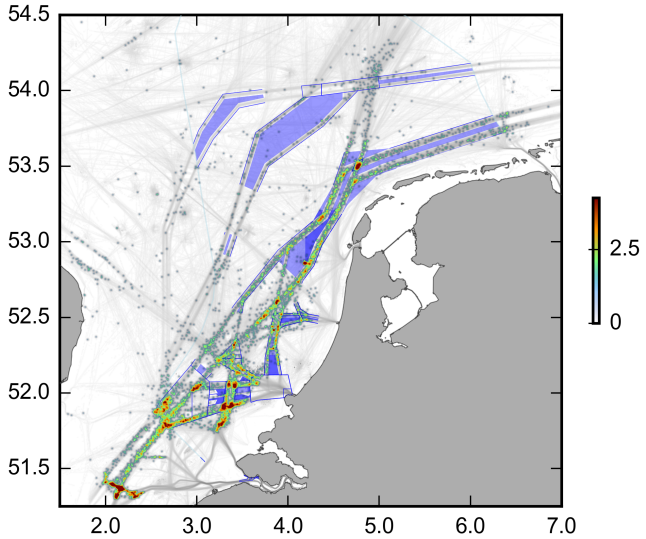


Figure 7. Conflict density of the area. A conflict requires a ship to manoeuvre within 450s to remain outside another ship's domain.

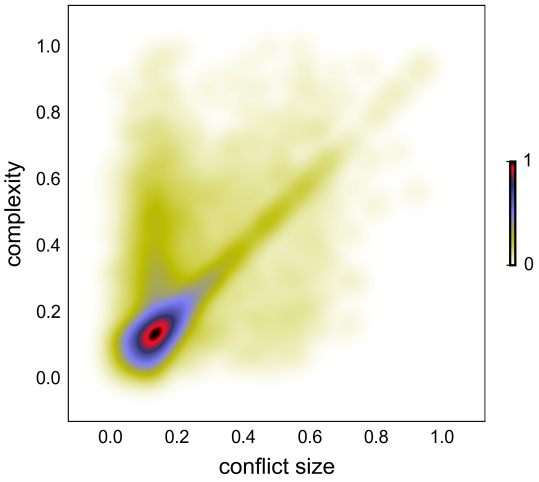


Figure 8. Density of conflicts plotted for conflict size and complexity. Single-ship conflicts are on the 45° axis. The effect of the number of ships on complexity is chosen $a = 0.5$.

Figure 7 shows the conflict density in the area. It can be seen that conflicts are not evenly distributed with traffic density. Also, since traffic within territorial waters is not analysed, the approaches of the ports show no conflicts.

1) Conflict density: Each conflict is characterised by conflict size and complexity. Figure 8 shows the density of conflicts expressed in these two dimensions ($T_{range} = 600s$). By definition, complexity cannot be smaller than conflict size. There can, however, be a problem of asymmetry of conflicts, due to the differences in ship size. In that case complexity can be smaller than conflict size. In Figure 8 it can be seen that the majority of conflicts is small and simple.

2) Near-miss density: When only near misses are selected, a pattern similar to traffic density can be observed (Figure 9). Further inspection of individual conflicts reveals that naviga-

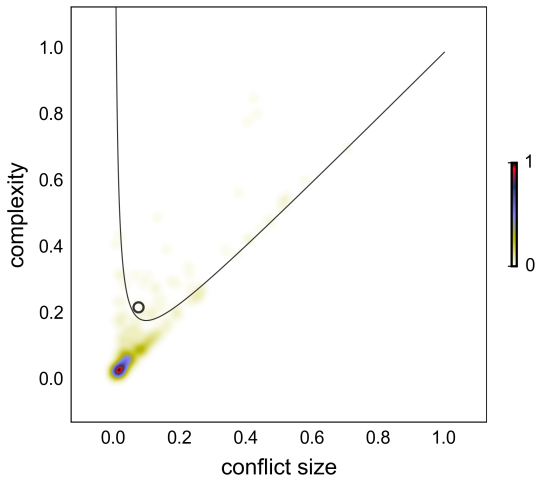


Figure 9. Density of near misses plotted for conflict size and complexity. This figure is a subset of the data in Figure 8.

