Postprint of: Szlapczynski R., Szlapczynska J., A ship domain-based model of collision risk for near-miss detection and Collision Alert Systems, Reliability Engineering & System Safety, Vol. 214 (2021), 107766, DOI: 10.1016/j.ress.2021.107766

A ship domain-based model of collision risk for near-miss detection and Collision Alert Systems

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ABSTRACT

The paper presents a new model of ship collision risk, which utilises a ship domain concept and the related domain-based collision risk parameters. An encounter is here described by five variables representing: degree of domain violation (DDV), relative speed of the two vessels, combination of the vessels' courses, arena violations and encounter complexity. As for the first three variables, their values can be directly computed based on positions, courses and speeds of two vessels. The last two variables require decomposing a close quarters situation into phases. For this purpose the method utilizes a number of auxiliary parameters derived from the concept of ship domain: time of domain violation (TDV), time of domain exit (TDE), timespan of close quarters situation and vessels' proximity, which is quantified based on the ship arena. The formulas and algorithms for determining all variables' values are provided in detail. Once all the values are computed, the final collision risk assessment is made. Possible applications of the presented model include: AIS-based near-miss detection, Collision Alert Systems (CAS) and collision avoidance decision support systems (DSS). Case studies for those applications are provided, including examples of encounter classification and quantification of collision risk.

KEYWORDS: Near-miss, ship collision risk, Collision Alert System, ship collision avoidance, ship domain.

ABBREVIATIONS

AIS *Automatic Identification System*

AV *Arena Violations*

CAS *Collision Alert System*

CRI *Collision Risk Index*

DAV *Domain or Arena Violations*

DCPA *Distance at Closest Point of Approach*

DDV *Degree of Domain Violation*

DSS *Decision Support System*

EC *Encounter Complexity*

ED *Encounter Difficulty*

M *Medium*

ML *Medium-Large*

L *Large*

OOW Officer Of the Watch

RICAS *Risk Informed Collision Alert System*

RS *Relative Speed*

RSC *Relative Speed and Course*

S *Small*

SM *Small-Medium*

TCPA *Time to Closest Point of Approach*

TDE *Time to Domain Exit*

TDV *Time to Domain Violation*

VC *Vessels' Courses*

VL *Very Large*

VTS *Vessel Traffic Service*

1. INTRODUCTION

Increasing traffic volume can be seen as a major source of risk in shipping, especially regarding casualties and damages caused by ship collisions [1]. One of the approaches to quantifying this risk is Collision Risk Index (CRI). However, proposing a universal rule for risk quantification is challenging and contemporary CRIs still suffer from various problems which seriously limit their application [2]. Another concept aiming at mitigation of the abovementioned risks is ship safety domain. Ship domain is a generalization of safe distance, which was introduced based on observation that the safe distance may often be longer or shorter in particular directions. Despite its over 50-year history, until now practical applications of the ship domain have been scarce [3], due to computational costs. Fortunately, this can be changed by combining ship domain and CRI with algorithms of low computational complexity.

Lately the availability of AIS data and algorithms for processing them have led to a progress in developing ship domain models. The domains are now often proposed for local water regions, thus encapsulating region-specific information on traffic intensity and associated navigators' expectations regarding separation between vessels. This in turn makes it possible to come up with new methods of ship collision risk assessments, which can then be applied to Collision Alert Systems (CAS) and collision avoidance decision support systems (DSS) as well as to detecting near-miss situations. A common perspective for both CAS and near-miss solutions has already been noted in [4]. The current paper addresses those similarities of CAS and near-miss detection and proposes a new method of domain-based quantifying collision risk in the form of CRI. The method can be customized to fit both above mentioned applications while being light in terms of computations. Below we present the details on related works followed by motivation behind this research.

1.1 RELATED WORKS

The following subsections briefly present works related to elements researched here, namely ship domains, ship arenas and Collision Risk Index (CRI) as well as their areas of application: near-miss detection, Collision Alert Systems (CASes) and ship Decision Support Systems (DSSes).

1.1.1 **Ship domain and ship arena**

Safe distance for long time was, and in some cases still is [5], one of the key safety measures utilized in ship collision avoidance. However, since the safe distance is not equal for all the ship courses in encounter situation, an extended measure named *ship domain* was proposed. For the first time the domain was introduced by Fuji in [6] as "*a two-dimensional area surrounding a ship which other ships must avoid – it may be considered as the area of evasion*". Ship domain by Fuji is an ellipse with the ship in its central point with major and minor axes specified in ship length. A domain proposed by Goodwin in [7] is based on discontinuous circular shapes split for three different sectors around the ship. Another ship domain proposed by Davis [8] is off-centred (to reflect basic COLREGs requirement) circular shape. Similar off-centred elliptic domain was proposed by Coldwell in [9]. All the above mentioned early ship domain proposals are now considered classic and often referred to in literature on ship collision avoidance. Up till now various other ship domain definitions have been proposed. According to a review presented in [3] contemporary ship domains may be classified as:

- empirical, created by gathering and processing real-life data e.g. from AIS [10] or Vessel Traffic Service (VTS) database [11];
- knowledge-based, accommodating experts' knowledge as e.g. in [12–14];
- analysis-based e.g. [15–17].

In order to apply ship domains into collision avoidance system successfully, some domain-based measures are necessary. Thus, in [18] two measures answering when the domain would be violated and to what extent have been proposed, namely Time to Domain Violation (TDV) and Degree of Domain Violation (DDV), respectively. Also, to improve practical applicability of ship domains, research on polygonal approximations of several state-of-the-art domains has been presented in [19].

Another term, which has been introduced for collision avoidance purposes is that of a *ship arena*. The concept of ship arena was first proposed in [8] and later developed in [20], where it has been defined as "*the area, around the domain which when infringed causes the mariner to consider whether to make a collision-avoidance manoeuvre*". Since then, numerous works on ship arenas and related concepts (evasive area, action area, critical distance) have been published. Many of these works take into account the manoeuvrability of the own ship, which is essential for determining the moment when the action has to be taken so as to avoid collision or close quarters situation [21], [22], [23].

1.1.2 **Collision Risk Index (CRI)**

Following Formal Safety Assessment (FSA) applied to maritime domain [24–26], risk in maritime transportation systems can be assessed by combining possibility (or probability) of an accident with its projected consequences. However, in papers on ship collision avoidance, collision risk is often associated with accident possibility [24,27] or probability [28–31] alone. This is especially true in proactive approach, where risk is quantified for collision avoidance purposes. Collision risk in ship encounter situation may be quantified by building an index (Collision Risk Index – CRI) and further utilized by a system triggering an alarm when CRI violates given pre-set threshold. There are different definitions of CRI including various variables taken into account, different methods of aggregating them or even different techniques (analytical or heuristic) for computing the final index value. The most straight-forward approach to CRI is based on weighted sum of two variables (DCPA and TCPA) [27] with arbitrarily set weight coefficients. For CRI computations the researchers often extend the basic formula by introducing some new variables e.g.:

- relative distance as in [32];
- relative distance and azimuth between the ships as in [2];
- distance, relative bearing and ratio of speed as in [33];
- relative distance, target position, ratio of speed as in [34];

Instead of a sum of products, in [35] multiplication of factors (related to DCPA, TCPA and degrees of danger as function of the type of encounter) was proposed. In RICAS [36] the authors utilize a vast set of 16 variables to compute the risk index set up into a compound index by a numerous set (194) of if-then rules. Another approach utilizing Support Vector Machine and

Genetic Algorithm to calculate CRI was presented in [34]. Similarly, neural networks accompanied by Genetic Algorithm for risk index calculation were described in [37]. To support calculations of the index Analytical Hierarchy Process (AHP) [2,33], Dempster-Shafer evidence theory [32] or evidence reasoning [33] can also be used.

Table 1. A summary of research on Collision Risk Index (CRI), M1: Huang Y. et al., 2015 [27], M2: Li B. et al, 2013 [32], M3: Nguyen M.C. et al., 2018 [2], M4: Zhao Y. et al., 2016 [33], M5: Gang L. et al., 2016 [34], M6: Mou J.M. et al., 2010 [35], M7: Goerlandt F. et al., 2015 [36], M8: Li C. et al., 2018 [37]

	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**
DCPA and TCPA	+	+	+	+	+	+	+	+
Target position /distance	-	+	+	+	+	-	+	-
Target speed / relative speed / ratio of speeds	-	-	-	+	+	-	+	-
Target heading / bearing / relative bearing	-	-	+	+	-	-	+	-
Type of encounter	-	-	-	-	-	+	+	-
Surrounding traffic	-	-	-	-	-	-	-	-
Ship domain	-	-	-	-	-	-	+/- (domain dimensions)	-
CRI computation type	weighted sum	Dempster-Shafer theory	AHP, weighted sum	AHP, evidence reasoning	Support Vector Machine + Genetic Algorithm	multiplication of factors	If-then rules reasoning	Adaptive Fuzzy Neural Networks + Genetic Algorithm

Summing up the abovementioned research is presented in Table 1. So far no CRI utilised a ship-domain (apart from simplified usage of domain dimensions), which is a drawback considering that ship domain encapsulates region-specific desired separation between ships. In order to build such CRI, one could possibly apply some measures reflecting distance and time remaining to domain violation (domain-based equivalents of DCPA and TCPA). As for possible techniques for CRI building, if-then rules technique seems promising, especially for combining variables of various types. However, this approach (as applied in RICAS [36]) results in numerous rules, which could be limited, if possible.

1.1.3 Near-miss detection

Near-misses (or near-miss collisions [38]) are situations in which encountering ships have almost collided with each other (but without any physical contact). In such cases a collision has been avoided due to actions taken by the navigators (safety manoeuvres) or just by luck [39]. It is certain that such encounters were associated with high collision risk, thus, it is well-grounded to identify and analyse them as well as map regions with high intensity of near-misses. Unfortunately, so far there is no clear definition of a near-miss [38]. In current studies the definition is usually given in relation to ship domain dimensions. However, also an approach in which domain-based and DCPA-based definitions are combined can be found. Such a hybrid approach has been presented e.g. in [40], where a near-miss has been defined by thresholds of DCPA (< 0.1 NM), TCPA (< 3 min.) and ship distance (< 0.3 NM) values. The research includes analysis of AIS traffic data for South Sea of Korea from 2014, a proposal of near-miss detection and a post-analysis map of near-miss regions in the considered waters. The author indicates that areas with high frequency of near-miss situations correlate with areas reporting significant number of actual ship collisions.

Ship domain based research on near-miss has been presented e.g. in [39,41–46]. Any ship domain (represented by Fuji domain) intrusion has been defined as a near-miss criterion in [39], accompanied by DCPA- and TCPA-based criteria. Similarly, Fuji domain has been utilized to screen AIS data against near-misses in static manner for open sea (Gulf of Finland) and dynamic manner for restricted waters (Danish Strait) in [45]. Analogically, Fuji domain has also been used for finding near-collisions based on AIS data from Tagus River Estuary in [46]. In [41] based on AIS North Sea data from 2011 typical encounter situations (head-on, overtaking and crossing) have been analysed for intrusion of an empirical domain around a relative ship's domain (that is an area around the ship that is violated only by 0.5% of passing vessels). The research results indicate elliptical domain shape, especially for head-on and overtaking encounters. In this research, apart from the ship's domain intrusion, also DCPA and TCPA have been taken into account as auxiliary indices. Similar region of North Sea but with different approach towards near-miss detection has been investigated in [42]. Here Fuji domain has been applied to define near-miss as a situation when intruding ships reduce the central ship's domain by more than 50%. The authors differentiate two types of near-miss situation: when multiple ships are converging and encounter with two ships only. It is stated there that the former situations might get critical due to significant limitation of the solution space. In general, the works above either identify a near-miss with a domain violation (especially with a serious one) or at the very least assume a strong correlation between those two. Such an assumption, however, is questioned in [47], which indicates that the actual correlation between domain intrusions and collision probability may be weak for certain type of ships and water regions and thus a wider context, including environmental conditions and local practice should be taken into account.

Another approach to near-miss research has been introduced in [48]. The authors propose there a vessel conflict ranking operator (VCRO) utilizing relative speed, heading difference and ship distance to rank severity of encounter. They strongly argue against utilization of DCPA/TCPA for general assessment of collision risk due to possible misclassification in case of certain head-on encounters and no possibility to account for the relative orientation of encountering ships. Then VCRO has been applied for screening AIS North Baltic Sea traffic data from 2011 in order to find near-misses, but final decision whether or not there is a near-miss situation has been left for navigational experts. The VCRO concept has been further developed by its authors in [44] to utilize also elliptical ship domain. As before VCRO has been used for finding near-misses in the AIS data set. The original VCRO in conjunction with safe distance ("circular domain") and elliptic domain has also been used by [43] for ship conflict detection in Southeast Texas waterway based on AIS data.

The above-given research on near-miss detection methods is summarised in Table 2.

