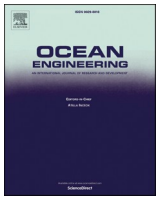
Ocean Engineering 261 (2022) 112029

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



COLREGs and their application in collision avoidance algorithms: A critical analysis

Jesús A. García Maza [a,*], Reyes Poo Argüelles [b]

[a] Marine Science and Technology Dept., University of Oviedo, Spain
[b] Electrical, Electronic, Communications and Systems Engineering Dept., University of Oviedo, Spain

A B S T R A C T

Ship collisions are some of the biggest risks in shipping, and Decision Support System/Collision Avoidance-Alert Systems (DSS/CAS) are being developed to prevent and avoid them. They must become an essential equipment for any vessel, especially for Maritime Autonomous Surface Ships (MASS).

Assuming the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREG 72) as the basis for every DSS/CAS, there is growing concern in the maritime field about the lack of consistency of published studies, in particular those on the design of algorithms for the control of ship collision avoidance manoeuvres, with the requirements of the current COLREG.

The methods applied for the assessment of scenarios and situations will be analyzed, since only a correct appraisal of the circumstances will bring about the adequate response for such critical situations.

COLREG is conceived to always have the Officers Of the Navigational Watch (OONW) (more specific than the overly generic expression Officer On Watch -OOW), at the center of every decision.

Therefore, in the design of a DSS/CAS, interpretations that approach collision situations from a different perspective than that of an OONW should be avoided. Safe communication with other vessels would reinforce and improve the information available to the OONW.

This paper aims to offer an insight into ship collisions avoidance according to COLREG 72 that may prove useful to the OONWs either on board or remotely, or even to autonomous systems. It is illustrated by examples taken from some works which, despite their great influence in the current literature, do not have a correct standpoint.

1. Introduction

A large number of studies point to human error as one of the prominent causes for maritime accidents (ALLIANZ, 2020; Antão and Guedes Soares, 2008; EMSA, 2020; Wróbel, 2021).

Ship collisions rank high on the list of maritime accidents. Many efforts have been set up to prevent them due to their harmful consequences and strategic importance on navigational safety (Zhang et al., 2018).

With the objectives of cost reduction, a race has begun towards the automation of ships aiming the downsizing of humans and therefore of OONWs. The devising of DSS/CAS to ship's trajectory planning, either as supporting elements or as direct decision making devices, has been one of the most common proposals to date.

As the primary source to define the situations to be avoided, all DSS/CAS must count on COLREG 72, the actual legal frame. An adequate knowledge of this standard seems crucial for the correct assessing of critical situations and for taking adequate actions.

Literature about algorithms that can be effective in MASS is becoming extensive, with very diverse approaches: fuzzy logic, evolutionary algorithms, neural networks, interval programming, 2D grid map, collision threat parameters area techniques, the fast marching method, differential games, velocity obstacle algorithms, etc.

However, when planning those algorithms in simulated or real scenarios, simplified and basic assumptions of COLREG 72 are far from its real complexity. The oversimplification that is common in most formulations reinforces the view of humans (OONW) as a weak link that can fail in an incomprehensible way facing a task that, apparently, is very simple.

This paper aims to generate a reflection on what has to be taken into account in the design of the algorithms that regulate the DSS/CAS or any equipment that attempts to perform a collision avoidance manoeuvre on a ship. To this end, the current work will be developed in a way accessible to people unfamiliar with the marine world.

The collision avoidance complexity can be assessed by showing the minimum requirements that a DSS/CAS must meet according to the current legislation.

COLREG 72 Rules directly related to the evaluation of vessel

* Corresponding author.
E-mail address: maza@uniovi.es (J.A. García Maza).

https://doi.org/10.1016/j.oceaneng.2022.112029
Received 27 September 2021; Received in revised form 15 July 2022; Accepted 16 July 2022
Available online 5 August 2022

Table 1
COLREG 72 spatial scope.

RULE	DEFINITION
1	*High seas and all waters connected therewith navigable by seagoing vessels.*
9	*Narrow channel or fairway*
10	*Traffic separation schemes*

Table 2
Types of encounters and their definitions.

ENCOUNTER	RESULT	RISK SITUATION
Collision	*Contact between vessels*	*Critical*
Close quarters	*Possible contact between vessels*	
Safe distance	*No contact between vessels*	*Safe*

encounters are analyzed, identifying possible problems of interpretation and some common mistakes found in recent literature, in particular a possible bad legacy from COLREG 60.

Finally, it should be noted that according to the definition of vessel given in COLREG 72 Rule 3:

> "The word "vessel" includes every description of water craft, including non displacement craft, WIG craft and seaplanes, used or capable of being used as a means of transportation on water."

All are obliged to comply with COLREGs, irrespective of their size.

2. COLREGS analysis

As above mentioned and despite the fact that some authors highlight its complexity (Crosbie, 2009), its lack of effectiveness (Belcher, 2002) and its unnaturalness (Kemp, 2009), the protocol to follow is COLREG 72. So, a perfect knowledge of the current text is necessary to take the right decisions in these situations.

It starts by specifying the spatial scope of its application, as shown in Table 1.

It should be noted that there may be different rules for certain navigation areas: (Suez Canal, 2015), (Panama Canal, 2019), etc.

In no case is traffic density taken into account as a factor that generates actions other than those specified for the indicated areas, beyond precautionary recommendations. Actions can be radically different from place to place and this must be taken into account when designing an evasive manoeuvre.

Secondly, undesirable or avoidable situations have to be identified.

There is no definition of the term *collision* in COLREG 72.

After collision, *close quarters* is the second type of undesired event to consider. Wang et al. (2017) said: "Nevertheless, there are no unified quantitative and qualitative interpretations on the term 'close-quarters situation' in the world, and the exact definition is also not given in the COLREGs by far" (p.487). It is one of the qualitative terms that need to be clarified (Tsai et al., 2017).

Rule 8 - Action to avoid collision, aims to describe safe passage between vessels. Although the information it provides may not be categorical, it allows for a definition of close quarters as some distance between *collision* and the *safe distance* of Rule 8 d), terms collected in Table 2.

Regarding the identification of critical situations, COLREG 72 Rule 7 b) and d), *Risk of collision,* states that the OONW:

- Must use: RADAR plotting or equivalent systematic observation of detected objects.
- Must consider possible risk of collision: when the compass bearing of an approaching vessel does not appreciably change, or even when an appreciable bearing change is evident, particularly when approaching a very large vessel or a tow or when approaching a vessel at close range.

In order to do so, notice must be taken of: *relative bearings (M°)*, and *distances (d)*. Fig. 1 shows the plotting used throughout this paper.

Since encounters are dynamic situations, continuous monitoring is required.

Thus, the distance at the Closest Point of Approach (CPA) allows us to identify the type of encounter as collision, close quarters or safe distance and the Time of the Closest Point of Approach (TCPA) is used to give priority to critical situations (Bole et al., 2014; Xu and Wang, 2014). CPA and TCPA terms are defined in IMO (IMO, 1986a).

It is to be noted that both CPA and TCPA must be measured according to a reference, as the Consistent Common Reference Point (CCRP) (IMO, 2004).

Measurement equipment is required to calculate distance. RADAR-

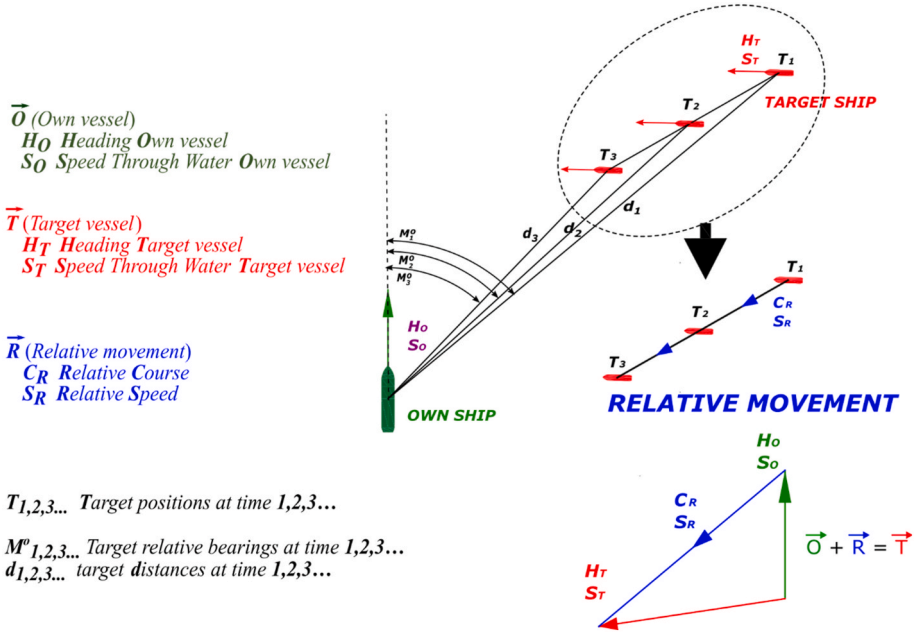


Fig. 1. Ship plotting.

Table 3
COLREG criteria.