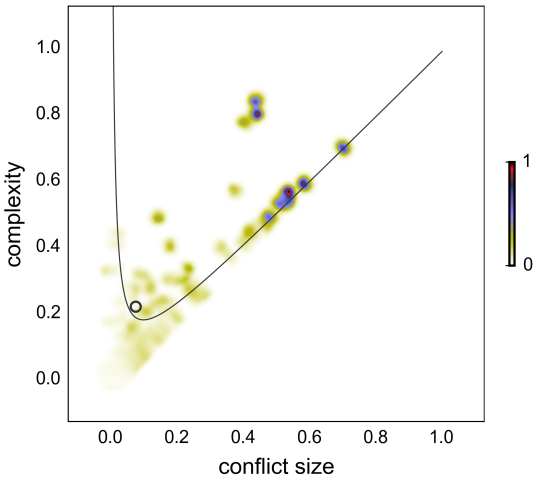


Figure 10. Relative density of near misses. This figure shows the proportion of conflicts that resulted in a near-miss, with simple conflicts (single-ship conflicts) removed. The curve is the complexity boundary from Figure 3. The small circle marks a reported collision.

tors seem to accept very small passing distances when there are no constraints set by other ships or the navigational area.

3) Relative near-miss density: The two densities can be combined to obtain a relative near-miss density (i.e., the proportion of conflicts that resulted in a near-miss) by dividing near-miss density by conflict-density. To enhance resolution, all simple conflicts, i.e., conflicts involving two ships only (size = complexity) are removed in Figure 10. These simple conflicts are far more common than complex conflicts, and consequently there are more simple near-misses than complex ones. When near-miss density is observed as a proportion of the conflict density, it can be seen that near-miss density increases with complexity. In other words, the probability that a conflict results in a near miss becomes larger when complexity is high. The line in the figure corresponds to the boundary of the area of complex conflicts defined above. For simplicity, conflicts in the lower-left half are transferred to the upper-left half by transferring the conflict size from the small ship to the large one. The small white circle is the projection of the reported collision.

Based on the definition of complex conflicts, and only considering crossing courses, the near-miss rate for complex conflicts is a factor 2.86 higher than for non-complex conflicts. On visual inspection, complex conflicts seem to develop differently. In simple conflicts, navigators tend to adjust only once. Here, some adjustments are made too small, and some are made too late to remain well clear of the other ship. In complex conflicts, navigators manoeuvre more, but the options are limited.

To verify if near misses develop more often in certain areas, or if collision risk concentrates in certain locations, the near-miss density is calculated for geographical location. In this calculation domain intrusion, simple near-misses and complex near-misses are combined, applying a weight of 1, 2 and 3 respectively. The result is presented in Figure 11. Although domain intrusions are rather spread, significantly increased probability of intrusion does concentrate in a few locations. Determining the impact of this risk, i.e., the estimated cost

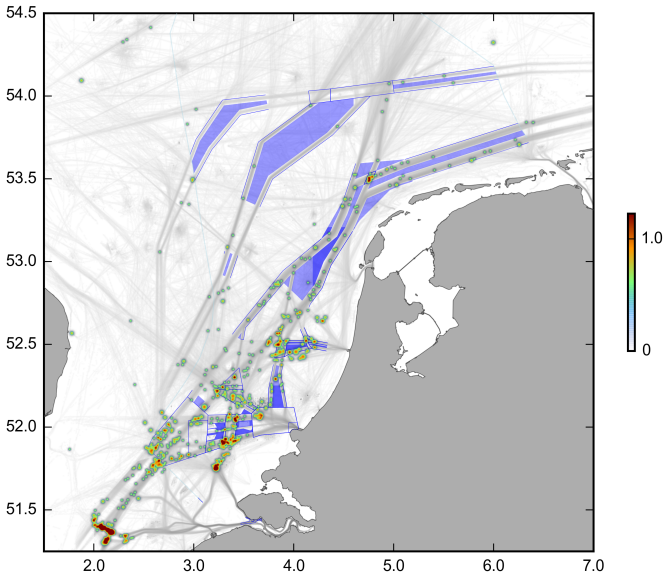


Figure 11. Distribution of near misses (hotspots). Near misses are weighted for simple and complex conflicts.

of an unwanted event, would require information that is not available for this study. In addition, some of the areas of high probability are under radar surveillance, but the effect of this surveillance on ship behaviour and risk is unknown.