Table 2. A summary of research on near-miss detection, M1: Yoo SL., 2018 [40], M2: Goerlandt F. et al., 2012 [45], M3: Rong H et al., 2015 [46], M4: van Iperen E., 2015 [41], M5: Zhang W. et al., 2015 [48], M6: Zhang W. et al., 2016 [44], M7: Wu X. et al., 2016 [43], M8: van Westrenen F. et a., 2017 [42], M9: Kim K. Il. et al., 2017 [39], M10: Szlapczynski R. et al., 2018 [49]

	Type	**Water region**	**Type of ship domain supported**	**Near-miss definition**	**Ship domain-based collision risk parameters**
M1	Hybrid (DCPA & domain-based)	South Sea of Korea	safe distance (circle)	Thresholds of DCPA (< 0.1 NM), TCPA (< 3 min.) and ship distance (< 0.3 NM) values	-
M2	Domain-based	static: Gulf of Finland, dynamic: Danish Strait	Fuji	Domain violation (static) or DSE (Dynamic Safety Ellipse) violation (dynamic)	-
M3		Tagus River Estuary	Fuji	Domain violation	-
M4		North Sea	empirical domain	Intrusion of an empirical domain around a relative ship's domain (that is an area around the ship that is violated only by 0.5% of passing vessels)	-
M5		North Baltic Sea	safe distance (circle)	Based on VCRO index including: - distance between the ships. - rate of change of the distance in the course of the encounter, determined by the relative speed of the ships, - the relative orientation of the two ships, determined by the difference between their headings.	-
M6		North Baltic Sea	elliptical ship domain	Based on modified VCRO index including: - distance between the ships. - rate of change of the distance in the course of the encounter, determined by the relative speed of the ships, - the relative orientation of the two ships, using the MDTC model, - ship domain size (indirectly).	-
M7		Southeast Texas waterway	safe distance (circle) and elliptical domain	Based on basic VCRO index (Zhang W. et al., 2015) with either safe distance or elliptic domain applied	-
M8		North Sea	Fuji	Intruding ships reduce the own ship domain by more than 50%	-
M9		South Korean waters (Busan)	Fuji	Domain violation	-
M10		Baltic Sea	off-centred elliptical ship domain	Neuro-fuzzy classifier taking into account domain violation accompanied by relative speed and courses	+ (off-centred elliptical domain, DDV and TDV risk measures)

As can be seen there, similarly to CRI, the works on near-miss research do not support ship domains in a manner, which would allow for domain configuration and quantitative approach to collision risk – a domain-based equivalent of DCPA and TCPA (the exception is [49], which documents an early stage of work). The main advantage of DCPA and TCPA is their clear interpretation so it is desired to apply domain-based parameters of similar simplicity. Unfortunately in existing works ship-domain perspective is based usually on domain dimensions applied directly, which makes it harder for visualization and interpretation. What is more, unfortunately, none of the abovementioned near-miss papers include sample encounter scenarios accompanied with their classification (near-miss or no near-miss) made in accordance with the presented methodology. The majority of papers present statistical studies, only in [44] six scenarios were presented, but without final near-miss / no near-miss classification. All that makes it difficult to compare quantitatively results of state-of-the-art near-miss research by different authors.

1.1.4 **Ship Decision Support System (DSS) and Collison Alert System (CAS)**

A Decision Support System (DSS) in general is usually software and/or hardware solution facilitating daily (or repeatable) operations to improve their efficiency and reduce possible human errors and consequences caused. In maritime transportation DSSes cover vast set of thematic categories [50], including collision avoidance [51,52], stability-related issues [53,54] and ship passage planning [55,56], among others. From this research perspective, obviously the most interesting DSS category is collision avoidance.

NAVDEC, a real-time ship-centric system described e.g. in [51,57], is a good example of DSS in ship collision avoidance. The system utilizes data fusion of multiple on-board sensors and offers detailed information board to the ship deck officers. The board includes, among others, suggested safe COLREGs compliant manoeuvres. Another recent paper [52] presents a collision avoidance system designed for autonomous surface vehicles (ASVs) based on model predictive control (MPC) and AIS data. The system is able to propose COLREGs-compliant maneuvering in real-time when in encounter situation. Its vehicle control station (VCS) viewer presents, in a way similar to NAVDEC, situation overview including indicators of collision threats. Successful sea trials of the system have been performed in the North Sea.

A Collision Alert System (CAS) may be considered as a special case of DSS in maritime transportation, designed particularly for Vessel Traffic Service (VTS) operators and ship navigators with special attention on signalling collision threats on various levels. CASes are usually based on IMO Resolution MSC.252(83) [58] and alerts the users on possible vessel collisions via visual, sound or text indicators. As stated in the resolution, indicator management in CAS ought to distinguish between priorities, namely alarms, warnings and cautions, as listed:

- alarms indicate the need of immediate attention and action;
- warnings indicate a change in conditions and thus should be presented for precautionary reasons (to notify that, if no action is taken, dangerous situation may develop);
- cautions indicate a non-dangerous situation that requires attention and special consideration of the situation or of particular information.

A general CAS framework staying in line with IMO recommendation has been proposed in [59]. It was inspired by air traffic control and based on empirical studies conducted on ships. The authors propose a 4-level notification of collision risk. Quite similar approach has been presented in [60], where CAS solution with radar input data from VTS is proposed. The proposed CAS has been also successfully tested in a series of simulator experiments with input of real radar data. In [61] a CAS system dedicated to vessels passing through narrow straits has been presented. The system utilizes Artificial Neural Networks trained with the use of the Levenberg–Marquardt algorithm. It provides VTS operators with double-level output (binary) of collision risk (situation for a ship is safe or some risk exists) and has been successfully tested for Istanbul Strait waters.

Another CAS solution focusing on the stand-on ship perspective has been proposed in [4]. It distinguishes three protective layers for collision prevention in a two-ship encounter. Conflict detection is based on Velocity Obstacle approach [27]. Proposed CAS framework offers typical IMO-compliant 4-level notification based on 9-class conflict severity ranking. The solution is

COLREGS-compliant, however it only considers selected rules (Rule 11 to Rule 18) and the stand-on ship perspective.

Risk-Informed CAS (RICAS) [36], based on fuzzy expert rules, is a compete CAS with in-depth risk theoretical background, inspired by road traffic encounters framework. It offers four output levels of collision risk compatible with IMO recommendations [58]. An encounter in RICAS is analyzed from different perspectives such as compliance with COLREGs, imminence of accident, deviation from reference level in similar situations and encounter ambiguity. In an encounter (limited to two-ship encounter only) risk levels are assigned via the rules based on number of parameters including DCPA/TCPA, bow cross range and time, relative bearing and visibility (good or restricted), among others. Quite detailed documentation of the case studies included in this paper indicates that RICAS is more accurate in collision risk assessment than previous CAS solutions. This documentation of case studies also makes it possible to compare new CAS-like solutions with RICAS. A limitation of RICAS is that the number of parameters used there results in a large number of decision rules and relatively hard customization of the system (adjustments to navigators' preferences and specifics of local practices). All of the above drawbacks could be eliminated by a solution, based on a configurable ship domain, which would replace some of RICAS decision variables. Such a solution would be open for customization and would make it possible to extend its functional scope without interfering with its main structure. A preliminary CAS framework aiming at that was proposed by the authors of this paper in [62]. The proposed framework actively applies to a 4-level alert system two domain-based parameters, namely Degree of Domain Violation (DDV) and Time to Domain Violation (TDV), introduced by the authors in [18]. COLREGs rules are considered there in a simplified manner by using an off-centered elliptical domain, which favors passing astern of a target. The paper does not use CRI and offers a general CAS framework for further development.

A summary of above literature research on CAS systems is given in Table 3. It reveals that, apart from [62], there is no CAS approach that would fully support ship domains. Moreover, surrounding traffic is not considered, even though it limits maneuvering space of a ship. When comparing Table 3 with Table 1 on CRI research, we can conclude that it is reasonable to propose a new solution expanding on if-then rules approach as proposed in RICAS in [36] and combined with domain-based approach proposed in [62].

Table 3. A summary of research on Collision Alert Systems (CAS), M1: Simsir U. et al, 2014 [61], M2: Baldauf M. et al, 2011 [59], M3: Bukhari AC et al., 2013 [60], M4: Goerlandt F. et al., 2015 [36], M5: Szlapczynski R. et al, 2017 [62], M6: Du L. et al., 2020 [4]

	Alert levels	**COLREGs compliance**	**Ship domain-based collision risk parameters**	**Surrounding traffic**
M1	2 levels: Safe, Risk exists	-	-	-
M2	4 levels: Safe, Caution, Warning Alarm	+ (checking basic obligations according to COLREGs)	-	-
M3		-	-	-
M4		+ (selected rules)	+/- (domain dimensions)	-
M5		+ /- (simplified, by off-centred elliptical ship domain)	+ (off-centred elliptic domain, DDV and TDV risk measures)	+ / - (multiple ship encounters are handled, but no other surrounding ships considered)
M6		+ (selected rules, from the stand-on ship perspective only)	+/- (domain dimensions)	+/- (via analyses of pair-wise collision situations, but no other surrounding ships considered)

1.2 MOTIVATION

The motivation behind the current paper is twofold. First, for many water regions of intense traffic ship domains and their sizes have been determined empirically based on the available AIS and radar data. Therefore, it is reasonable to make use of the region-specific information encapsulated in the ship domain dimensions when addressing the issue of ship collision risk. Although not all water regions have ship domains dedicated specifically for them, it must be noted that ship domains determined for various regions show similarities in terms of their shapes. As for their sizes, they are mostly dependent on the density of traffic in a given region.

Therefore a system operator can use an existing ship domain and adjust its size to the local conditions if needed. Applying ship domain for collision risk assessment can be done by replacing some commonly used parameters with ship domain-based ones, which can be determined analytically so as not to slow down computations [18].

As for the second motivation, it can be noticed that the problems of near-miss detection and collision avoidance are strongly related and the methods used for both of them utilize similar data. This observation has also been made in [4]. At the same time, most of state-of-the-art research in both areas can be attributed similar limitations. Namely, they focus on basic ship-to-ship encounter parameters while neglecting surrounding traffic and other context-related information – e.g. manoeuvres made relatively late. This is a serious drawback, because (as observed in [42]) the above mentioned factors also affect overall collision risk and thus should be taken into account. Therefore the current paper's aim is to provide a general ship collision risk model, which would make use of context-specific information, including a ship domain (customizable for a given water region) as well as quantified knowledge on the behaviour of ships engaged in an encounter situation and local traffic surrounding those ships. Such a model could be applied to a number of marine safety-related problems, including already listed near-miss detection as well as CAS and DSS systems alike. The first step towards this was made in [49], where a near-miss detection method applied ship domain and a Mamdani neuro-fuzzy classifier. Then preliminary framework for a domain-based Collision Alert System was proposed in [62]. The current paper expands on that, introducing a much larger set of collision risk parameters and a more general model with possible wider application. As for collision risk parameters, the current paper uses Degree of Domain Violation (DDV) and Time to Domain Violation (TDV) introduced in [18] as well as new ones – Time to Domain Exit (TDE) and arena-related parameters. Other extensions of [18], [49] and [62] include a ship domain-based analysis of encounter development as well as taking into account traffic complexity and late manoeuvres of a vessel. As a result, in CAS / DSS case the model widens the perspective of the own vessel's, so that her OOW's decisions are also informed by the other vessel's view. And in near-miss detection case the model serves as an overview of an encounter which focuses on the two vessels directly involved in an encounter but also considers other vessels in the vicinity. The rest of the work is organized as follows. The proposed model is presented in Section 2, which includes a decomposition of a ship encounter as well as quantification and aggregation of risk factors. This is followed by a description of simulations, the results and a discussion given in Section 3. Finally, the conclusions are gathered in Section 4.

2. COLLISION RISK MODEL FOR MULTI-SHIP ENCOUNTERS

Deciding whether a situation can be classified as a near-miss (or as requiring an action in CAS / DSS system) depends on multiple factors. In this section those factors are described and transformed to numerical variables, which allows to quantify the degree in which given situation falls under near-miss or requiring an action. This involves clarifying some necessary encounter-related terms first.

2.1 DESCRIBING ENCOUNTER SITUATION

Since the proposed approach is based on the concept of ship domain, which has multiple definitions in literature [6], [9], [8] this term is explained first. Its definition in the current paper is based on the ones provided in the works listed above.

Ship domain is defined here as *the area around the ship, which the navigator would like to keep clear of other ships and objects*. It is worth noticing that this involves the navigator's subjective sense of safety and comfort. Therefore, it is not identical with the area, whose violating can be automatically interpreted as a collision or a near-miss.

A concept directly related to *ship domain* is already mentioned *ship arena*. In the current paper a *ship arena* is defined as *an area around the central ship, whose entering by another* *ship should be followed by monitoring the other vessel's relative position and motion parameters for the purpose of a potential evasive manoeuvre*.

Yet another term useful for the proposed model is that of a *close quarters situation.* A *close quarters situation* is defined here as *violation of a ship domain*. Due to the definition of the ship domain given above, quite large domains are applied throughout this research. As a result, domain violation is a wider category than a near-miss, which is here understood as especially dangerous case of a close quarters situation / domain violation. Consequently, throughout the paper we assume that minor domain violations can be occasionally tolerated, as long as they are not accompanied by other factors contributing to the rise in collision probability.

Near-miss is consequently defined as a close quarters situation (domain violation) combined with one or more of the following circumstances contributing to the rise in collision risk.

1) Large relative speed: the larger the relative speed the shorter the time for a reaction and evasive manoeuvre.
2) Ships' courses close to perpendicular: as long as courses of two vessels are nearly parallel, even small distances can be interpreted as relatively safe. However, if courses are closer to perpendicular than to parallel, collision is harder to avoid, because it takes an earlier and more substantial manoeuvre.
3) Manoeuvre performed in proximity of another vessel: late manoeuvres are always a source of confusion and thus can contribute to collision risk. A *late manoeuvre* is here defined as *a course or speed alteration manoeuvre performed within another vessel's arena*.
4) Encounter's complexity (multi-ship encounter): any close quarters situation is more dangerous if one of the two vessels is in proximity of a third vessel, which limits her room for manoeuvres resulting in harder decision-making.

As for the first of the above listed factors, making the collision risk dependent on the relative speed may rise some doubts. Arguably, relative speeds are usually largest in case of head-on encounters, where the collision risk is generally smaller than in case of a crossing because a minor course alteration done by either ship is usually enough to avoid domain violation [22]. However, ships' courses are accounted for by the second variable, so relative speed is supposed to reflect solely the decision time diminishing linearly with a rise in this speed. Similar doubts may be associated with late manoeuvres. It must be emphasised here that this factor is taken into account independently of ship domain violation: its purpose is to favour early manoeuvres over late ones. However, if a manoeuvre has not been performed early, performing it later is still necessary in order to avoid domain violation. As for the last factor, the importance of traffic complexity and associated traffic conflicts has been documented in [63]. Following this, it has been observed in [42] and [64] that encounter complexity seriously affects development of near-misses and thus also collision risk. The above works clearly indicate that it is reasonable to include this factor in the current model.