VISIBILITY	KIND OF PROPULSION	RESTRICTIONS
Part A - General (Rules 1–3)	Part A - General (Rules 1–3)	Part A - General (Rules 1–3)
Part B-Steering and Sailing	*Part B-Steering and Sailing*	*Part B-Steering and Sailing (Rules 4–19)*
Section I		*Section I*
Conduct of vessels in any condition of visibility (Rules 4–8)		*Conduct of vessels in any condition of visibility (Rules 9 and 10)Technical*
Section II	*Section II*	*Section II*
Conduct of vessels in sight of one another (Rules 11–17)	*Conduct of vessels in sight of one another (Rule 18)*	*Conduct of vessels in sight of one another (Rule 18) Geographical.*
Section III		
Conduct of vessels in restricted visibility (Rule 19)		

Let's take a deeper look at the COLREG criteria.

Table 4
Vessels in sight situations.

SITUATION	M°	S_R	REFERENCE
VESSEL OVERTAKING	$292.5^\circ < M^o < 360^\circ$ $0^\circ \leq M^o < 67.5^\circ$	$S_R < S_O$	H_O, H_T
VESSEL BEING OVERTAKEN	$112.5^\circ < M^o < 247.5^\circ$	$S_R > 0$	H_O
HEAD-ON	*Not specified*	$S_R > S_O$	H_O, C_O, H_T, C_T
CROSSING	$247.5^\circ \leq M^o < 360^\circ$ $0^\circ \leq M^o \leq 112.5^\circ$, *as long as above situations have been discarded*	$S_R > 0$	H_O, H_T

Table 5
Vessels not in sight situations.

SITUATION	M°	S_R	REFERENCE
FORWARD OF THE BEAM	$270^\circ < M^o < 360^\circ$ $0^\circ \leq M^o < 90^\circ$	$S_R > 0$	H_O
ABEAM OR ABAFT THE BEAM	$90^\circ \leq M^o \leq 270^\circ$	$S_R > 0$	H_O

Table 6
Sound signal: range of audibility.

LENGTH OF VESSEL (METERS)	AUDIBILITY RANGE (NAUTICAL MILES)
200 or more	*2*
75 but less than 200	*1.5*
20 but less than 75	*1*
Less than 20	*0.5*

ARPA is the only aid overtly acknowledged by the COLREG 72, even though Rule 5 states that others could also be used. Along the same lines IMO Resolution A.1106 (29) accepts the Automatic Identification System (AIS) for onboard use as another useful tool to this end (IMO, 2015).

These calculations should start according to Rule 7 b): "… including long-range scanning to obtain early warning of risk of collision …"

The term *Long-Range Scanning* (LRS) is not yet defined. For that, the difference in the distances at which the involved vessels detect a collision risk situation can lead to confusing situations.

In the absence of RADAR or similar equipment (AIS), LRS is understood to be the visual or audible range. If both RADAR and AIS exist, the first reliable information given by these devices should initiate the analysis of the situation, even if the information comes from a long distance.

When a critical situation is observed, compliance with COLREG 72 is mandatory. Its rules are organized around three major criteria:

Table 7
Means of propulsion recognized by COLREG.

PROPULSION	COLREG RULES	Passage preference
Power-driven vessel	*Rules 3, 10, 14, 15, 17, 18, 19, 23, 24, 27, 28, 34, 35. Annex I Rules 2 and 4; Annex III Rule 2 b)*	*No*
Oars	*Rule 25*	*(Possible)*
Sail	*Rules 3, 9, 10, 11, 12, 18, 25 and 35. Annex I Rule 10*	*Yes*
Mix Sail and Power-driven	*Rule 25*	*(Possible)*
Seaplanes	*Rules 3 and 31*	*No*
Non-displacement craft	*Rules 3 and 23*	*No*
Wing-In-Ground (WIG) craft	*Rules 3, 18, 23 and 31*	*No*

The type of propulsion could imply some passage preference, hence the importance of its identification.
This classification from COLREG 72 does not correspond to that from AIS, issue that could be avoided by standardizing classifications.

Table 8
Restrictions related to characteristics or vessel activities.

RESTRICTIONS	COLREG RULES	AIS NAVIGATIONAL STATUS
Vessel not under command	*Rules 3, 18, 27 and 35*	*Not under command*
Vessel restricted in her ability to manoeuvre	*Rules 3, 10, 18, 27 and 35*	*Restricted in ability to manoeuvre*
Vessel engaged in mine clearance operations	*Rule 27*	
Vessel engaged in fishing	*Rules 1, 3, 9, 10, 18, 26, 35; Annex I Rules 2 and 4; Annex II Rule 3*	*Engaged in fishing*
Sailing vessel	*Rules 3, 9, 10, 12, 18, 25, 35; Annex I Rule 10*	*Underway by sail*
Vessel constrained by her draught	*Rules 3, 18, 28 and 35*	*Constrained by draught*
Anchored vessel or anchor	*Rules 3, 9, 10, 26, 27, 29, 30, 35; Annex I Rules 2 and 9*	*At anchor*
Vessel aground	*Rules 3, 30, 35*	*Aground*
Vessel made fast to the shore	*Rule 3*	*Moored*

Table 9
Restrictions based on geographical considerations.

RESTRICTIONS	COLREG RULES
Narrow channels (NC)	*Rule 9*
Traffic separation schemes (TSS)	*Rule 10*
Inshore traffic zone (ITZ)	*Rule 10*
Traffic Lane (TL)	*Rule 10*

Visibility, Kind of Propulsion and Restrictions both technical and geographical, discussed in COLREG sections 3 to 7, and outlined in Table 3.

3. The visibility criterion in COLREG 72

Visibility is very often the only criterion taken into account when designing a DSS/CAS (Goerlandt and Kujala, 2011; Lopez-Santander and Lawry, 2017; Montewka et al., 2010; Perera et al., 2009, 2010, 2011; Smeaton and Coenen, 1990).

In addition to using this single criterion, it is usually simplified by reducing it to the vessels in sight scenario. The reason for this may be that COLREG 60 continues to apply, as it includes nothing that prevents the application of the rules used for vessels in sight to restricted visibility scenarios.

COLREG 72 is more complex and provides a customized response for

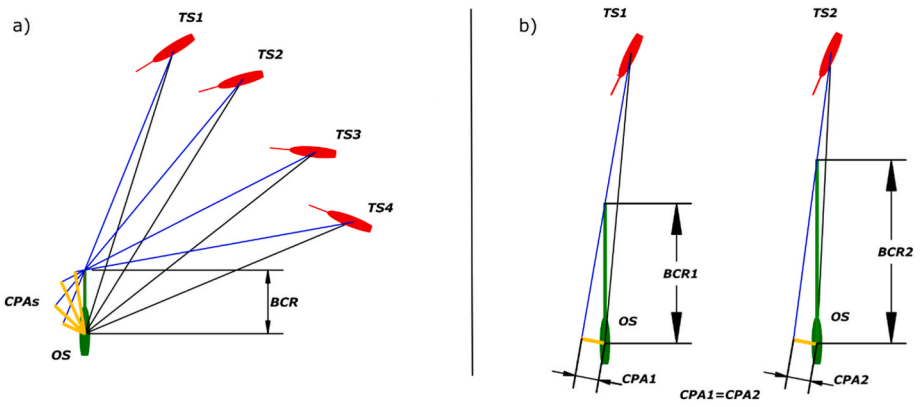


Fig. 2. CPAs and BCRs.

5.3. Scenario 3: Crossing

In this simulation experiment, we designed a crossing scenario with a small angle. There is a TS keeping direction and speed, and the OS needs to avoid the TS from reaching the target point. Table 5 shares the initial information of the OS and TS.

Table 5. Initial information (crossing).

Ship List	Position*	Course	Speed	RD	Bearing
OS	(38.82° N, 118.25° E)	51.3°	10 kn	0 nm	0
TS	(38.82° N, 118.26° E)	355.0°	10.5 kn	3.7 nm	93.0°