VIII. Discussion

The results show that most conflicts are resolved effectively, especially considering the conflict time of 450s. More than 90% is fully resolved by the navigator. The fraction of conflicts that result in a near miss is 2.6%. This includes all types of conflicts. When conflicts are further subdivided based on complexity, it can be seen that complex conflicts lead to almost three times more near misses than non-complex conflicts.

In this paper it was hypothesised that traffic complexity increases the probability of near misses. This indeed appears to

be the case when the current results are considered. These near misses are the result of the reduced resolution space, making them difficult to deal with. There is, however, a second type of near miss: when manoeuvring space is abundant and there are only two ships involved (simple conflict), some ships select a passing distance not based on safety but efficiency and/or workload. This behaviour is consistent with behaviour in other human-machine systems, e.g. [25]. This type of behaviour can also be seen in aviation, e.g. [26]. Since the majority of conflicts is simple, the tendency of operators to optimise for efficiency leads to a significant number of intentional near misses, which brings the system closer to the boundary of safety.

In this study, no distinction is made between ship types, ship sizes, or any other distinguishing features. Only the size of the own ship, the ship that had to give way, defined the domain, and the conflict geometry defined the conflict. Also, no distinction was made between the type of conflict (overtaking, crossing, head-on). The type of conflict was only used to determine which ship would be analysed. In other studies it was found that different ship types can have significantly different risks for different types of conflicts, e.g. [11], [22]. However, since no rationale was provided for this difference it was decided not to include this in the analysis.

Risk hotspots are the result of traffic density and route structure. The route structure is largely defined by TSS's, which means that risk hotspots are largely the result of design decisions. Some risk hotspots are on locations under radar surveillance (e.g. the entrance to the Channel (N51.4,E002.1), Channel Navigation Information Service; western approach of Rotterdam, Port of Rotterdam). It is unknown how this affects complexity and near misses. Some near-misses were detected near anchorages in which departing ships were involved. The speed of these ships is generally very low, making the seriousness of such a near-misses unknown (one such location is an anchorage near Amsterdam (N52.45/E004.20)).

Recently, AIS has become mandatory for almost all ships. AIS has great potential as an additional information source next to radar. Unfortunately, due to shortcomings in definition, implementation and installation, it cannot be utilised to its full potential.

Finally, navigators need to deal with the collision regulations that are incomplete by definition. To start: conflicts are not defined. Navigators depend on conflict resolution mechanisms not supported by the Colregs. In complex situations the rules can be conflicting for the different ships involved. And conflicts can be asymmetrical, leading to additional uncertainty for the navigator.

IX. Conclusion

In this study no account is given to the environment. The navigable area is not constrained by depth or underwater formations. Structures like buoys, rigs and windmills were ignored. Traffic management measures like Traffic Separation Schemes were ignored. In addition environmental situations like wind, waves and current were also ignored. Including these might have an effect on the outcomes, although what the effects might be is unknown at this moment.

When vessel traffic is dense, conflicts cannot be avoided. In general navigators are effective in resolving these conflicts. In the studied area, with 645 sailing vessels per day, the number of near misses is low but significant. Accidents are by definition in the tail of the distribution. Near misses, however, are far more frequent, and can be used as a precursor for accidents. It was shown that near misses concentrate in a few area's, and that traffic complexity is an important factor in the development of these near misses.

There are two types of near misses. Type one is when several ships converge, creating a complex situation with decreasing resolution space. Such situations are sparse but potentially critical, and possibly cannot not be resolved safely by the individual navigators. Because convergence of multiple ships is prerequisite, static traffic management has the potential to create near-miss hotspots. The implementation of dynamic traffic management might therefore be considered [27]. For near misses of type two, only two ships are involved and resolution space is abundant: Some navigators choose to minimise the passing distance. This is possibly the result of optimising for efficiency and workload, at the cost of safety.

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