Literature on this subject includes more parameters, which can be taken into account. Among others, it has been evidenced that strong wind conditions can significantly increase collision likelihood, especially in port areas [65]. Similarly, collision risk is heavily affected by COLREGS compliance (where particular rules that should be applied depend on visibility conditions). Unfortunately, not all parameters (especially weather-related ones) can be easily quantified or obtained from the AIS data. Therefore, those listed above have been chosen as the essential. The following subsections describe how they are transformed to numerical variables so as to quantify their contribution to a near-miss. First some ship domain-based encounter parameters are introduced in Section 2.2 and then, based on this, algorithms and formulas for quantifying collision risk are provided in Section 2.3.

2.2 PARAMETERS USED TO DECOMPOSE AN ENCOUNTER

Ship domain-based collision risk parameters and encounter parameters have been discussed in detail in [18]. Formulas for determining those parameters have been derived there step by step. A brief summary and extension of this work is presented below, as it will be applied in the current research.

For an encounter of two ships the approach factor f_{min} is defined as the scale factor by which the central ship's domain has to be multiplied so that the other ship passed on the boundary of the f_{min}-scaled central ship's domain (assuming unchanged courses and speeds of both ships). $f_{min} \geq 1$ represents here safe passages and $f_{min} < 1$ indicates domain violations. Following this, for a given f_{min}, the degree of domain violation (DDV) has been be defined as:

$$DDV = \max(1 - f_{min}, 0) \quad (1)$$

An example illustrating parameters introduced above is given in Figure 1, where an elliptic domain is applied.

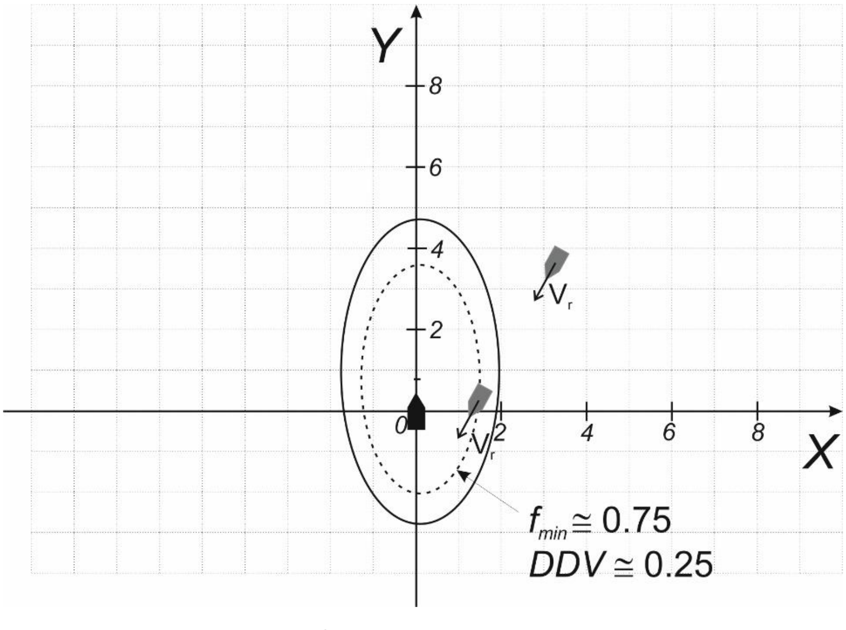

Fig. 1 A predicted violation of a vessel's domain presented in the other vessel's relative coordinate system (V_T – true speed, V_r – relative speed)

DDV is a convenient alternative for DCPA when ship domains are applied. Among others, it supports COLREGS (albeit in a limited way), by using domain dimensions, which favour passing astern of a target. Furthermore, it can be determined analytically for any ellipse-shaped domain, including off-centred ones. It is also possible to determine analytically the time remaining to reaching DDV value – it is denoted here as: time to DDV – t_{DDV}. Likewise, we can determine the time remaining to the moment when one ship will cross the other ship's domain boundary – Time of Domain Violation (TDV).

Similarly to TDV, a related parameter of Time of Domain Exit (TDE) is now introduced in the current paper. Both parameters are determined based on the fact that at both TDV and TDE a target vessel is on the boundary of the central vessel's domain. The detailed formula for TDV is given in Appendix A of [18]. TDV is by definition the smaller of the two roots of the second degree polynomial equation given there. Likewise, TDE will always be the larger of the two roots of the same equation. A target vessel violates the central vessel's domain at TDV, transits it and finally leaves it at TDE, which is summarised by Figure 2.

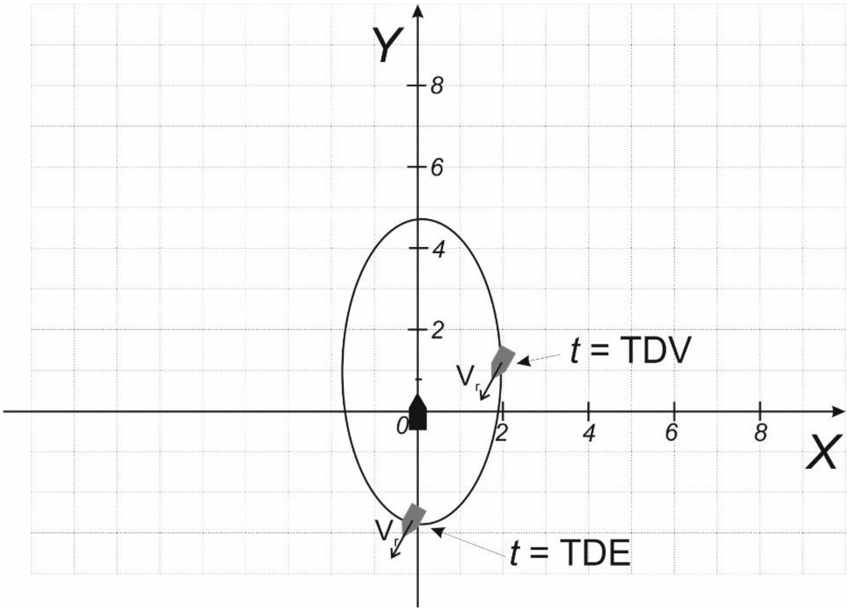

Fig. 2. Illustration of times related to domain violation: TDV and TDE

Based on Figure 2, for unchanging speeds and courses of two vessels a close quarters encounter can be decomposed into three phases:

- pre domain violation,
- during domain violation,
- post domain exit.

The timespan of the close quarters situation covering above three phases is given by

$$timespan_{close\_quarters} = \langle TDV, TDE \rangle, \qquad (2)$$

where:

TDV – time of domain violation, discussed in detail in [18],

TDE – time of domain exit, computed analogically to *TDV*.

While a ship domain is commonly used as a collision risk or safety criterion, it is not always sufficient and does not fulfil all needs. Namely, an additional threshold criterion is needed for monitoring targets in the vicinity of a central ship. Hence, a ship arena (defined in Section 2.1) is additionally applied for this purpose. As mentioned in Section 1.1.1, in recent works arena sizes and shapes are determined based on the ship's manoeuvring abilities. This can be of great use in CAS / DSS systems, where an arena should be considerably larger than an action area, whose intruding should trigger a manoeuvre of OS. Such an action area, determined in [22] is used as a ship's arena in the CAS / DSS version of the proposed model. Unfortunately, in case of AIS data-based near-miss detection there is no access to manoeuvrability parameters of all vessels. Furthermore, these parameters are strongly dependant on the ship's construction, engine type, rudder type etc., so they cannot be easily deduced or approximated based on the vessel dimensions. Therefore, specifically for near-miss detection some kind of a generic arena, independent of the vessel's manoeuvring abilities has to be used here instead. The authors propose to use an enlarged domain-shaped area, whose size, when compared to the original domain is parameterised by a scale factor s_f. An s_f –scaled domain-shaped ship arena and its relation to the original domain is shown in Figure 3. The arena is used for a new decomposition of extended encounter phases, namely into:

- pre arena violation,
- during arena violation but pre domain violation,
- during domain violation,
- post domain exit but pre arena exit,
- post arena exit.

The above phases have been illustrated in Figure 3, where scale factor s_f equal to 3 has been used.

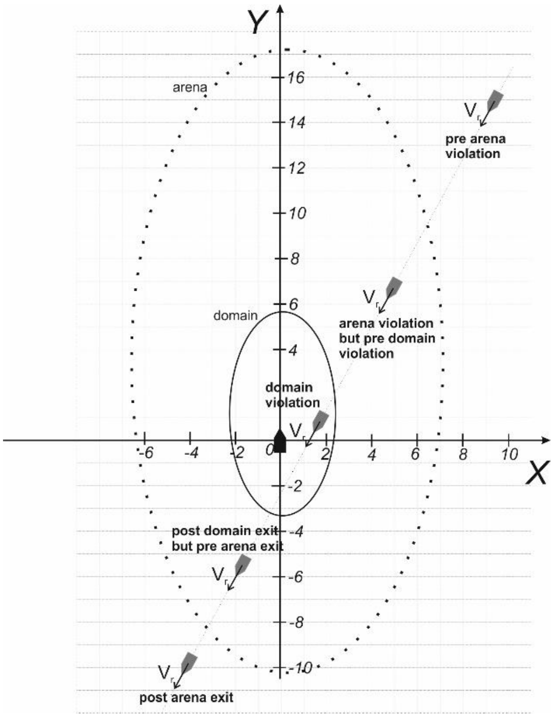

Fig. 3. Five different phases of arena (sf-scaled domain) and domain violation (sf = 3)

For determining encounter complexity and detecting late manoeuvres a searching time interval has to be selected first. The authors propose to narrow this time interval to the second, third and fourth phase of a close quarters encounter:

- during arena violation but pre domain violation,
- during domain violation (if such violation occurs),
- post domain exit but pre arena exit.

Arguably, manoeuvres directly preceding domain violation are of interest here, hence the interval cannot be narrowed to the domain violation phase. However, manoeuvres performed after the arena has been exited are of little meaning here, even if the target is still within sights or radar range of the central ship. Once the arena is clear of a target and the target is steering away from the central ship, it does not seriously affect the central ship’s situation. Similarly, the process of determining encounter complexity can be narrowed to the same time interval: if the target ceases to affect the central ship, then the encounter complexity associated with meeting this target is no longer relevant.

Concluding, the searching time interval covering the above mentioned three phases of the close quarters encounter can be presented as:

$$timespan_{searching} = \langle TDV_{s_f}, TDE_{s_f} \rangle. \qquad (3)$$

TDV_{s_f} is here the time of violating an s_f –scaled domain-shaped ship arena and TDE_{s_f} is the time of leaving this arena. Both times can be determined and are equal to (4) and (5):

$$TDV_{s_f} = s_f(TDV - t_{DDV}) + t_{DDV}, \qquad (4)$$

$$TDE_{s_f} = s_f(TDE - t_{DDV}) + t_{DDV}, \qquad (5)$$

where:

t_{DDV} – the time of reaching maximal domain violation, when *DDV* will be measured. (It can be shown that t_{DDV} of the s_f –scaled domain-shaped ship arena is always equal to the t_{DDV} of the original ship domain.)

The above timespan for detecting late manoeuvres and for determining encounter proximity is illustrated in Figure 4.

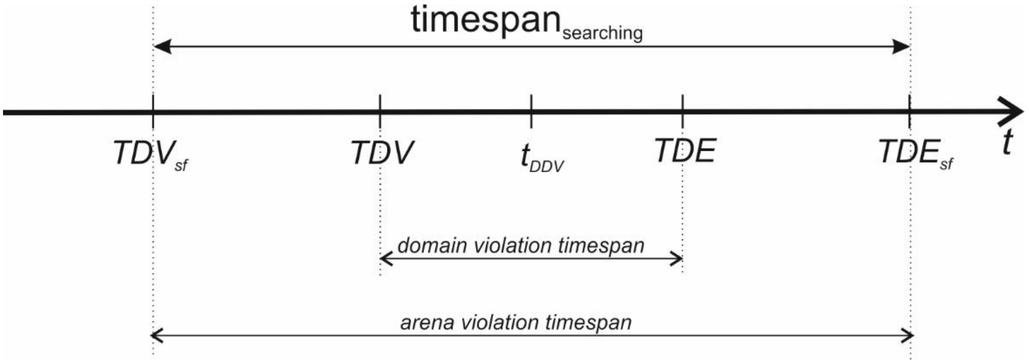

Fig. 4. Illustration of symbols: TDV_{s_f}, TDV, t_{DDV} and TDE_{s_f}

After substituting (4) and (5) for TDV_{sf} and TDE_{s_f} in (3) we get:

$$timespan_{searching} = \langle s_f(TDV - t_{DDV}) + t_{DDV}\ ,\ s_f(TDE - t_{DDV}) + t_{DDV} \rangle, \qquad (6)$$

2.3 PROPOSED VARIABLES USED TO QUANTIFY COLLISION RISK

Based on the encounter description provided in section 2.1, five decision variables are proposed and briefly described below. Those variables are: Degree of Domain Violation (DDV), Relative Speed (RS), Combination of the Vessels' Courses (VC) and Arena Violations (AV). All variables are cost-type that is their minimal values are desired and their maximal values should be avoided as far as possible. The aggregation of those variables into new ones and finally – into CRI is shown below in Figure 5.

Cascade aggregation of the abovementioned variables involved expert elicitation. Following the procedure presented in [36], originating in description provided in [66], here the procedure consists of six steps, including defining knowledge domain, identification of candidate-experts, determining experts selection criteria, final selection of the experts, selecting proper elicitation method and finally knowledge elicitation via written questionnaires or oral interviews.