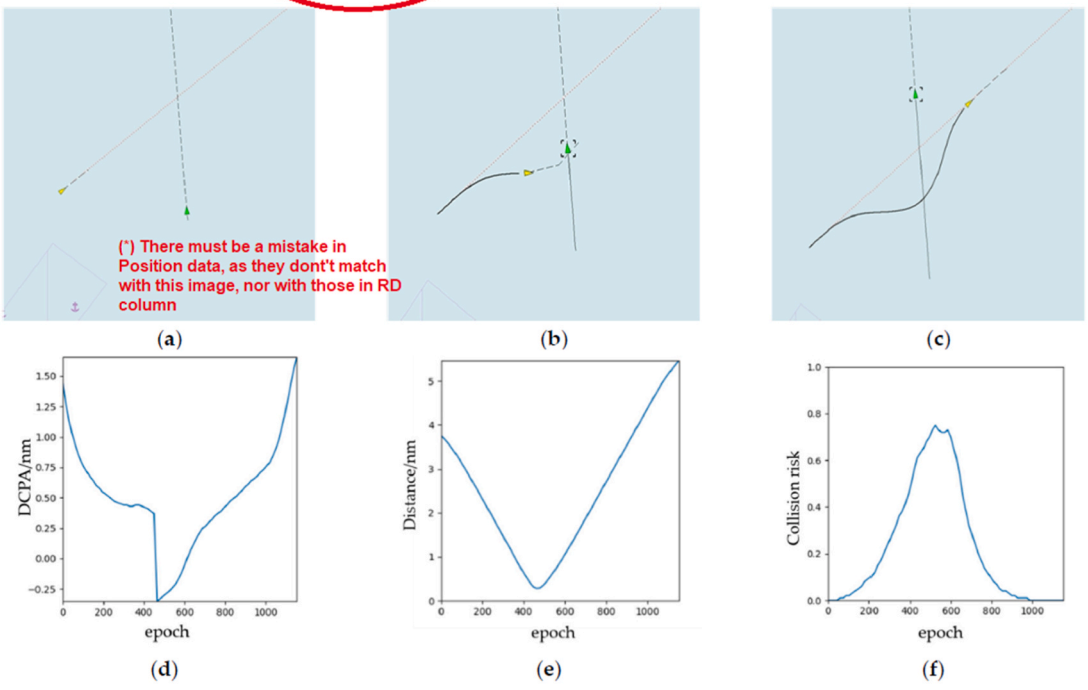


Fig. 3. Excerpt from Zhang X et al. (2021).

each visibility scenario. Thus, Rule 3- General Definitions, defines in section l) the term *restricted visibility* as "any condition in which visibility is restricted by fog, mist, falling snow, heavy rainstorms, sandstorms or any other similar causes". It is worth mentioning that the literature has made a wide interpretation of "any other similar causes" as in Cockcroft and Lameijer (2011): "Examples of 'other similar causes' are smoke from own vessel, other vessels, or ashore, and dust storms" (p.16).

The conduct of vessels in restricted visibility or not in sight is governed by Rule 19 considering two possible sequences of events described in sections d) and e).

So, in all, according to the visibility in the encounter area, COLREG 72 distinguishes between:

- Vessels in sight,
- Vessels not in sight with RADAR and
- Vessels not in sight without RADAR.

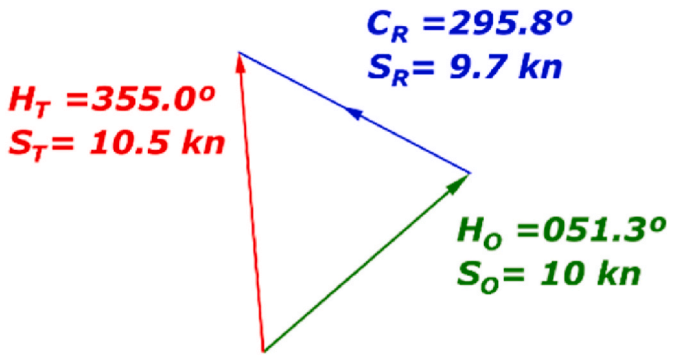


Fig. 4. Ship plotting from Fig. 3 data.

An analysis will be made of each scenario.

3.1. Vessels in sight

COLREG 72 Section II: Vessels in sight, considers three possible critical situations:

- Overtaking (Rule 13),
- Head-on (Rule14) and
- Crossing (Rule 15).

In the three situations, establishing the vessels' Headings (and not Courses Over Ground (COGs)) is a must. Once this is done, a priority system is established according to the Rules 16 and 17:

- Rule 16 - Give-way: keep out of the way of another
- Rule 17 - Stand-on: shall keep her course and speed (keep the way)

The system is further refined by Rules 8 f) iii), 17 a) ii), 17 b), which signal when a vessel the passage of which is not to be impeded, or a stand-on vessel, must take an action to avoid collision. Therefore, it can be referred to as a "limited priority system".

A brief description of each situation will follow, identified by the relative bearing and speed (M^o, S_R), and taking as reference heading and course of own and target ships (H_O, C_O, H_T, C_T), as shown in Table 4. The values for M^o are deduced from the description of Rules 13, 14, 15, 19 and 21. Light sector tolerances defined in Annex I. 9 of COLREG 72 are not considered for these values (at night, tolerances for the light sectors are: 0°/360° ± 3°; 112.5° and 247.5° ± 5°).

3.1.1. Overtaking

Overtaking is the first situation to consider. It involves an Overtaking vessel and a Being Overtaken vessel, as stated in Rule 13 a): "… any vessel overtaking any other shall keep out of the way of the vessel being overtaken".

The Being Overtaken vessel finds herself in an easier situation since, a priori, she needs neither to manoeuvre nor to know the heading of the

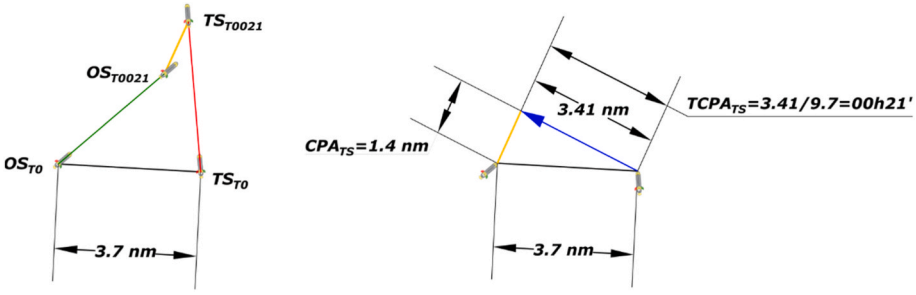


Fig. 5. Passing distance.

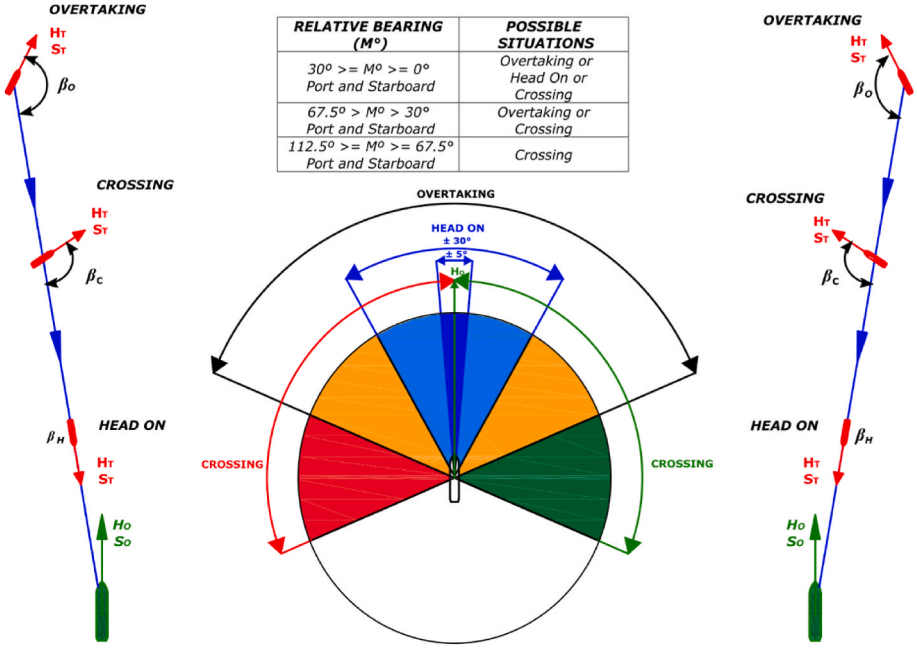
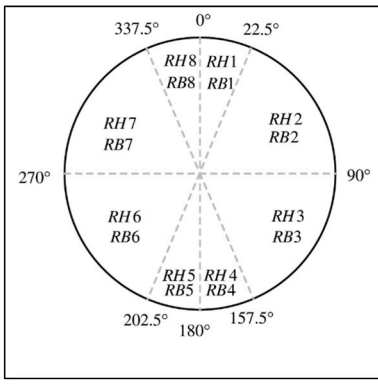


Fig. 6. Vessels in sight. Multiple situations for the same relative bearing.



Ship COLREGs identity	RH1	RH2	RH3	RH4	RH5	RH6	RH7	RH8
RB1	OT	SF	CR/SO	CR/SO	HO/GW	CR/GW	CR/GW	OT
RB2	OT	SF	SF	SF	CR/GW	CR/GW	CR/GW	OT
RB3	OT	SF	SF	SF	SF	CR/GW	CR/GW	OT
RB4	OT	SF	SF	SF	SF	SF	CR/GW	OT
RB5	OT	CR/SO	SF	SF	SF	SF	SF	OT
RB6	OT	CR/SO	CR/SO	SF	SF	SF	SF	OT
RB7	OT	CR/SO	CR/SO	CR/SO	CR/GW	SF	SF	OT
RB8	OT	CR/SO	CR/SO	HO/GW	CR/GW	CR/GW	SF	OT

Fig. 7. Regions and encounter array (Du et al., 2021).

Overtaking vessel. By night, the lights of a vessel are a great help as long as they are in visible range and a safe distance separates the vessels (Rule 22 - Visibility of Lights).

3.1.2. Head-on

Head-on is the hardest situation to determine. According to Rule 14 a), "When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other".