In this case the domain of knowledge is ship navigation with special attention to collision avoidance issues. Thus, possible candidate external experts would be active/retired navigators or instructors from appropriate training institutions with sufficiently long professional experience. Based on candidates' professional experience and their availability, a group of three external experts has been selected including two active officers and one retired. The authors, have also provided their input to the expert pool, based on literature analysis. Point estimation [66] method of elicitation has been applied during information gathering process via oral interviews. Thus final results of the variables' aggregation have been obtained by averaging responses over the entire pool of votes (rounded up towards the nearest available value, with the authors making final decision concerning rounding up).

Normalization of all variables, detailed decision rules and cascade aggregation process are presented and discussed in the following subsections.

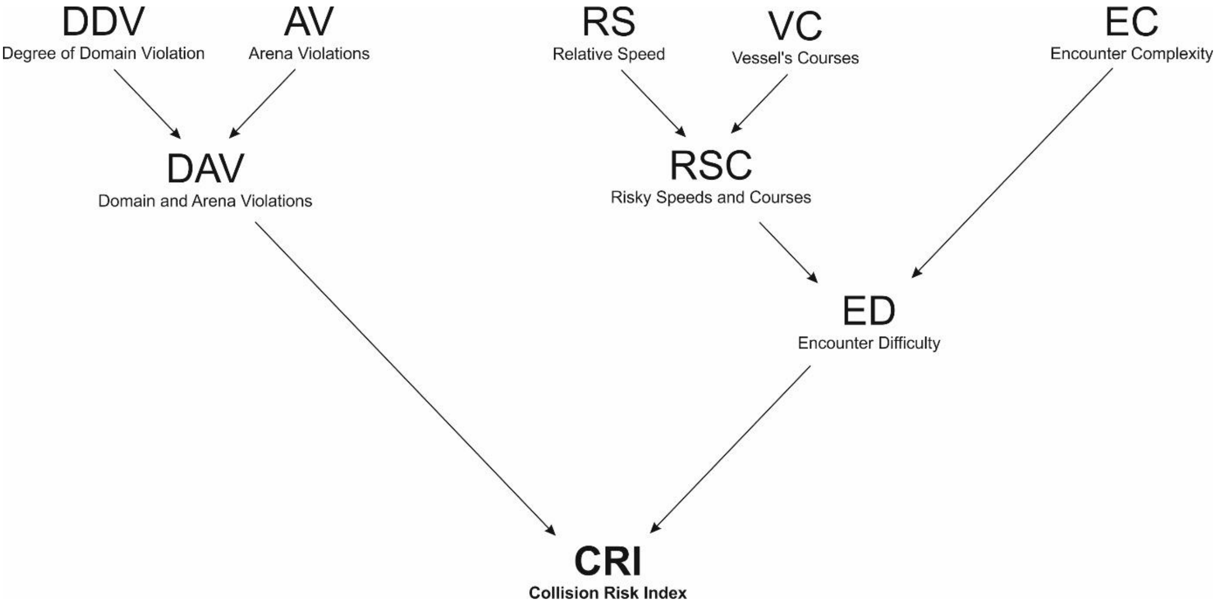

Fig. 5. Cascade aggregation of decision rules

2.3.1 Degree of Domain Violation (DDV)

Domain violation is measured here by means of a degree of domain violation (*DDV* – Section 2.2), which has been introduced in [18], where it is explained in detail how this parameter's value is computed. *DDV* factor is always within <0,1> range, where 0 means no violation and 1 – a physical contact of two vessels. *DDV* is the primary variable taken into account for near-miss detection and collision risk assessment.

It must be noted here, that in case of near-miss detection, DDV mean the actual degree of domain violation, which was registered. However, for CAS / DSS applications DDV is a predicted value, based on the assumption that both vessels engaged in an encounter keep their courses and speeds unchanged. Also, to make sure that the method is consistent for CAS and DSS, the applied DDV value is always the minimum of DDV computed for both ships involved in an encounter: $DDV = \min(DDV_{i,j}, DDV_{j,i})$, where i and j are indexes of both ships.

2.3.2 Relative Speed (RS)

In case of near-miss detection relative speed is compared with the maximum relative speed for an encounter of two vessels that has occurred within analysed amount of AIS data. It is then condensed down to the relative speed factor from <0, 1> range as given by the following formula:

$$relative\_speed = \frac{relative\_speed_i}{\max_i relative\_speed_i}. \qquad (7)$$

In case of CAS / DSS system, maximal relative speed is set in the system, based on ship speeds in a given water region. By default it is set to 30 knots.

2.3.3 Combination of the Vessels' Courses (VC)

This factor is also from <0, 1> range and it is equal to 0 for parallel courses (either head-on or overtaking) and equal to 1 for perpendicular ones (crossing only). It is computed as follows:

$$\varphi = |\varphi_1 - \varphi_2|\,, \qquad (8)$$

$$vessels\_courses = \frac{min\big(min(\varphi, 360° - \varphi), 180° - min(\varphi, 360° - \varphi)\big)}{90°}, \qquad (9)$$

where:

φ_1, φ_2 – true courses of the two vessels.

Computing the variable's value is exemplified in Figure 6.

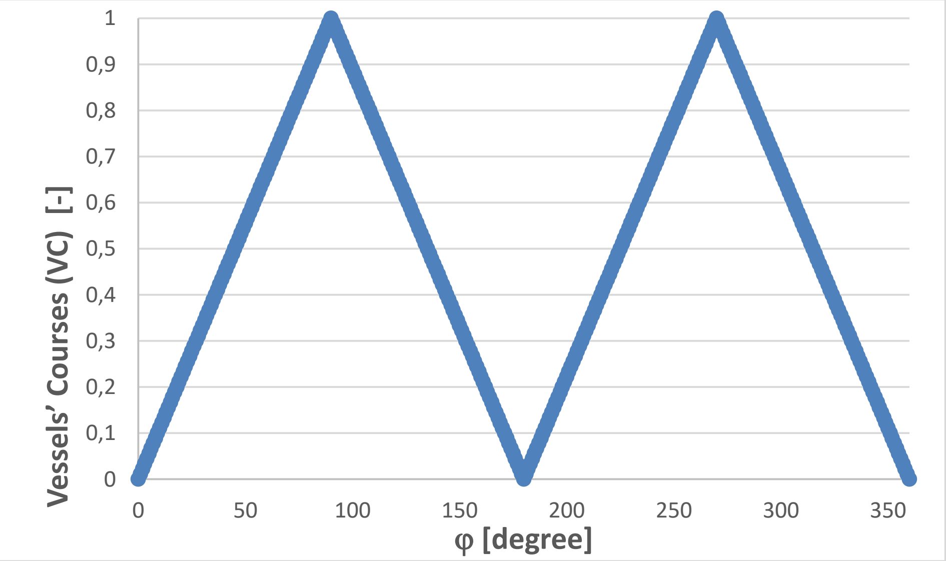

Fig. 6. Illustration of course variable values in function of course difference φ

The impact of the vessels' relative courses on collision risk has been researched, among others in [67]. It has been found there that the encounter is more difficult to avoid when the relative course is 120-140 degrees. However this has been done for true velocities of both vessels. For fixed true velocities, relative courses closer to 180 degrees will result in a larger relative speed and smaller relative courses - in a smaller relative speed. In the current paper two independent decision variables are considered: relative course and relative speed, thus relative speed variable is not affected by relative course. Consequently, a smaller relative course than 120-140 deg. is more dangerous in this case. Based on the research done in [22], depending on the maximum allowed course alteration, rudder angle and speed reduction various relative courses are most demanding in terms of necessary action distance. However, on the average those relative courses were about 90 degrees, so this value has been selected as the maximum of VC variable.

2.3.4 Arena Violations (AV)

Arena Violations is a meta-variable, which, depending on the context (near-miss detection or CAS / DSS) represents one of two variables reflecting the risk resulting from a lack of an early manoeuvre:

- $late\_manoeuvre\_variable$ (for near-miss detection method), which quantifies the impact of manoeuvres done within the other vessel's arena,
- $arena\_intrusions\_variable$ (for CAS / DSS), which quantifies the impact of TS approaching OS.

AV is a single variable, which is computed differently for the above two cases because the differences in the above two purposes translate to largely different formulas. In case of near-miss detection, it is known whether and when exactly a manoeuvre was performed. In case of CAS / DSS it is only possible to state how close two vessels approached each other until the current moment. However, both variables perform a similar role in an overall assessment of aggregated risk elements (they reflect risk due to a lack of an early manoeuvre) and therefore are gathered here.

When quantifying late manoeuvre of a vessel, only one aspect is of interest: the time when such a manoeuvre is performed. As for the consequences of a manoeuvre's (or lack of it), they are handled by the resulting value of DDV – a separate variable described in section 2.3.1. It is assumed here that any manoeuvre performed within a vessel's arena is a late one, may be a source of confusion for the central vessel and should be accounted for. Quantifying of such late manoeuvre is presented below.

For the timespan given by formula (6) it is checked, whether one of the vessels engaged in the encounter situation performed a manoeuvre, when already within another vessel's arena. Depending on the exact time when the manoeuvre was performed, this factor is assigned a value from the <0, 1> range, where 0 means that the discussed event has not occurred and 1 – that an action has been taken when the vessels were close to each other. It is assumed here that the variable's value grows linearly from 0 (if the manoeuvre was performed at TDV_{sf}) to 1 (if the manoeuvre was performed at t_{DDV} and was larger or equal to 90 degrees). Similarly it is assumed that the variable's value falls linearly to 0 (if the manoeuvre was performed at TDE_{sf}). This dependency is illustrated in Figure 7.

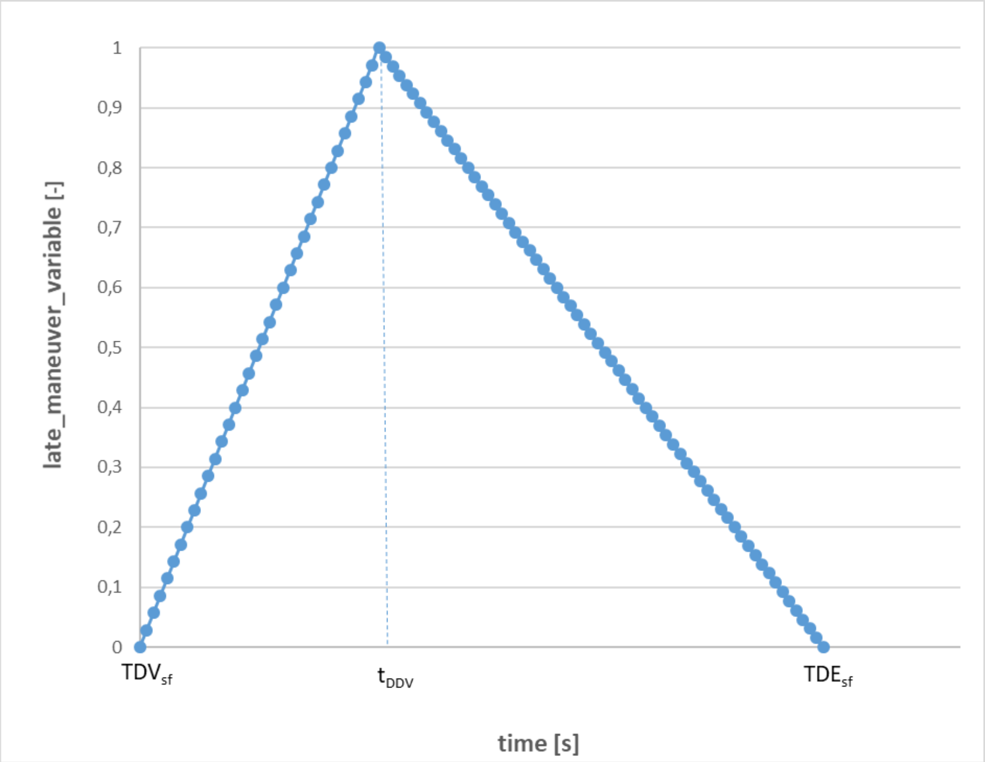

Fig. 7. Illustration of a late maneuver variable values in function of time

Taking into account the above, the final formulas for determining this variable's value are as follows.

For $TDV_{s_f} \leq t_{LM} \leq t_{DDV}$:

$$late\_manoeuvre\_variable = \frac{t_{LM}-TDV_{s_f}}{t_{DDV}-TDV_{s_f}}, \qquad (10)$$

where t_{LM} – the time of a late manoeuvre.

It can be noticed that, as expected, the second factor of (10) is equal to 0 for t_{LM} = TDV_{sf} (manoeuvre performed at the moment when the s_f –scaled domain-shaped arena is being entered) and to 1 for $t_{LM} = t_{DDV}$ (manoeuvre performed when maximal domain violation is being reached).

After substituting (4) and (5) for TDV_{sf} and TDE_{sf} in (10), we get the following formulas.

For $TDV_{s_f} \leq t_{LM} \leq t_{DDV}$:

$$late\_manoeuvre\_variable = \frac{t_{LM}+s_f(t_{DDV}-TDV)-t_{DDV}}{s_f(t_{DDV}-TDV)} \qquad (11)$$

As for the complementary case of $t_{DDV} < t_{LM} \leq TDE_{s_f}$, similarly we get:

$$late\_manoeuvre\_variable = \frac{TDE_{s_f} - t_{LM}}{TDE_{s_f} - t_{DDV}} \qquad (12)$$

It can be noticed that, as expected, the second factor of (12) is equal to 1 for t_{LM}= t_{DDV} (manoeuvre performed at maximal domain violation) and to 0 for t_{LM}= TDE_{s_f} (manoeuvre performed when the arena is exited).

The variable as a whole can be equal to 0 if there were no manoeuvres during the specified time interval. As for variable's maximal values, the value of 1 can occur if and only if a vessel's course is changed at the moment of maximal approach (t_{DDV}). It must be noted here that an encounter with a late manoeuvre will usually be still assessed as safer than the same encounter without an evasive action at all. This is due to the fact that in the former case DDV variable will be much larger (worse) than in the latter, which will affect the final CRI value.