The context of Rule 14 refers to *heading* (not *course*), mostly if section b) is considered:

Rule 14 b) Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

Phrases such as "ahead or nearly ahead" and "masthead lights of the other in line or nearly in a line" clearly refer to the Headings of both vessels. In this case they are used as reinforcement in the description of the situation, since course and heading are not the same. In fact, the IMO Sub-Committee On Safety Of Navigation in the *Standard Marine Communication Phrases (SMCP)* (IMO, 2001) provides the following definitions:

- Course: The intended direction of movement of a vessel through the water.
- Heading: The horizontal direction the vessel's bows at a given moment measured in degrees clockwise from north.

In this regard, Bowditch (2019) warns: "It is easy to confuse heading and course. Heading constantly changes as a vessel yaws back and forth across the course due to sea, wind and steering errors" (p.5).

Unfortunately, $\boldsymbol{M}^{\circ}$ range is not specified in COLREG 72, although it was in past versions (Cockcroft and Lameijer, 2011). The word *nearly* is difficult to quantify, and not without controversy.

3.1.3. Crossing

Crossing should be considered once Overtaking and Head-on situations have been discarded. Rule 15 describes the response to a crossing situation, using the vessel's heading as reference:

> When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

It is quite common in this situation to assume that, in terms of the give-way vessel changing course, the reaction must be an alteration to starboard. However, for situations where the target vessel speed ($\boldsymbol{S_T}$) is greater than own vessel speed ($\boldsymbol{S_O}$) and the vessels keep getting closer, a change to port may be more effective and safer.

3.1.4. Rule 17, the limited priority

As already pointed out, in some situations in the vessels in sight scenario, a ship is given priority over another. However, that priority is limited by Rule 17 b):

> When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.

The wording of this Rule may lead to errors of interpretation.

In the encounters between vessels each one knows her own manoeuvring characteristics, but doesn't know those of the other vessel. With that perspective, the vessel that requires to keep course and speed might have a problem deciding whether to act or not. And the decision is more likely to be wrong if the manoeuvring characteristics of both vessels are quite different.

To avoid this added risk, it is necessary to establish the following requirement: the distance at which the give-way vessel should start to manoeuvre must be greater than the distance set to comply with Rule 17 b) for the stand-on vessel.

Only by knowing the safety distance defined for the stand-on vessel can it be respected, so that she is not forced to manoeuvre.

This is a topic not usually addressed in the literature on collision avoidance, although it represents a challenge in ship-to-ship encounters and suggests the need of sharing or communicating extra information about the defined manoeuvring distances for the involved ships in the encounters.

More than ships' intentions (Du et al., 2020), information is what the OONW needs.

3.2. Vessels NOT in sight

Vessels not in sight scenario is key in the already mentioned over-simplification. COLREG 60 only mentions a limitation in the manoeuvres to change course for navigation in restricted visibility:

> 6)" … An alteration to starboard, particularly when vessels are approaching apparently on opposite or nearly opposite courses, is generally preferable to an alteration to port".

An important change was introduced in COLREG 72, establishing rules to change course different to those for vessels in sight. It has generated some controversy (Fujiwara et al., 2017; Salinas, 2006), and its rules are difficult to be discerned by the OONWs (Mohovic et al., 2016). It must be clear for those in charge of the navigation (humans or autonomous ships) which scenario are they in, to be sure that they apply the same rules.

This scenario is subdivided in vessel not in sight with RADAR, and

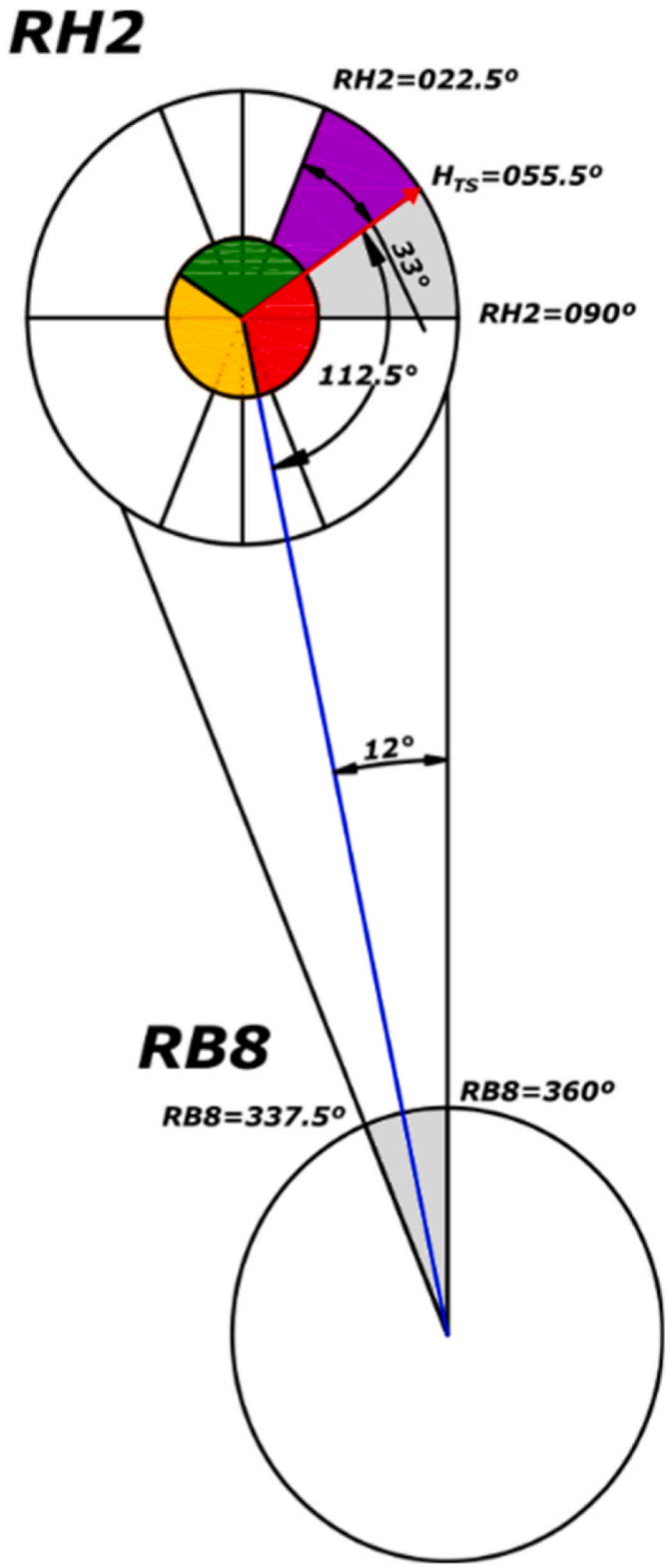


Fig. 8. TS in RB8, RH2.

vessel not in sight without RADAR.

3.2.1. Vessels not in sight with radar

Few studies take into account vessels not in sight scenario and situations, or, when they do, they assume conducts not included in COLREG 72 for a restricted visibility scenario (Hilgert and Baldauf, 1997; Szlapczynski et al., 2018). There are no priorities in this scenario, so there is neither give-way nor stand-on vessel.

There are three situations:

- Overtaking,
- Forward of the beam,
- Abeam or abaft the beam.

Overtaking appears in COLREG 72, Section III Rule 19 d) (i): "… other than for a vessel being overtaken". But the only reference to the overtaking concept is included in Section II: Conduct of Vessels in Sight of One Another.

The problem of the possible extension to any state of visibility was clearly solved in COLREG 60, while a rather obscure wording was approved in COLREG 72:

- COLREG 60 Rule 24 a) "Notwithstanding anything contained in these Rules, …"
- COLREG 72 Rule 13 a) "Notwithstanding anything contained in the Rules of Part B, Sections I and II, …"

Is the concept of overtaking limited to vessel in sight or could it be extended to any condition of visibility? There is a problem of indeterminacy and therefore an increased risk of collision in the application of COLREG Rule 19 d) when a vessel is being overtaken:

- the vessel being overtaken will manoeuvre, in application of Rule 19 (d)(ii), avoiding an alteration of course towards the vessel abaft the beam. It is not so clear how this (overtaking) vessel should manoeuvre.
- It is not specified how will they manoeuvre when the vessel abaft the beam comes dead astern.

Any algorithm to be implemented in a CAS must be free from doubt and the interpretation should be homogeneous for all CAS.

Forward of the beam, and abeam or abaft the beam characteristics are shown in Table 5.

3.2.2. Vessels not in sight without radar

Identified in Rule 19 e), hearing plays the key role in this situation, although it is to be used in everyday look-out duties according to COLREG 72, Rule 5.

- The vessel which hears apparently forward of her beam the fog signal has a Give-way status.
- The vessel which hears apparently NOT forward of her beam the fog signal has a Stand-on status.

The short range of audibility of sound signals, according to Rule 35 and Annex III of COLREG 72 (Table 6) becomes another problem in this scenario.

4. Other COLREG 72 criteria

As previously mentioned, COLREG 72 includes two other criteria in addition to visibility: Kind of Propulsion and Restrictions.

4.1. Kind of propulsion

The means of propulsion recognized by COLREG 72 are shown in Table 7.

4.2. Restrictions

COLREG identifies the limitations or restrictions on the normal functioning of vessels. Two groups of restrictions can be differentiated. The first group, shown in Table 8, has to do with characteristics or

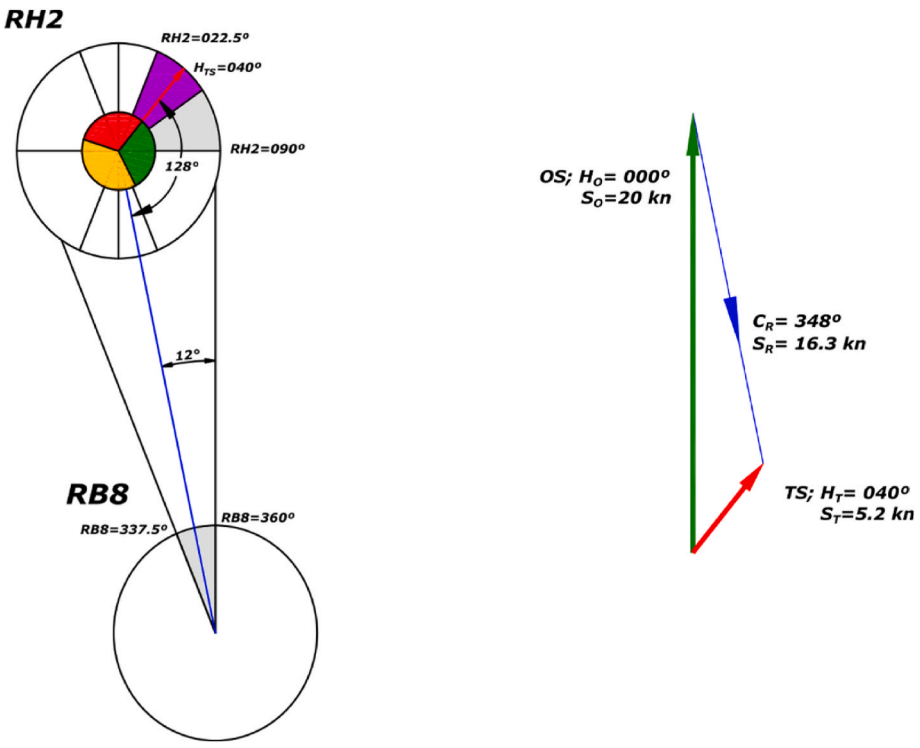


Fig. 9. TS with RB = 348°, RH = 040°.

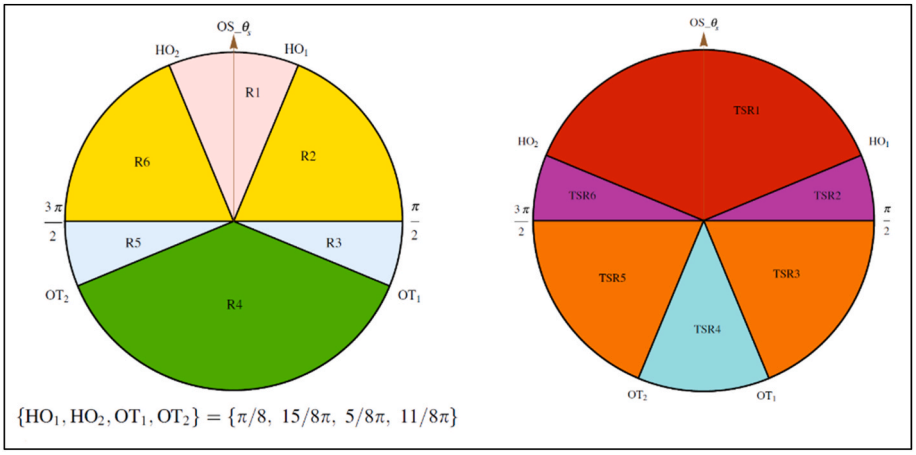


Fig. 10. Regions used to categorise position and heading of the obstacle (Tam and Bucknall, 2010).

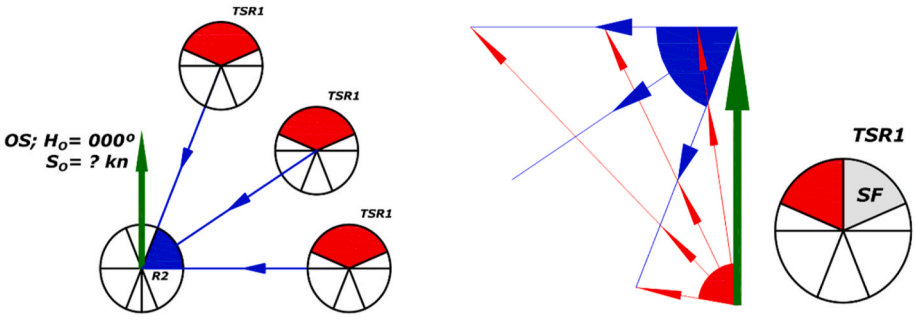


Fig. 11. Examples with TS in R2, TSR1.

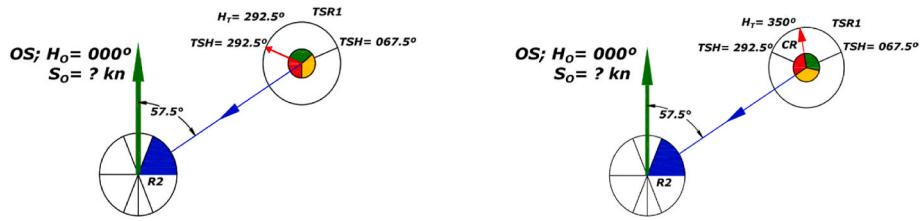


Fig. 12. Crossing encounter with TS in R2, TSR1.

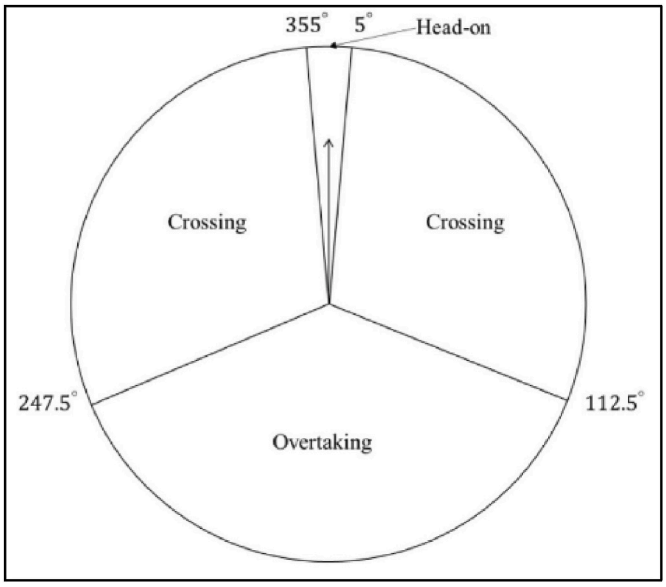


Fig. 13. Encounter regions (Rong et al., 2021).

activity of the vessel. AIS dynamic messages include a navigational status flag related to these restrictions.

For the above restrictions there may be a number of acoustic signals, lights and/or markings that allow visual or acoustic identification, within their range.

The second group of restrictions is based on geographical considerations (Table 9).

There are neither marks nor lights that can be displayed by a vessel to indicate that she is in a restriction based on geographical considerations.

Every vessel must obtain this information through the combined use of navigational aids: bouys, sound signals, RADAR or AIS with nautical charts or ECDIS.

Ignorance of this situation can generate problems when two vessels encounter with different geographical restrictions each other (Ever

Table 10
Rule 19 and Guo et al. (2020) interpretation.

COLREG RULE 19	ARTICLE	REMARKS
*..so far as possible the following shall **be avoided**:*	*In addition, in situation where the visibility of the sea environment is restricted, there will be no responsibility separation between the stand-on vessel and the give-way vessel. The COLREGS made the following rules for the situation of the ship at this time:*	COLREG say what to avoid, not what to do.
(i) an alteration of course to port for a vessel forward of the beam, other than for a vessel being overtaken;	*For coming ships in the range of (0°, 90°) and (270°, 360°), the self-ship will turn to the right.*	*It would be possible to change speed. It does not cover the overtaking situation.*
(ii) an alteration of course towards a vessel abeam or abaft the beam	*Self-ship **takes a turn towards** other ships for coming ships in the range of (90°, 180°) and (180°, 270°).*	*It is just the opposite.*

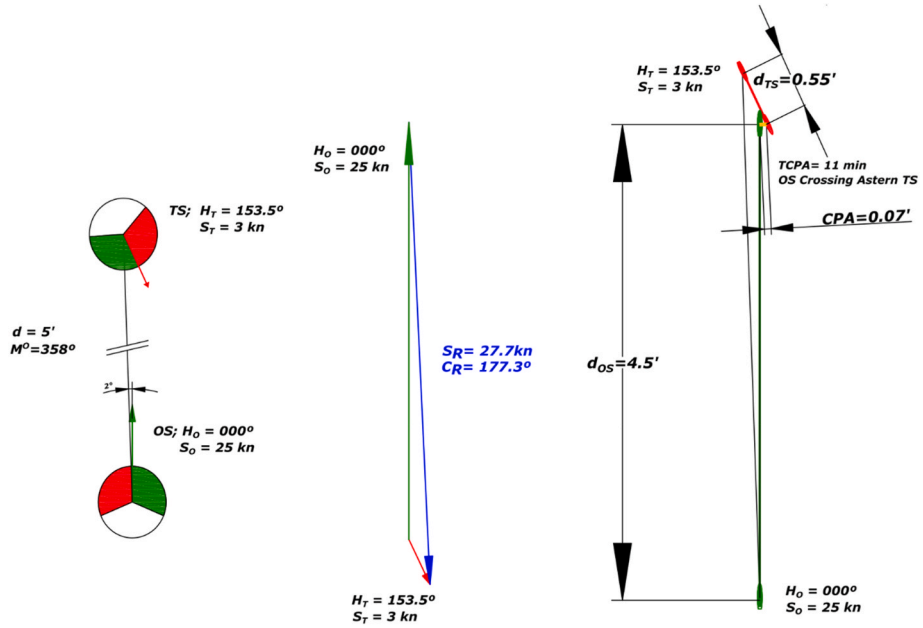


Fig. 14. Crossing situation with relative bearing = 358°.