As opposed to near-miss detection, where we have access to a full history of an event (including actual DDV value), in CAS / DSS systems only the up-till-this-moment data are available (including predicted DDV). On the other hand, in CAS / DSS systems we are looking on the encounter from the OS perspective, which allows us to replace a vessel's generic arena with a more appropriate are determined based on the OS manoeuvrability. Taking it all into account, the authors have decided to apply the variable described above for near-miss detection only and handle the remaining time and distance issue in a different way for CAS / DSS case. Namely the following formula (13) is used for quantifying the impact of TS approaching OS:

$$arena\_intrusion\_variable \ = min\left(\frac{d_a}{d}, 1\right), \qquad (13)$$

where:

d – the current distance between OS and TS, which are engaged in an encounter,

d_a – action distance, at which a manoeuvre has to be executed in order to avoid domain violation [22].

The quotient $\frac{d_a}{d}$ represents the time-dependent necessity of a manoeuvre based on the action distance determined in [22]. This necessity increases with the diminishing distance *d* between two ships and becomes equal to 1 for $d = d_a$. The *min()* function is additionally used to make sure that the value of 1 is not exceeded for $d < d_a$ (in practice an evasive action should be taken before *d* becomes equal d_a).

2.3.5 Encounter Complexity (EC)

The encounter complexity variable is determined the same way for near-miss detection and CAS/DSS alike. The only difference lies in interpretation: *DDV* values, which are used for computations are actual values in case of near-miss detection and predicted ones in case of CAS/DSS. Other than that, the procedure is the same for both cases. For each of two vessels engaged in a close quarters situation, it is checked whether there are any other vessels in their proximity. Then for each of the two engaged vessels approach factors related to other vessels are computed for the timespan of $\langle TDV_{s_f}, TDE_{s_f} \rangle$ and, based on that, the complexity factor is determined for the encounter. The complexity factor is from the <0, 1> range. Complexity factor equal to 0 means that neither of the two vessels should be limited in her potential evasive manoeuvres by other vessels in proximity. Complexity factor equal to 1 means that at least one of the two vessels may have seriously limited possibilities of performing a collision avoidance manoeuvre due to the presence or potential manoeuvres of other vessels. Complexity variable is computed according to the following formula (14).

$$encounter\_complexity = \min\left(\sum_i DDV_{sf,i,1} + \sum_i DDV_{sf,i,2}, 1\right), \qquad (14)$$

where:

DDV_{sf} – degree of arena violation, where the arena is a vessel’s domain multiplied by a scale factor *sf*,

$DDV_{sf,i,1}$ – degree of arena violation, for the first of the two vessels engaged in an encounter and the i-th of the surrounding vessels,

$DDV_{sf,i,2}$ – degree of arena violation for the second of the two vessels engaged in an encounter and the i-th of the surrounding vessels.

A sum of the two added elements in (14) can exceed 1, if one or both of the engaged vessels are in close quarters situation with one or more surrounding vessels. Therefore a *min()* function is used in (14) to make sure that the variable's value does not exceed 1.

2.4 AGGREGATED QUANTIFICATION OF COLLISION RISK

A common approach in case of both near-miss detection and CAS / DSS is formulating decision rules. Such rules can either be generated by a software tool based on previously obtained data set (e.g. by means of expert elicitation) or may be directly proposed by experts. In the case of proposed method, rules have been consulted with experts and formulated directly – without using software. To limit the overall number of rules a cascade aggregation method has been used, where output of one aggregation stage is the input for the next one. The aggregation structure has already been shown in Figure 5. As can be seen there, the order of aggregation is as follows. First, DDV variable and Arena Violations (AV) meta-variable are aggregated into Domain and Arena Violations (DAV). Simultaneously, Relative Speed (RS) variable and Vessel's Courses (VC) variables are aggregated into Risky Speeds and Courses (RSC) variable. Following this, in the second stage, Encounter Complexity (EC) variable and newly obtained RSC variable are aggregated into Encounter Difficulty (ED) variable. Finally, in the third stage, the previously obtained DAV and ED variables are aggregated into Collision Risk Index (CRI). Owing to this structure, the overall rules number is reduced from 405 (one five-level variable and four three-level variables would produce 5 x 3^4 rules) to just 65 rules. An additional rule is that if DDV = 0 then "No" value is returned for near-miss detection and "Safe" value is returned as a CAS / DSS risk level, other decision variables notwithstanding.

Mapping of decision variable values to linguistic values is gathered in Table A.1, where Small, Medium and Large linguistic values are denoted by S, M and L respectively. Additional mid-levels of Small-Medium (SM) and Medium-Large (ML) are taken into account for DDV, which is the primary decision variable. The values presented in Table A.1 as well as the following aggregations in Tables A.2 to A.5 are constant and used throughout the simulations in Section 3. The first of aggregation actions is presented in Table A.2, where DDV and AV variables are aggregated into DAV. Five levels of resulting DAV variable are assumed, including SM and ML. It has also been decided that DDV is of larger importance than AV and that the resulting variable will be rounded up. Similarly, also during the first stage, RS and VC variables are aggregated into RSC (Table A.3). A similar importance of both input variables is assumed. Following this, in the second stage, RSC and EC variables are aggregated into ED, as shown in Table A.4. Again, five levels of output variable are assumed. Since RSC is an aggregated variable representing both RS and VC, it is assumed that its importance is larger than that of EC. Consequently, the resulting ED values are rounded towards RSC.

Finally, in the third stage, the outputs of first stage (DAV) and second stage (ED) are aggregated into CRI, which is given in Table A.5. A larger importance of DAV variable is assumed, since this variable encapsulates the crucial encounter-related parameters: DDV representing the actual largest approach (in case of near-miss) or largest predicted approach (in case of CAS/DSS) and AV representing a vessels presence and behaviour within the other vessel's arena. Therefore, the resulting CRI values are usually rounded towards DAV values.

Once the aggregation is complete, the linguistic values of CRI are assigned near-miss detection decisions and CAS/DSS risk levels and alerts. This is gathered in Table 4.

Table 4. Final mapping of CRI values to near-miss decisions and CAS risk levels and alerts.

CRI linguistic value	**Near-miss**	**CAS risk level / alert type**

None (DDV=0)	No	Safe
S	No	Caution
SM	No	Warning
M	Yes	Warning
ML	Yes	Alarm
L	Yes	Alarm

As can be seen, in case of CAS, DDV > 0 will always result in some kind of alert, though its type will depend on the exact DDV value as well as other four variables. An encounter is classified as a near-miss for Medium or higher CRI, however an alarm for CAS is generated if CRI rises to at least Medium-Large value.

All of the variables aggregated in this section are symmetric concerning two vessels involved in an encounter – the same variable values are used for computing CRI of both vessels. In particular: DDV is a minimum of DDVs obtained for each of two vessels, the same rule is applied for AV, RS and VC variables are symmetrical by nature and so is EC, as can be seen in (14).

3. SIMULATION RESULTS

In this section results of simulations carried out for three scenarios are presented. The objectives of those simulations are to verify the model's suitability in overtaking, head-on and crossing encounters and to compare the results with those obtained by RICAS method. Therefore all three scenarios used here have been taken from the work on RICAS [36].The last scenario from [36] is not used here as it was not possible to replicate it in the developed simulation software due to a large number of course alterations. For each scenario, only the first two phases of each manoeuvre are analysed: before and after collision-avoidance course alteration, because the subsequent phases (when all ships' courses are safe) are not essential from collision-avoidance and collision risk assessment point of view. Following the comparison with RICAS for basic scenarios from [36], extended scenarios (featuring additional surrounding traffic) are discussed so as to show the impact of encounter complexity (EC) variable on the final CRI values. The surrounding ships, which are added to basic scenarios are denoted with an '*' symbol next to a ship number.

The same set of input data has been used for both near-miss classification and collision risk assessment for CAS/DSS purposes in Scenarios 1 to 3. The main differences for those two cases are:

- the first of the vessels listed in the tables is assumed to be OS in case of CAS/DSS,
- determining the values of AV variable differs for near-miss classification and CAS/DSS,
- a situation is classified as near-miss for CRI ≥ Medium, however an alarm for CAS is generated for CRI ≥ Medium-Large.

For all scenarios an elliptic, off-centred domain of a ship is assumed, whose dimensions are as follows:

$a=5L$ – semi-major axis,
$b=2L$ – semi-minor axis,
$\Delta a=1.25L$ – a ship's displacement from the ellipse's centre towards aft along the semi-major axis,
$\Delta b=0.5L$ – a ship's displacement from the ellipse's centre towards port along the semi-minor axis,
L – ship's length.

The domain's shape and dimensions are roughly based on Coldwell [9] and updated according to newer empirical works based on AIS data, e.g. Hansen et. al. [10]. In [10] it was stated that the domain proposed there was the smallest possible and in many cases navigators would opt for something larger, hence the updated dimensions.

In general, using an off-centred ellipse makes it possible to apply multiple classic domains: Fuji [6], Davis [8] [20], Goodwin [7] and Coldwell [9] as well as some newer ones e.g. already mentioned one by Hansen et. al. [10]. An off-centered ellipse may also approximate with reasonable accuracy some polygonal domains [11]. Furthermore, all of those domains can be handled analytically, which does not affect computational complexity of the method.

As for ship's arena, the action distances determined in [22] are used in the CAS / DSS case and simplified domain-shaped enlarged area is used in the near-miss detection case, where ships' manoeuvrability is not known.

In all three scenarios a collision is avoided by a wide margin: evasive manoeuvres are performed in advance and predicted domain violations never actually occur. As a result, none of the situations would be classified as a near-miss and neither of them is interesting in terms of near-miss detection. Therefore altered scenarios are considered for near-miss analysis, namely it is assumed that all ships keep their courses: evasive manoeuvres are not performed and predicted domain violations are fully realized. Based on this, it is shown whether a given situation would or would not be ruled as a near-miss (bottom rows of Tables: 7-8, 11-12 and 15-16).

Scenarios 1 to 3 (Sections 3.1 to 3.3) are followed by a comparison of results obtained by RICAS and the proposed method (Section 3.4). Finally, since Scenarios 1 to 3 have been designed by RICAS authors with CAS comparison in mind, we have added one more scenario dedicated to near-miss situations solely (Section 3.5). Its purpose is to illustrate the impact of the time when an evasive action is taken on the final near-miss classification. It follows the comparison summary so as not to interfere with the narration of the CAS-dedicated scenarios and paper sections.

3.1 SCENARIO 1: OVERTAKING ENCOUNTER

Starting positions, speeds and Courses Over Ground (COG) are given in Table 5. They are additionally visualised in Figure 8 (basic scenario) and Figure 9 (scenario extended by two additional targets). In Figure 8 ship 2 approaches ship 1 from astern, with a small DCPA value. In Figure 9 two more ships (no. 3 and 4) are ahead of the beam of ship 1, which increases the encounter's complexity.

Table 5. Scenario 1, phase 1: ship 2 approaches ship 1 from astern, with a small DCPA value (time: 1–271 s). Additional ships for the extended scenario are marked with '*' symbols.

	Start X [NM]	Start Y [NM]	V [kn.]	COG [deg.]	L [m]
Ship 1	0.00	0.00	12.00	90.00	219
Ship 2	-1.00	-0.05	18.00	90.00	150

Ship 3*	3.00	0.90	10.00	90.00	200
Ship 4*	2.00	-0.90	9.00	90.00	250

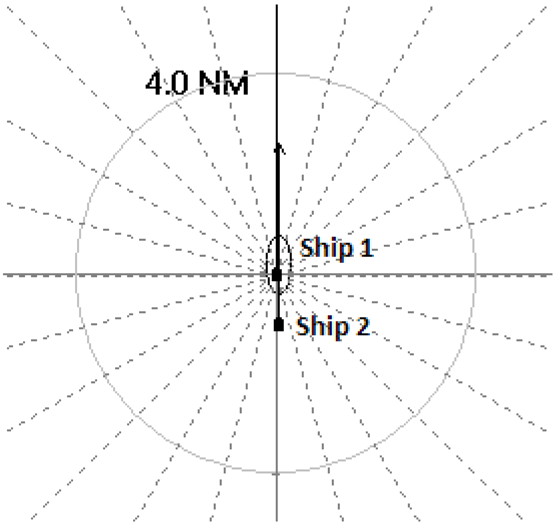

Figure 8. Scenario 1-basic, phase 1: ship 2 approaches ship 1 from astern, with a small DCPA value.

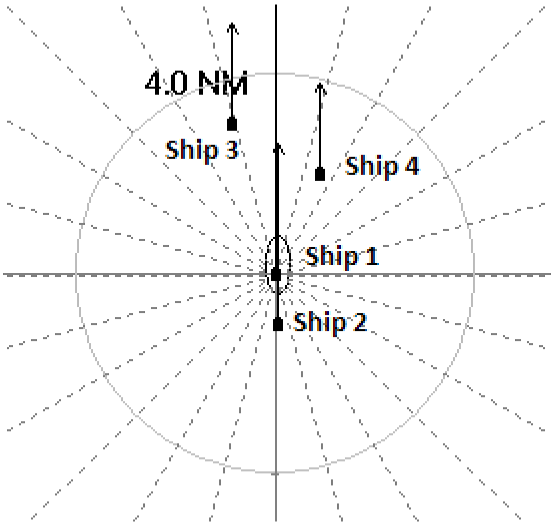

Figure 9. Scenario 1-extended, phase 1: ship 2 approaches ship 1 from astern, with a small DCPA value. Additional two ships are ahead of bow of ship 1.

Ship 2 avoids a collision with ship 1 by doing an over 22-degree turn to starboard (Table 6 and Figure 10). In the extended scenario the situation is more complicated due to the presence of two targets ahead of ship 1 (Figure 11).

Table 6. Scenario 1, phase 2: ship 2 has changed her course by about 22.58 deg. (time: 286 s). Additional ships for the extended scenario are marked with '*' symbols.