Table 11
Head-on sectors in literature.

HEAD-ON SITUATION	
M° (Port and Stbd)	AUTHORS
5°	(Cockcroft, 1982; Du et al., 2020; Tsou et al., 2010)
5.7°	He et al. (2017)
10°	Montewka et al. (2011)
15°	Szlapczynski and Krata (2018)
22.5°	Tam and Bucknall (2010)
30°	IALA (2018)

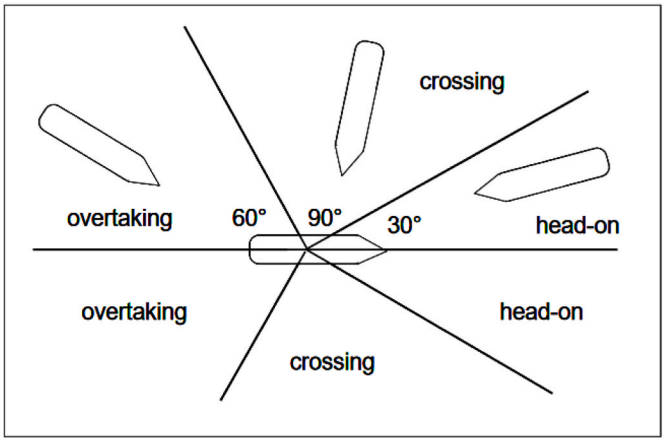


Fig. 15. Definition of the three encounter types (IALA, 2018).

Smart-Alexandra1, 2015).

There is no definition at the level of international law in the case of the NC, as there is in the other three cases: TSS, ITZ and TL, which are elements of Ship Routeing Systems (IMO, 1986b). In these areas, actions may differ greatly from the general provisions (COLREG 72 Rules 8, 9 and 10).

5. Discussion

From reading the previous sections, it might seem that the COLREG analysis carried out is not important enough to be the subject of a publication of this kind. However, an analysis of the articles on the subject in high-impact journals is sufficient to realise that fundamental things that should be common for all those working in this field do not seem to be so. We will show, with examples taken from influential or recent publications on collision avoidance, some inaccuracies in the application of COLREG, which will adversely affect the implementations derived from them.

5.1. Plotting the target SHIP (TS)

COLREG requirement for plotting the TS seems to be an issue that many authors struggle with. Usually, on board, this is done with a reference system relative to the Own Ship (OS). In this way, the information necessary for the classification of the situation is obtained by establishing a prediction of minimum passing distance CPA or time of maximum approach. And so (CPA) it appears on ships' navigational equipment. The use of the expression Distance at/to Closest Position of Approach, which is used in academic works, is curious, as it is understood as a redundancy in the maritime professional field.

Plotting provides further information: the time at which that maximum approach will occur (TCPA), the relative and the true movement of the TS.

Once all this information has been analyzed, the encounter can be assessed from the perspective of COLREG Rule 8 (d): "Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance … ".

It is important to know the potential of plotting as it covers all the information needs for collision avoidance. There are statements that may be surprising, such as the following:

> The model proposed in this paper incorporates some novelties regarding how an encounter between two ships on a coastal restricted and open sea area is considered. Unlike most existing approaches, it combines three variables relevant to collision risk, namely, the distance between encountering ships; the relative speed of the ships; and the difference between the headings of the ships, referred to as the phase (Zhang et al., 2015, p.67).

What it offers is exactly what plotting, as already described in Brown (1971), gives us.

The mentioned work from Zhang W. et al. also uses some measures well known in the maritime world and whose limitations must be understood:

> First, in certain head-encounters, if the other ship crosses ahead of own ship with a small value of the closest point of approach (CPA) but sufficiently wide bow cross-range (BCR), the small CPA would not imply an unsafe encounter. In such cases, the BCR is informative and can be used to make inferences, where the CPA could have led to misclassification of a safe encounter as unsafe. (p.62)

One of the dangers that every seafarer has to be aware of is the false sense of reassurance that a safe BCR can give over an unsafe CPA. There is no such thing as a safe encounter with an unsafe CPA.

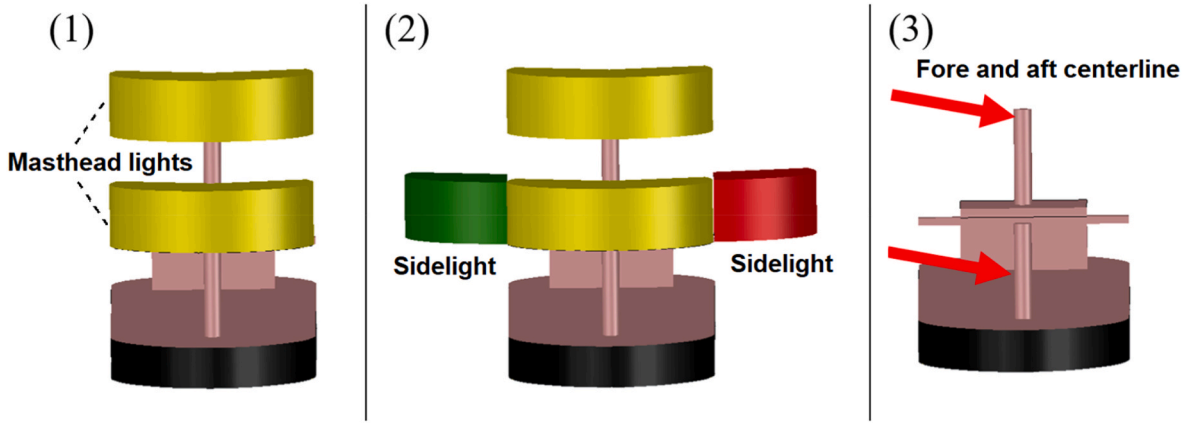


Fig. 16. Head-on situation. Rule 14 (b).

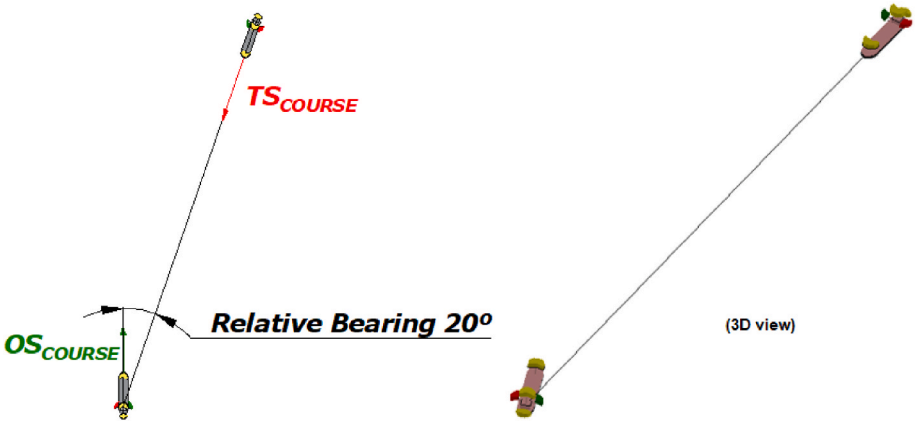


Fig. 17. Encounter with relative bearing = 20°.

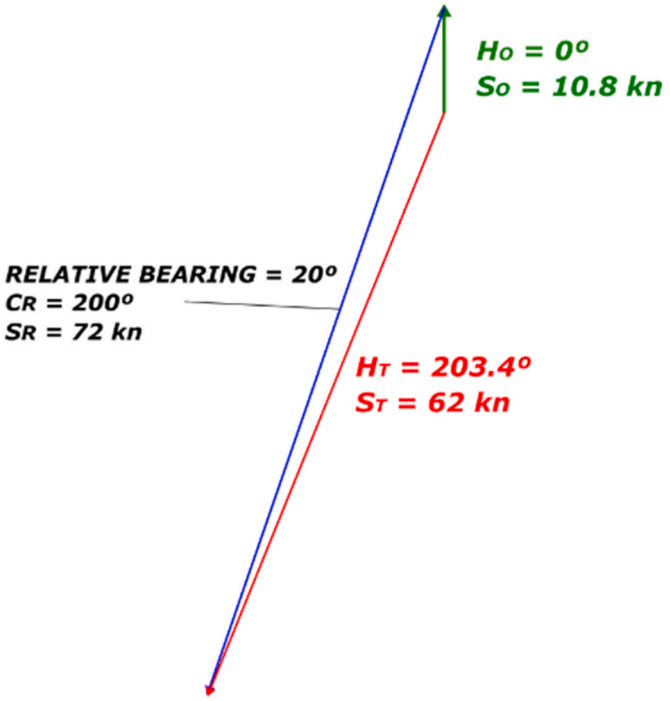


Fig. 18. Head-on collision situation with relative bearing = 20°.

Suppose different relative bearing for the same BCR (Fig. 2a). It can be seen that the CPA is always lower than the BCR. The closer the vessel is to the bow (lower relative bearing), the lower the CPA. Similarly, for the same CPA (Fig. 2b), the further the vessel is forward or in opposition, the higher the BCR will be.

So, the BCR cannot be a reliable sign of a safe encounter.

In a recent publication (Zhang et al., 2021), the case shown in Fig. 3 does not comply with the behaviour indicated in COLREG. Authors indicate that the OS needs to manoeuvre to move away from the TS.

Analysing the proposed movements (Fig. 4) we obtain the passing distances shown in Fig. 5, in true (left) and relative (right) movement. It can be seen how, without any manoeuvre, OS would not cross ahead TS as advised by COLREG and would pass at a distance of 1.4 nm, which can be considered safe, so OS should not manoeuvre.

It is also surprising that after the manoeuvre, which is estimated to be necessary, the passing distance is about 0.30 nm.

5.2. Definition of encounters

Having defined an encounter as unsafe, whether collision or close-quarters, the next step is to analyse who must initiate an evasive manoeuvre and how. It should be remembered that all vessels are obliged to manoeuvre to avoid a collision, even if they have an initial situation of preference. COLREG provides answers to these two questions. It is therefore very important not to simplify its content.

As already mentioned, literature mostly reflects the analysis of vessel in sight encounters, with head-on, crossing and overtaking situations. It is also common the definition of fixed sectors, the application of which any OONW knows cannot be generalised.

Sectors are never exclusive. As an example, possible encounters with relative bearings within the supposed head-on sector on both sides of the vessel are given. Fig. 6 shows the three possible vessel in sight situations with the same Relative Course. β, *aspect*, indicates the angle between the heading of the target vessel and her relative bearing (β_O = Overtaking aspect; β_C = Crossing aspect; β_H = Head-on aspect).

The concept of closed encounter sectors is striking and gives rise to considerable errors. The following shows that the methodology presented in Du et al. (2021), adapted from Goerlandt et al. (2015) and Tam and Bucknall (2010), two of the most cited publications in the collision avoidance literature (Gil et al., 2020), like its predecessors is not effective in identifying potential collision situations and the corresponding manoeuvring.

The ship COLREGs identity presented in Du et al. (2021) is determined according to the relative bearing (RB) and relative heading (RH) (Fig. 7).

There are some inaccuracies in the array of encounter identifications of OS. For example, a TS observed in sector RB8, i.e. in [337.5°, 360°], with a relative Heading in sector RH2, [022.5°, 090°]. Although not indicated, it is assumed that the boundaries are included in all sectors.

As can be seen in the table included in Fig. 7, authors state that any encounter combining RB8 and RH2 is a CR/SO, i.e. the OS should maintain course and speed, at least initially, as it is considered a Stand On vessel in a Crossing encounter scenario.

Fig. 8 shows a case included in these sectors, TS with RB = 348° (in the Fig. 012° = 360°–348°) and RH = 055.5°. For relative bearings in RB8, RH = 055.5° would be the limit for a CR/SO encounter scenario. For lower RH, in the range [022.5°, 055.5°[, the OS is a Give Way vessel in an Overtaking scenario (OT/GW), so the OS should mano euvre.

Fig. 9 illustrates this affirmation, with an example without changing the Relative Bearing = 348° and with RH = 040°.

It is an overtaking encounter, as OS visual enters through the sternlight sector of TS.

Also very surprising is the classification of encounters made for the intersection of sector RB1 with sectors RH4 and RH5 (Fig. 7): (RB1,

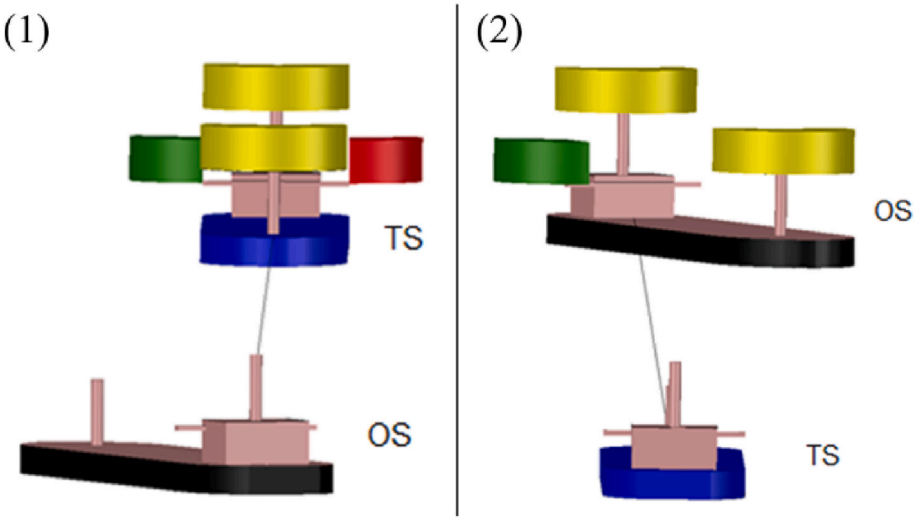


Fig. 19. Views from OS and TS

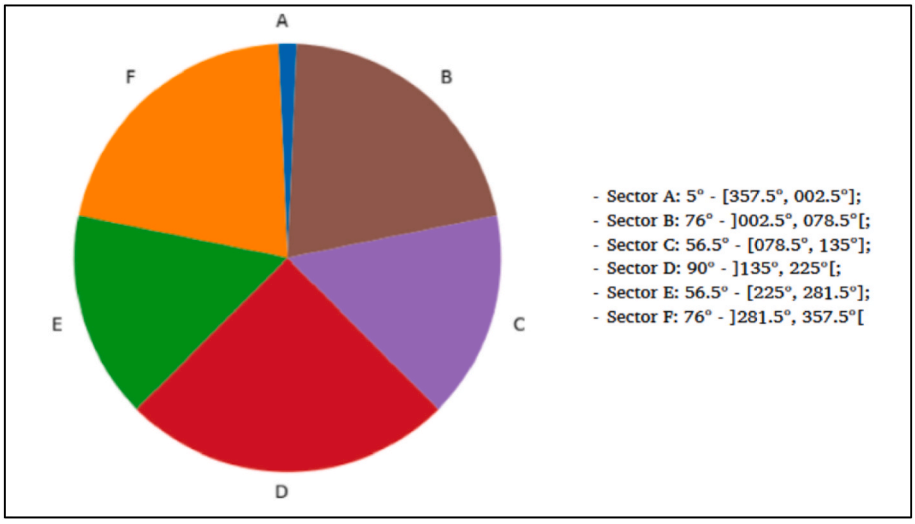


Fig. 20. Sectors defined in Silveira et al. (2021).

RH4) = CR/S0; (RB1, RH5) = HO/GW.

According to this classification, assuming a RB = 001° and RH = 179°, it is a CR/SO. However, with the same RB but with a RH = 181° it is a HO/GW.

Limit values for the sectors RB1 and RB8 ($\pi/8$, $11\pi/8$) are larger than those recommended, following the indication in Tam and Bucknall (2010) to avoid changes from HO to CR with small variations in OS heading. But, as shown in the previous paragraph, a change of 2° in TS heading (RH from 181° to 179°) would have the same effect of switching from HO/GW to CR/SO.

As mentioned, similar problems with fixed encounter sectors can be found in Tam and Bucknall (2010) (Fig. 10).

From this article: "For example, if the obstacle is located in the region R2, and the heading of the obstacle is in the zone TSR1, the resulting encounter type for the obstacle will be an overtaking (OT) encounter" (p.260).

According to Fig. 10, R2 angles are in [22.5°, 90°] and TSR1 angles in [292.5°, 67.5°]. Fig. 11 shows the region R2 including 3 examples of relative bearings with respect to the heading of the OS and the TSR1 zones for the TS. For the encounter to be dangerous, the relative course must generate a situation of collision or close-quarters. We have taken the collision option as the most obvious. In that case, relative courses are the opposite of relative bearings. The range of possible TS headings to generate this dangerous situation is much more limited than the TSR1 indicated by the authors. In a close-quarters situation it would not be so restrictive, but it would not reach the proposed values either.