	Start X [NM]	Start Y [NM]	V [kn.]	COG [deg.]
Ship 1	0.95	0.00	12.00	90.00
Ship 2	0.42	-0,05	17.80	112.58
Ship 3*	3.79	0.90	10.00	90
Ship 4*	2.72	-0.90	9.00	90

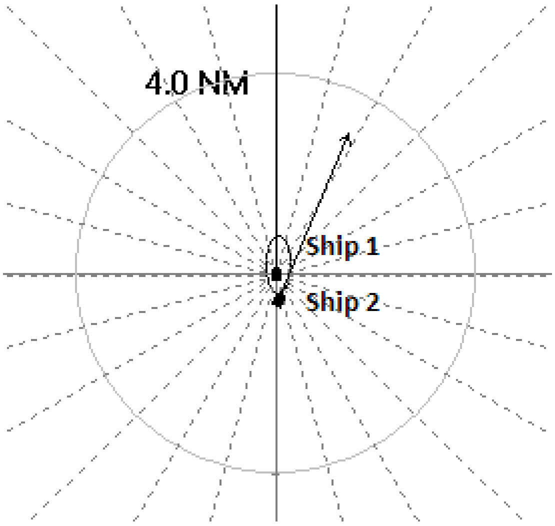

Figure 10. Scenario 1-basic, phase 2: ship 2 has changed her course by about 22.58 deg. (time: 286 s)

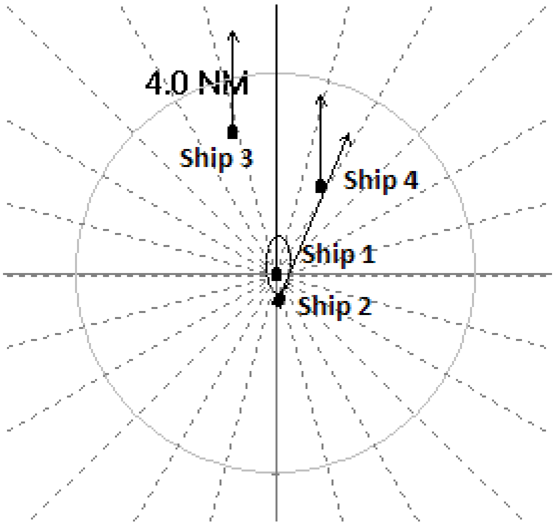

Figure 11. Scenario 1-extended, phase 2: ship 2 has changed her course by about 22.58 deg. (time: 286 s).

Table 7 and Table 8 present decision variable values and the resulting CRI values for basic and extended scenario respectively. As can be seen in Table 7, predicted degree of domain violation (DDV) is about 0.8, while the AV rises from 0.53 to 0.75, meaning that one ship will cover 3/4 of the way from arena's boundary to the other ship, before the course alteration manoeuvre is eventually performed. Those two variables lead to DAV changing from Large (before the manoeuvre) to Small (after manoeuvre, when predicted DDV falls down to 0). Variables responsible for relative speed (RS), combination of vessels' courses (VC) and encounter complexity have all values of Small due to overtaking, vessels' motion parameters and no surrounding traffic. As a result encounter difficulty (ED) is assessed as Small, which causes the final CRI to be slightly lower – Medium-Large instead of Large value of DAV. However, the situation is different in case of surrounding traffic (Table 8) – here the extra two ships result in EC being 0.98, which in turn leads to ED being Medium and final CRI value of Large. Both Medium-Large and Large values of CRI are generating alarms according to proposed CAS method, though in practice the alarm would be triggered much sooner in case of extended scenario – before the Start positions of all ships are reached. Arguably, such an early alarm is justified because the additional ships contribute to the greater uncertainty of the scenario development. In terms of near-miss detection CRI is also higher for the extended scenario (Medium-Large instead of Medium). Therefore, even though a near-miss is registered for both versions of this scenario, it is more significant for the extended one (it would happen here even is a smaller ship domain was applied).

Table 7. Scenario 1-basic, decision variables' values for CAS and near-miss detection. For near-miss detection it is assumed that all ships keep their courses (ship 2 does not manoeuvre)

CAS	**DDV**	**AV**	**RS**	**VC**	**EC**	**DAV**	**RSC**	**ED**	**CRI**
Start (time: 1s)	0.80 L	0.53 M	0.20 S	0.00 S	0.00 S	L	S	S	ML alarm
Before turn (time: 271s)	0.80 L	0.61 M	0.20 S	0.00 S	0.00 S	L	S	S	ML alarm
After turn (time: 286s)	0 None	0.75 L	0.27 S	0.25 S	0.00 S	S	S	S	Safe
NEAR-MISS (ships keep their courses)	0.80 L	0.00 S	0.20 S	0.00 S	0.00 S	ML	S	S	M near-miss

Table 8. Scenario 1-extended, decision variables' values for CAS and near-miss detection. For near-miss detection it is assumed that all ships keep their courses (ship 2 does not manoeuvre)

CAS	**DDV**	**AV**	**RS**	**VC**	**EC**	**DAV**	**RSC**	**ED**	**CRI**
Start (time: 1s)	0.80 L	0.53 M	0.20 S	0.00 S	0.98 L	L	S	M	L alarm
Before turn (time: 271s)	0.80 L	0.61 M	0.20 S	0.00 S	0.98 L	L	S	M	L alarm
After turn (time: 286s)	0 None	0.75 L	0.27 S	0.25 S	0.92 M	S	S	M	Safe
NEAR-MISS (ships keep their courses)	0.80 L	0.00 S	0.20 S	0.00 S	0.00 S	ML	S	M	ML near-miss

3.2 SCENARIO 2: HEAD-ON ENCOUNTER

Data of all ships are involved in the encounter are given in Table 9 and also shown in Figure 12 (basic scenario) and Figure 13 (extended scenario). In Figure 12 ship 2 approaches ship 1 from ahead of the beam with a small DCPA value. In Figure 13 there are additional ships 3 and 4 between ship 1 and ship 2, which contributes to the encounter's higher complexity.

Table 9. Scenario 2, phase 1: ship 2 approaches ship 1 from ahead of bow to port side, with a small DCPA value (time: 1–166 s). Additional ships for the extended scenario are marked with ‘*’ symbols.

	Start X [NM]	Start Y [NM]	V [kn.]	COG [deg.]	L [m]
Ship 1	0.00	0.00	14.00	90. 00	219
Ship 2	4.50	0.15	15.00	270. 00	150
Ship 3*	2.00	-0.50	10.00	90.00	150
Ship 4*	2.50	0.65	10.00	270.00	150

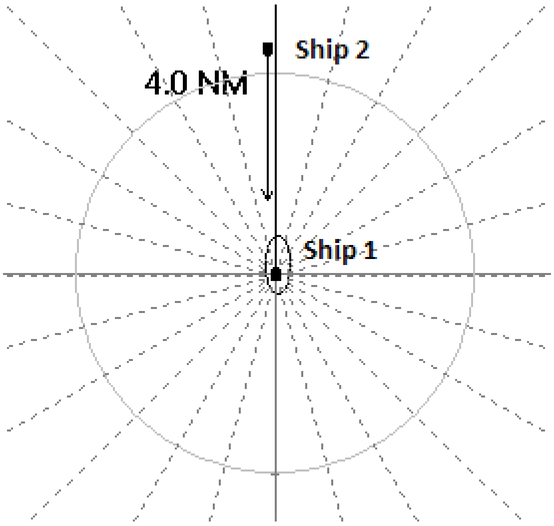

Figure 12. Scenario 2-basic, phase 1: ship 2 approaches ship 1 from ahead of bow to port side, with a small DCPA value (time: 1–166 s).

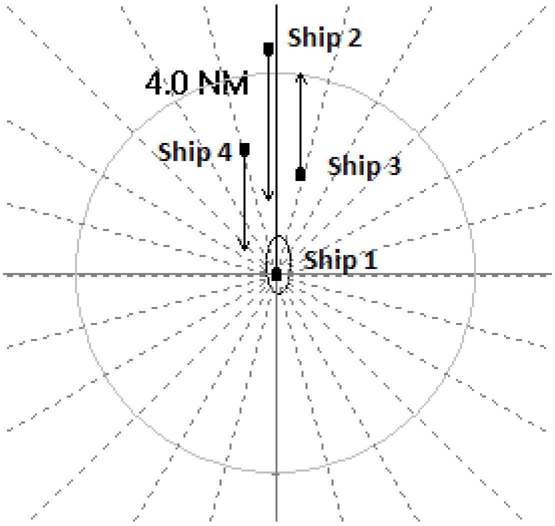

Figure 13. Scenario 2-basic, phase 1: ship 2 approaches ship 1 from ahead of bow to port side, with a small DCPA value (time: 1–166 s). Additional two ships are between ship 1 and 2.

Direct results of evasive manoeuvre performed by ship 2 are shown in Table 10 and Figure 14. Ship 2 successfully avoids collision with ship 1 by a 13-degree turn to starboard. In case of the extended scenario with surrounding traffic (Figure 15) ship 2 will additionally overtake ship 3.

Table 10. Scenario 2, phase 2: ship 2 has changed her course by about 12.86 deg. (time: 181 s). Additional ships for the extended scenario are marked with ‘*’ symbols

	Start X [NM]	Start Y [NM]	V [kn.]	COG [deg.]
Ship 1	0.70	0.00	14.00	90. 00
Ship 2	3.75	0.15	15.00	282.85
Ship 3*	2.50	0	10.00	90.00
Ship 4*	2.00	0.15	10.00	270.00

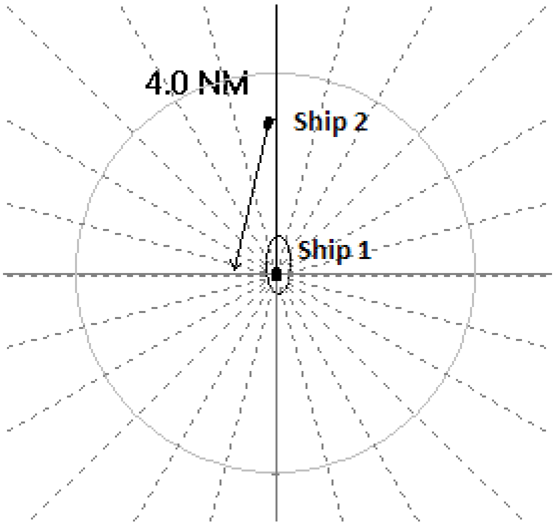

Figure 14. Scenario 2-basic, phase 2: ship 2 has changed her course by about 12.86 deg. (time: 181 s).

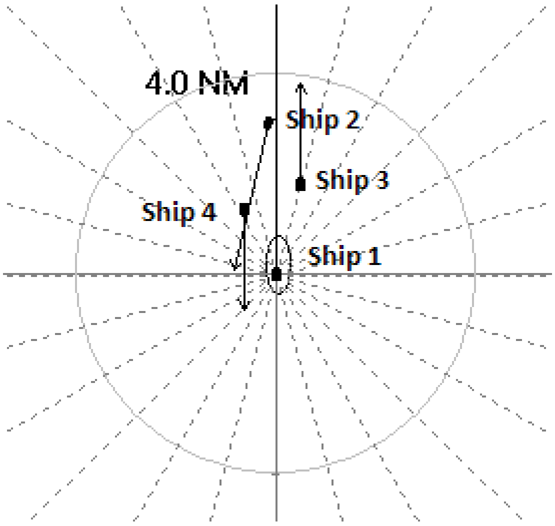

Figure 15. Scenario 2-extended, phase 2: ship 2 has changed her course by about 12.86 deg. (time: 181 s). Additional two ships are between ship 1 and 2

Detailed decision variables values for basic and extended scenario are given in Tables 11 - 12. As for the basic scenario (Table 11), minor domain violation is predicted (*DDV*=0.1) and actual arena violation (AV) changes from 0.44 to 0.49 directly before manoeuvre. Therefore, the main decision variable of DAV is Small-Medium before the manoeuvre. When aggregated with Small-Medium EC (affected by relative speed variable being nearly 1 for head-on) it gives CRI of Small-Medium and an early warning is generated. The warning does not change into alarm because of the minor predicted violation and the fact that ship 2 changes course before a significant rise in AV variable. The situation is assessed as more risky (CRI of Medium) for the extended scenario with two more ships, where EC is 0.91. In this case a warning would be generated before Start situation and an alarm would be triggered sooner than for the basic scenario, if ship 2 would not manoeuvre in due time. Arguably, the additional ships make it harder to plan an evasive action, which should be done in advance because of the more limited manoeuvre options and greater uncertainty. Also, in this extended scenario (Table 12), for the reasons given above, the method keeps a caution after the manoeuvre has been performed. As for near-miss detection, even if none of the ship manoeuvred, the situation would not be classified as a near miss neither for the basic scenario nor for the extended one. However, a larger CRI for the extended scenario (Small-Medium instead of Small) indicates that this situation is close to a near-miss (which starts from Medium CRI) and a near-miss could be ruled if a slightly larger ship domain was applied.

Table 11. Scenario 2-basic, decision variables' values for CAS and near-miss detection. For near-miss detection it is assumed that all ships keep their courses (ship 2 does not manoeuvre)

CAS	**DDV**	**AV**	**RS**	**VC**	**EC**	**DAV**	**RSC**	**ED**	**CRI**
Start (time: 1s)	0.10 S	0.44 M	0.97 S	0.00 S	0.00 S	SM	M	SM	SM warning
Before turn (time: 271s)	0.10 S	0.49 M	0.97 S	0.00 S	0.00 S	SM	M	SM	SM Warning
After turn (time: 286s)	0 None	0.45 M	0.96 S	0.14 S	0.00 S	S	M	SM	Safe
NEAR-MISS (ships keep their courses)	0.10 S	0.00 S	0.97 S	0.00 S	0.00 S	S	M	SM	S no near-miss

Table 12. Scenario 2-extended, decision variables' values for CAS and near-miss detection. For near-miss detection it is assumed that all ships keep their courses (ship 2 does not manoeuvre)

CAS	**DDV**	**AV**	**RS**	**VC**	**EC**	**DAV**	**RSC**	**ED**	**CRI**
Start (time: 1s)	0.10 S	0.44 M	0.97 S	0.00 S	0.91 L	SM	M	ML	M warning
Before turn (time: 271s)	0.10 S	0.49 M	0.97 S	0.00 S	0.91 L	SM	M	ML	M warning
After turn (time: 286s)	0 None	0.45 M	0.96 S	0.14 S	0.86 L	S	M	ML	S caution
NEAR-MISS (ships keep their courses)	0.10 S	0.00 S	0.97 S	0.00 S	0.91 L	S	M	SM	SM no near-miss

3.3 SCENARIO 3: CROSSING ENCOUNTER

All ships' data for this scenario are given in Table 13 (starting positions and courses), Figure 16 (basic scenario) and Figure 17 (extended scenario). In Figure 16 ship 1 approaches ship 2 from ahead of the beam on the port side, with a small DCPA value. In Figure 17 there is additionally ship 3 on the port side of ship 1, which limits manoeuvring possibilities, thus increasing the encounter's complexity.

Table 13. Scenario 3, phase 1: ship 1 approaches from ahead of the beam of ship 2, with small DPCA value (time: 1–196 s). An additional ships the for extended scenario is marked with an ‘*’ symbol.

	Start X [NM]	**Start Y [NM]**	**V [kn.]**	**COG [deg.]**	**L [m]**
Ship 1	-1.81	0.00	14.00	90.00	219
Ship 2	2.46	-1.82	17.00	315.00	150
Ship 3*	-1.00	0.70	8.00	90.00	200

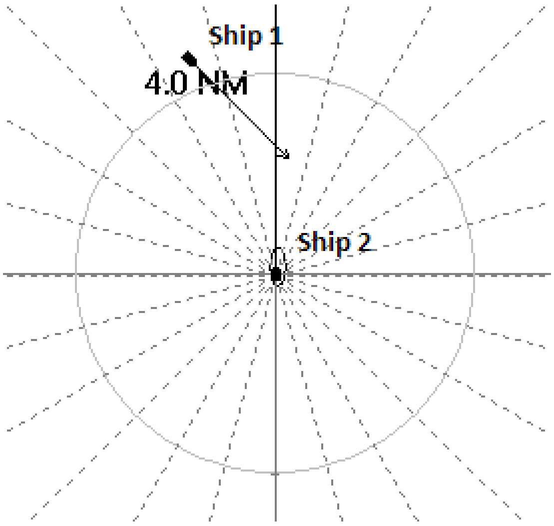

Figure 16. Scenario 3-basic, phase 1: ship 1 approaches from ahead of the beam of ship 2, with small DPCA value (time: 1–196 s).

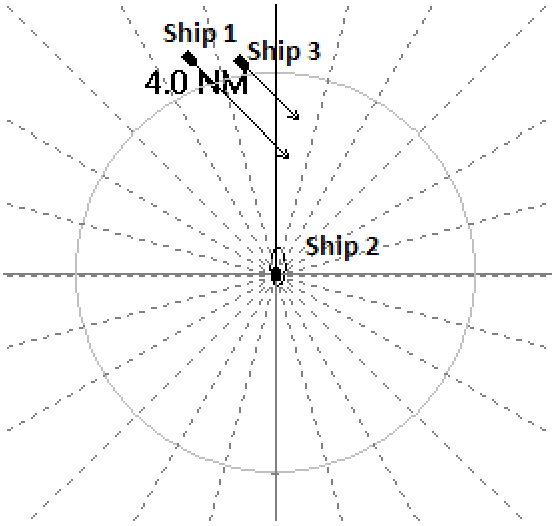

Figure 17. Scenario 3-extended, phase 1: ship 1 approaches from ahead of the beam of ship 2, with small DPCA value (time: 1–196 s). An additional ship is on the port side of ship 1.

As can be seen in Figure 18 and accompanying data (Table 14), ship 1 successfully avoids collision with ship 2 by a 13-degree turn to starboard. The manoeuvre is done without any conflict with ship 3 on port side of ship 1.

Table 14. Scenario 3, phase 2: ship 1 has changed her course by about 12.93 deg. (time: 211 s). An additional ships for the extended scenario is marked with an ‘*’ symbol

	Start X [NM]	Start Y [NM]	V [kn.]	COG [deg.]
Ship 1	-0.99	0. 00	14.00	102.93
Ship 2	1.75	-1.12	17.00	315.00
Ship 3*	-0.53	0.70	8	90

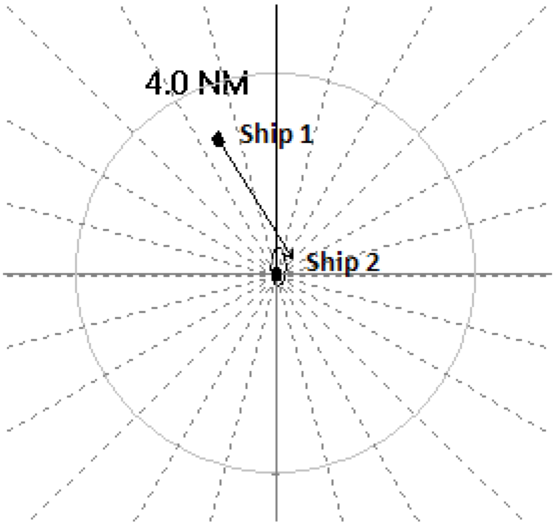

Figure 18. Scenario 3-basic, phase 2: ship 1 has changed her course by about 12.93 deg. (time: 211 s)

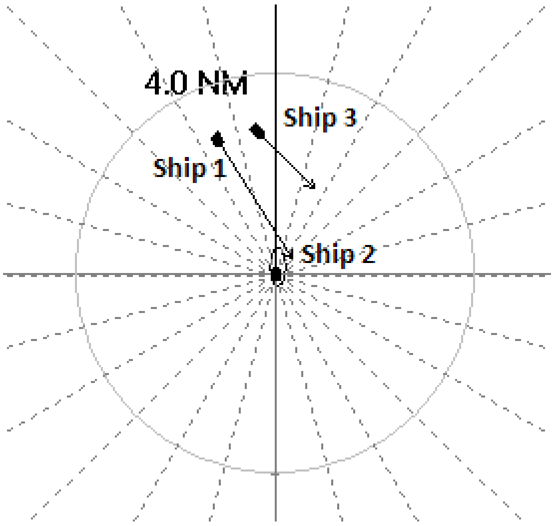

Figure 19. Scenario 3-extended, phase 2: ship 1 has changed her course by about 12.93 deg. (time: 211 s). An additional ship is on the port side of ship 1

Decision variables' values and final CRI for the basic scenario are provided in Table 15. Small-Medium DDV (predicted domain violation) combined with Medium AV (time-dependent advancement of arena violation) produce Medium aggregated value of DAV. This, when put together with Medium value of ED (caused by relative speed and combination of courses) results in Medium CRI. Thus, a warning is generated early on and sustained until after the course change, when the situation is eventually assessed as safe. However, the risk is assessed as significantly larger in presence of one more ship, as given in Table 16. Here the encounter complexity of 1.00 leads to a higher encounter difficulty (Medium-Large instead of Medium), which results in CRI of Medium-Large instead of Medium and an alarm instead of a warning. This is reasonable for the additional ship may either change course or her sheer presence may affect behaviour of one of the primary two ships involved in an encounter. For the same reason a caution is sustained in the extended scenario after the manoeuvre of ship 1. Another difference noted for the two scenarios is that if neither of ships manoeuvred, the situation would be classified as a near-miss for the extended scenario, though not for the basic one (Medium CRI for extended scenario and Small-Medium for basic one).

Table 15. Scenario 3-basic, decision variables' values for CAS and near-miss detection. For near-miss detection it is assumed that all ships keep their courses (ship 2 does not manoeuvre)

CAS	DDV	AV	RS	VC	EC	DAV	RSC	ED	CRI
Start (time: 1s)	0.37 SM	0.40 M	0.95 L	0.5 M	0.00 S	M	ML	M	M warning
Before turn (time: 271s)	0.37 SM	0.46 M	0.95 L	0.5 M	0.00 S	M	ML	M	M warning
After turn (time: 286s)	0 None	0.47 M	0.99 L	0.36 S	0.00 S	S	ML	M	Safe
NEAR-MISS (ships keep their courses)	0.37 SM	0.00 S	0.95 L	0.5 M	0.00 S	SM	ML	M	SM no near-miss

Table 16. Scenario 3-extended, decision variables' values for CAS and near-miss detection. For near-miss detection it is assumed that all ships keep their courses (ship 1 does not manoeuvre)

CAS	DDV	AV	RS	VC	EC	DAV	RSC	ED	CRI
Start (time: 1s)	0.37 SM	0.40 M	0.95 L	0.5 M	1.00 L	M	ML	ML	ML alarm
Before turn (time: 271s)	0.37 SM	0.46 M	0.95 L	0.5 M	1.00 L	M	ML	ML	ML alarm
After turn (time: 286s)	0 None	0.47 M	0.99 L	0.36 S	1.00 L	S	ML	ML	S caution
NEAR-MISS (ships keep their courses)	0.37 SM	0.00 S	0.95 L	0.5 M	1.00 L	SM	ML	ML	M near-miss

3.4 SCENARIO 4 – HOW THE TIME OF EVASIVE ACTION AFFECTS NEAR-MISS CLASSIFICATION

The input data for the scenario are gathered in Table 17 and additionally visualised in Figure 20.

Table 17. Scenario 4, phase 1: ship 2 approaches from ahead of the beam of ship 1on starboard, with small DPCA value and predicted large domain violation.

	Start X [NM]	Start Y [NM]	V [kn.]	COG [deg.]	L [m]	Predicted DDV
Ship 1	-1.54	0.00	14.00	90.00	200	0.93
Ship 2	2.46	-1.82	17.00	315.00	250	

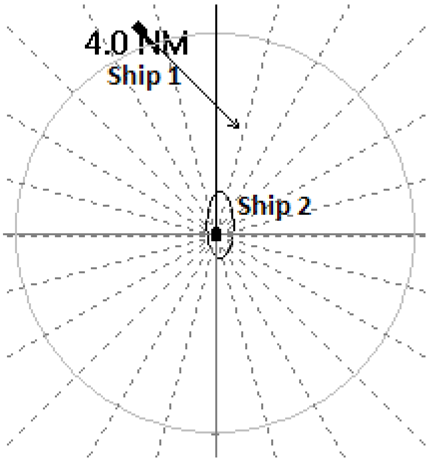

Figure 20. Scenario 4, Ship 2 approaches from ahead of the beam of ship 1on starboard, with small DPCA value and predicted large domain violation

Ship 2 approaches from ahead of the beam of ship 1 on starboard, with small DPCA value and predicted large domain violation (DDV = 0.9). Ship 1 turns to starboard decreasing predicted DDV from 0.93 to 0.25. However, depending on a particular analysed case, this turn is either by 30 degrees and is made after 20 minutes from the start (Case 1) or is 60 degrees and is made after 30 minutes (Case 2). The positions of both ships directly after turn are shown in Table 18, where the upper rows present Case 1 and the lower ones – Case 2. Both cases are illustrated in Figure 21 and Figure 22 respectively. Similarly, the positions of both ships during passing each other are shown in Table 19 and depicted in Figure 23 and Figure 24.

Table 18. Scenario 4, phase 2: ship 1 has turned to starboard and DDV has decreased to 0.25

		X [NM]	Y [NM]	V [kn.]	COG [deg.]	Predicted DDV
Case 1: ship 1 turns 15 deg. to starboard after 5.5 min.	Ship 1	-0.24	0.00	14.00	75.00	0.25
	Ship 2	1.34	-0.70	17.00	315.00	
Case 2: ship 1 turns 27 deg. to starboard after 7.5 min.	Ship 1	0.23	0.00	14.00	63.00	
	Ship 2	0.94	-0.30	17.00	315.00	

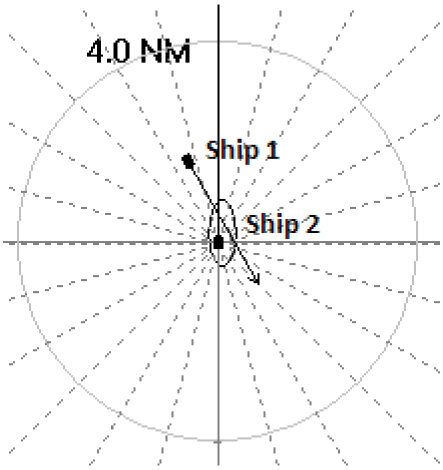

Figure 21. Scenario 4, Case 1: Ship1 turned to starboard by 15 degrees 5.5 min. from the start of the simulation

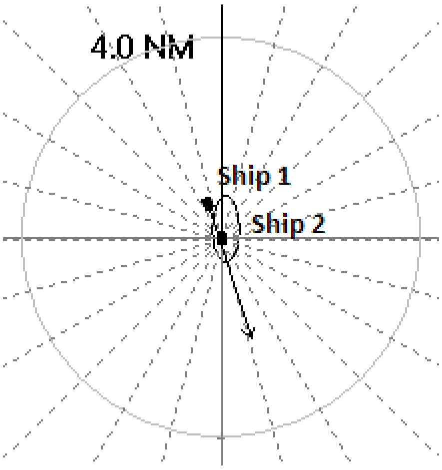

Figure 22. Scenario 4, Case 2: Ship 1 has turned to starboard by 27 degrees 7.5 min. from the start of the simulation

Table 19. Scenario 4, phase 3: the ships pass each other, DDV = 0.25

		X [NM]	**Y [NM]**	**V [kn.]**	**COG [deg.]**	**Actual DDV**
Case 1 (ship 1 turned 15 deg. to starboard after 5.5 min)	Ship 1	0.36	-0.16	14.00	90.00	0.25
	Ship 2	0.81	-0.17	17.00	315.00	
Case 2 (ship 1 turned 27 deg. to starboard after 7.5 min)	Ship 1	0.41	-0.09	14.00	90.00	
	Ship 2	0.76	-0.12	17.00	315.00	

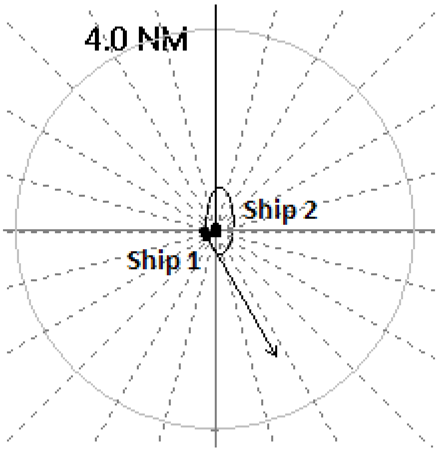

Figure 23. Scenario 4, Case 1: Ship 1, which turned to starboard by 15 degrees after 5.5 min. from the start of the simulation, is now passing ship 2

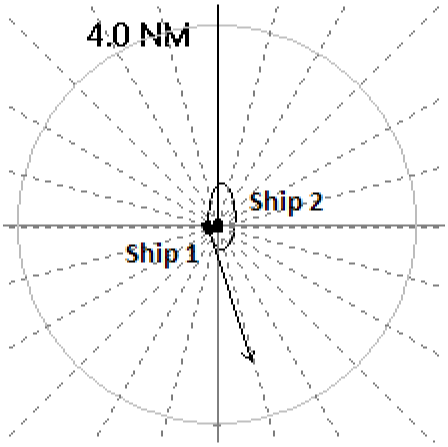

Figure 24. Scenario 4, Case 2: Ship 1, which turned to starboard by 27 degrees after 7.5 from the start of the simulation, is now passing ship 2

The results of near-miss assessment for both cases from Scenario 4 (Section 3.4) are gathered in Table 20. As can be seen, late turn in Case 2 leads to a larger value of AV variable (0.72 – Large instead of 0.32 - Small). This in turn causes DAV to be Medium-Large instead of Small-Medium and finally – CRI to be Medium-Large instead of Small-Medium, which results in classifying the encounter as a Near-miss for Case 2, as opposed to No near-miss obtained for Case 1. Finally, in Case 3 of Table 20 we can see a situation where Ship 1 does not manoeuvre at all. As a result, the AV variable is equal to 0 (lack of a late manoeuvre), however DDV is 0.93 (VL), which leads to CRI being L – a larger CRI value than for Case 2 and a definite Near-miss result.

Table 20. Scenario 4, Near-miss decision variables' values for two cases: ship 1 has turned to starboard at either 200s or 300s (ship 2 does not manoeuvre)

NEAR-MISS	**DDV**	**AV**	**RS**	**VC**	**EC**	**DAV**	**RSC**	**ED**	**CRI**
Case 1: Ship 1 turns after 20 min.	0.25 SM	**0.32** **S**	0.95 L	0.5 M	0.00 S	**SM**	ML	M	**SM** **No near-miss**
Case 2: Ship 1 turns after 30 min.	0.25 SM	**0.72** **L**	0.95 L	0.5 M	0.00 S	**ML**	ML	M	**ML** **Near-miss**
Case 3: Both ships keep their courses and speeds	0.93 VL	**0** **S**	0.9 L	0.6 M	0.00 S	**L**	ML	M	**L** **Near-miss**

3.5 DISCUSSION

3.5.1 Comparison with RICAS

The summary of alerts generated by RICAS [36] and the proposed ship domain-based CAS method is given in Table 21.

Table 21. A comparison of alerts according to RICAS and proposed method for all three scenarios

		RICAS	**Proposed method's CRI values and alerts for basic scenarios**		**Proposed method's CRI values and alerts for extended scenarios**	
			CRI	**alert**	**CRI**	**alert**
Scenario 1	**Start**	**Caution**	Medium-Large	**Alarm**	Large	**Alarm**
	Before turn	**Warning**	Medium-Large	**Alarm**	Large	**Alarm**
	After turn	**Safe**	Safe	**Safe**	Safe	**Safe**
Scenario 2	**Start**	**Caution**	Small-Medium	**Warning**	Medium	**Warning**

	Before turn	**Warning**	Small-Medium	**Warning**	Medium	**Warning**
	After turn	**Caution**	Safe	**Safe**	Small	**Caution**
Scenario 3	**Start**	**Caution**	Medium	**Warning**	Medium-Large	**Alarm**
	Before turn	**Warning**	Medium	**Warning**	Medium-Large	**Alarm**
	After turn	**Caution**	Safe	**Safe**	Small	**Caution**

As can be seen, for the timespan included in the scenarios RICAS generates a caution at the start of each scenario, followed by a warning. A short alarm is usually generated during the course change (this phase is not included in Table 21), followed by either Safe state or a sustained Caution once the new course is set. Unlike RICAS, the proposed CAS generates a caution considerably earlier (before the Start time of each scenario), so a warning or an alarm is generated at the Start. This warning or an alarm is then sustained until a turn is made. In general, the assessment of risk for early phases of an encounter in the proposed method is similar in RICAS, the only difference being a slightly lower threshold for warnings and alarms resulting in triggering them earlier. As for the last phase of an encounter, in two out of three cases RICAS sustains Caution after a turn was made, while the proposed method returns Safe as soon as one of the ships sets on a collision-free course. It must be noted here that triggering each kind of alert by the proposed method depends on the dimensions of the ship domain, which are configurable. To avoid information overload in heavy traffic areas, an OOW may apply a smaller ship domain. This would eliminate some of the alerts as well as result in a smaller action distance. Consequently, the remaining alerts would be generated considerably later.

The major difference in risk assessment is that the proposed method also takes into account the impact of surrounding traffic by means of EC variable. As a result, CRI is usually larger by one level, if a ship-to-ship encounter is associated with additional ships in the vicinity. For Scenario 1 this means CRI of Large instead of Medium-Large until the manoeuvre is performed. For Scenario 2 it results in CRI of Medium instead of Small-Medium before the manoeuvre and a Caution instead of Safe just after the manoeuvre. For Scenario 3 CRI is Medium-Large instead of Medium and thus it triggers an Alarm instead of a Warning. Also, a Caution is sustained after the manoeuvre. Similar differences can be noticed when comparing alerts generated by the proposed method for extended scenarios with those returned by RICAS for basic scenarios (alarms instead of warnings or cautions). Arguably, the presence of other ships contributes to a considerable rise in collision risk, which should be reflected by an appropriate alert. The proposed method is able to address this issue directly, while RICAS (in version presented in [36]) does not take it into account and would generate the same alerts for basic and extended scenarios alike.

3.5.2 How the time of evasive action affects near-miss classification

The assessments done by the proposed method for Scenario 4 (Section 3.4) are in accordance with both COLREGS and good marine practice because the give-way ship's manoeuvre should have been performed early in this case (Figure 21) instead of a larger turn done nearly at the last moment (Figure 22). It is reasonable to classify the situation from Figure 22 (late manoeuvre) as a near-miss as opposed to the one depicted in Figure 21 (early manoeuvre). It should also be noted that while the lack of a manoeuvre results in a zero value of AV variable (accounting for late manoeuvres), it also leads to a much larger DDV variable, whose impact on the final CRI is larger. As a result, CRI gets a value of Large, which informs us that this particular near-miss encounter was indeed very close to a physical incident. The scenario shows how the method favours early manoeuvres over later ones, although a late manoeuvre is still a better solution than keeping a dangerous course and passing too close to another target.

4. CONCLUSIONS

In the paper a ship domain-based model of collision risk has been proposed. According to this model an encounter is described by five decision variables representing: degree of domain violation, relative speed of the two vessels, combination of the vessels' courses, arena violations and encounter complexity. While some of those variables can be directly computed based on positions, courses and speeds of two vessels, others require decomposing an encounter situation into phases. Those phases are: pre arena violation, during arena violation but pre domain violation, during domain violation, post domain exit but pre arena exit and post arena exit. The detailed time for start and end of each phase can be computed analytically based on a set of auxiliary variables presented in the paper. Once all decision variables' values are computed, the collision risk index (CRI) is computed. Possible applications of this CRI include: AIS-based near-miss detection, Collision Alert Systems (CAS) and collision avoidance decision support systems (DSS). Case studies for the first two applications have been provided, including a brief comparison with RICAS [36]. A quantitative assessment of the comparison's results is not possible due to a limited set of scenarios and a lack of benchmark. However, the comparison shows how the proposed CRI is able to address the issue of surrounding traffic affecting the collision risk between two vessels.

Another important feature is that the model makes it possible to adjust user's settings according to their particular needs. A user may apply a different (smaller or larger) ship domain depending on the particular water region and own experience, e.g. a less experienced navigator may prefer a larger ship domain. Such a change can be easily made and does not affect other parameters of the method. This is a considerable advantage when compared with a CAS utilizing a larger number of parameters directly applied in decision rules. As for the potential near-miss application, the proposed method strongly favours early manoeuvres and an encounter with two ships passing at the same distance may be classified as a near-miss or not, depending on the time when an evasive action was made.

The proposed model is not void of drawbacks and they mostly result from its general character. The fact that the same (albeit adjusted) model is applied for both near-miss detection and CAS means that the model must rely on easily available AIS data-derived parameters. In case of CAS, they are supplemented by additional data on own ship's maneuverability. Unfortunately no such data are available in case of near-miss detection. For near-miss case it would be beneficial to have at disposal a method offering a rough approximation of a ship's manoeuvrability based on its type and dimensions. Such an approximation, even if flawed would still be informative and in many cases more accurate than a generic elliptic arena based on the up-scaled domain shape, which the model uses at present for near-miss detection. Another feature for further development is more advanced COLREGS-compliance. At present COLREGS rules are only supported by means of a ship's domain dimensions, which encourage vessels to pass astern of stand-on targets. Fortunately, the model's modular structure, where each variable is computed separately and then aggregated with others, offers a room for improvement (especially considering that current number of decision rules is relatively small when compared to that of RICAS). It is also planned to extend the method by adjusting and refining the proposed solution by enlarging the pool of candidate external experts and restarting the elicitation procedure. Alternative or upgraded methods of computing the presented decision variables can easily be incorporated into the model to offer better collision risk assessment. Such methods will be investigated in the ongoing research on the proposed model. Once this is completed, the work on the model's practical application will be started. In case of near-miss this will involve verification of the method on the large AIS data sets. For CAS-oriented method, the additional future work will be focused on handling stationary objects and constraints by means of Electronic Navigational Charts (ENC). The method will have to be integrated with ENC-class software and installed onboard for real environment tests.

ACKNOWLEDGEMENTS

This research was supported by Gdynia Maritime University, Faculty of Navigation under internal research grant no. WN/2020/PZ/02 and its continuation in 2021.

APPENDIX

Table A.1. Variable values mapped to linguistic values. Linguistic values: Small (S), Small-Medium (SM), Medium (M), Medium-Large (ML), Large (L)

Variable name	Value range	Linguistic value
DDV	(0.0; 0.2)	S
DDV	[0.2; 0.4)	SM
DDV	[0.4; 0.55)	M
DDV	[0.55; 0.7)	ML
DDV	[0.7; 0.85)	L
DDV	[0.85; 1.0]	VL
AV	[0.0; 0.33]	S
AV	(0.33; 0.67)	M
AV	[0.67; 1]	L
RS	[0.0; 0.33]	S
RS	(0.33; 0.67)	M
RS	[0.67; 1]	L
VC	[0.0; 0.33]	S
VC	(0.33; 0.67)	M
VC	[0.67; 1]	L
EC	[0.0; 0.33]	S
EC	(0.33; 0.67)	M
EC	[0.67; 1]	L

Table A.2. Aggregating Degree of Domain Violation (DDV) and Arena Violation (AV) into Domain and Arena Violations (DAV)

DDV linguistic value	AV linguistic value	Resulting DAV linguistic value
S	S	S
S	M	SM

S	L	M
SM	S	SM
SM	M	M
SM	L	ML
M	S	SM
M	M	M
M	L	ML
ML	S	ML
ML	M	ML
ML	L	L
L	S	ML
L	M	L
L	L	L
VL	S, M, L	L

Table A.3. Relative Speed (RS) and Vessels' Courses (VC) are aggregated into Risky Speeds and Courses (RSC)

RS linguistic value	**VC linguistic value**	**Resulting RSC linguistic value**
S	S	S
S	M	SM
S	L	M
M	S	SM
M	M	M
M	L	ML
L	S	M
L	M	ML
L	L	L

Table A.4. Aggregating Risky Speeds and Courses (RSC) and Encounter Complexity (EC) into Encounter Difficulty (ED)

RSC linguistic value	EC linguistic value	ED linguistic value
S	S	S
S	M	SM
S	L	M
SM	S	SM
SM	M	SM
SM	L	M
M	S	SM
M	M	M
M	L	ML
ML	S	M
ML	M	ML
ML	L	ML
L	S	M
L	M	ML
L	L	L

Table A.5. Aggregating Domain and Arena Violations (DAV) and Encounter Difficulty (ED) into final Collision Risk Index (CRI)

DAV linguistic value	ED linguistic value	CRI linguistic value
S	S	S
S	SM	S
S	M	SM
S	ML	SM
S	L	M
SM	S	SM
SM	SM	SM
SM	M	SM
SM	ML	M
SM	L	M
M	S	SM
M	SM	M
M	M	M
M	ML	ML
M	L	ML
ML	S	M
ML	SM	M
ML	M	ML
ML	ML	ML
ML	L	ML
L	S	ML
L	SM	ML
L	M	L
L	ML	L
L	L	L

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