Furthermore, not all combinations of TSR1 with R2 generate an overtaking situation. As an example, Fig. 12 shows that for a relative bearing of 57.5° (relative course 237.5°) and TS heading in [292.5°, 350°] there is a Crossing (CR) situation, not a OT.

On the other hand, Li et al. (2021), Rong et al. (2021) and Guo et al. (2020) coincide on the identification of 4 regions associated with the Head-on, Overtaking and Crossing situations (2) shown in Fig. 13.

As a counterexample, Fig. 14 shows a Crossing situation within the region associated with Head-on in the aforementioned articles.

Guo et al. (2020) take into account encounters between vessels not in sight, although they interpret rule 19 in a way that is far from the COLREG statement, as shown in Table 10:

Fortunately, they state that: "We mainly study the situation of good visibility at sea in this article" (p.13).

Another feature found in the literature is the variety of criteria for defining the Head-on sector (Table 11), the strangest of which is found in a paper on encounter analysis sponsored by the IALA (2018) (Fig. 15).

Not a few studies adopt a Head On sector of ($-\pi/8$, $+-\pi/8$). The origin

may lie in the work of Tam and Bucknall (2010):

> … there is no explicit guideline in Rule 14 of the COLREGs that defines a head-on encounter, except when discussing the visibility of the masthead light and side-lights; sidelight visibility is defined in Annex I 9(a) of the COLREGs to be small (1–3°). In this study, instead of the recommended values, the HO_1 and HO_2 values were increased (to angles of π/8 radians), and they will be discussed later. (p.259)

We will see that these increased values for HO1 and HO2 will not allow compliance with COLREG Rule 14 (b):

> Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

It is important to highlight the fact that COLREG uses the OONW viewpoint, not a bird's-eye view. The visual condition in a Head-on situation is established in Rule 14 (b) and the light horizontal sectors in Annex I.9. Simulating the appearance would look as shown in Fig. 16: by night, masthead lights of the other in a line or nearly in a line (1) and/or both sidelights (2). By day, the corresponding aspect of the other vessel (3).

Fig. 17 shows the simulation of an encounter with relative bearing = 20° (i.e. 2.5° less than the sector proposed by the authors and therefore within it).

According to the visual definition in COLREG Rule 14 (b), for a collision situation to occur in a Head-on encounter, i.e. for the relative motion to give a CPA = 0′, the speed of the TS would have to be ∞, because for **both ships** to see the lights perfectly aligned, a Heading/Course parallel to the relative bearing would be required. Even allowing for the margin of error of the visible arcs of the lights and a moderate ship yaw, TS Heading should be almost parallel to the relative bearing.

As the authors have not mentioned possible disturbance forces (wind, currents, waves) that would force us to distinguish between Course and Heading, it can be assumed that the two coincide.

As an example, Fig. 18 shows that a TS speed approximately 6 times the OS speed would be required to obtain that situation with small difference between relative bearing and target heading slopes. This mean that for usual OS speeds between 12 and 15 knots, TS speed would be between 72 and 90 knots.

This is the first of the problems with setting wide Head-on angles on each side of the OS.

Also, to qualify the encounter as Head-on it has to be taken into account that **both vessels** must see the same scenario.

From the OS, ignoring the magnitude of the speeds required, it could be accepted the TS is sighted according to Rule 14(b), as shown in Fig. 19 (1).

But it is clear that from the TS the view is different (Fig. 19 (2)).

Therefore, applying Rule 14 (b), the OS might qualify the encounter as Head-on but the TS would qualify it as Crossing.

To conclude this section on the study of sectors, mention should be made of the recent article by Silveira et al. (2021) (Fig. 20). In it, authors refer to the criterion of 5 experts that "decided to define six sectors with six different risk levels" (p.6):

They point out that: "Regarding the risk of collision, the experts' judgement on the order of the sectors, from higher risk to lower risk, is C, E, F, B, A, D".

It is striking, particularly with this assessment of sector C as the most dangerous, that no account has been taken of the fact that, within this sector, relative bearings in]112.5°, 135°] correspond to an overtaking encounter, while relative bearings in [78.5°, 112.5°] correspond to a crossing encounter on the starboard side. In other words, two totally different types of encounters within the same sector.

If overtaking, OS would have to wait for TS to manoeuvre, in order to follow Rule 17, which can be a distressing situation. If crossing on the starboard side, OS has to take the initiative, so the perception of risk should be really different.

It seems that the "Duty to take action" criterion mentioned in the paper has not been taken into account for the risk assessment.

6. Conclusions

COLREG 72 attempts to establish safe coordination in the movement of two vessels in a given close-quarters or collision encounter. With the aim of being a universal and simplified guideline, it establishes a series of rules that respond to the technical means of the time. It always seeks the essential character, avoiding the superfluous, and includes a number of rules establishing more specific communication protocols: Rule 9 d) e) and f); Rule 34, etc.

Any difference in the interpretation and application of COLREG 72 leads to an increased risk of collision in a ship-to-ship encounter. New technological developments offer new forms of communication that can be harnessed to enable a better understanding of the ships' intentions within the rules to be complied with. A handshaking protocol for dialogues and agreements between the OONWs of both ships about the rules/manoeuvres to apply can also be added, as in Argüelles *et al.* (2019; 2021), using the same COLREG philosophy, short and unambiguous messages.

At present, DSS/CASs should be adapted to the requirements of COLREG 72 as a fundamental part of their designs. It is necessary to apply the whole COLREG 72 and not just a part of it, nor to develop schemes based on COLREG 60.

In this paper, basic criteria to consider when making decisions in vessel encounters in accordance with COLREG have been identified and classified.

The results of the analysis of COLREG 72 call for immediate action to unify criteria for the calculations of DSS/CAS algorithms, which the IMO should address as soon as possible:

- Disparity in head-on sectors,
- uncertainty in the interpretation of overtaking in not in sight vessels,
- lack of standardization of the classification of types of propulsion, and restrictions for all navigation aids,
- identification of special COLREG areas,
- ambiguity in the application of Rule 17,

are subjects that need urgent attention.

An analysis of how maritime traffic develops will be necessary. Many paths can be chosen. In any way IMO should take homogeneous criteria for the regulation of navigable areas in order to reduce the possibility of problematic encounters, especially with the emergence of MASS.

It is essential to add some inter-ship communications for data sharing in order to achieve safer encounters. Vessels engaged in an encounter need to be aware of the fact that they are part of the same scenario and situation, which might develop into a critical situation. Having the possibility of sharing and contrasting this information helps making decisions in a consistent way.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

References

ALLIANZ, 2020. Safety and shipping review 2020 [WWW Document]. URL. https://www.agcs.allianz.com/content/dam/onemarketing/agcs/agcs/reports/AGCS-Safety-Shipping-Review-2020.pdf, 9.15.21.

Antão, P., Guedes Soares, C., 2008. Causal factors in accidents of high speed craft and conventional ocean going vessels. Reliab. Eng. Syst. Saf. 93, 1292–1304. https://doi.org/10.1016/j.ress.2007.07.010.

Belcher, P., 2002. A sociological interpretation of the COLREGS. J. Navig. 55, 213–224. https://doi.org/10.1017/S0373463302001686.

Bole, A., Wall, A., Norris, A., 2014. Radar and ARPA Manual Radar and Target Tracking for Professional Mariners, Yachtsmen and Users of Marine Radar, third ed. Butterworth-Heinemann.

Bowditch, N., 2019. American Practical Navigator. An Epitome of Navigation, ume I. National geospatial-intelligence agency.

Brown, E., 1971. Radar Navigation Manual (Pub 1310). U.S. Naval Oceanographic Office.

Canal, Suez, 2015. Rules of navigation [WWW Document]. URL. https://www.suezcanal.gov.eg/English/Navigation/Pages/RulesOfNavigation.aspx, 9.14.21.

Cockcroft, A.N., 1982. The circumstances of sea collisions. J. Navig. 35, 100–112.

Cockcroft, A.N., Lameijer, J., 2011. A Guide to Collision Avoidance Rules. Butterworth-Heinemann.

Crosbie, J.W., 2009. Revisiting the lessons of the early steering and sailing rules for an e-navigation age. J. Navig. 62, 109–117.

Du, L., Goerlandt, F., Valdez Banda, O., Huang, Y., Wen, Y., Kujala, P., 2020. Improving stand-on ship's situational awareness by estimating the intention of the give-way ship. Ocean. Eng. https://doi.org/10.1016/j.oceaneng.2020.107110, 201.

Du, L., Valdez Banda, O., Huang, Y., Goerlandt, F., Kujala, P., Zang, W., 2021. An empirical ship domain based on evasive maneuver and perceived collision risk. Reliab. Eng. Syst. Saf. 213 https://doi.org/10.1016/j.ress.2021.107752.

EMSA, 2020. Annual overview of marine casualties and incidents 2020 [WWW Document]. URL. http://www.emsa.europa.eu/publications/reports/item/4266-annual-overview-of-marine-casualties-and-incidents-2020.html, 9.14.21.

Fujiwara, S., Fujimoto, S., Fuchi, M., KOnishi, T., 2017. Gap between detailed information by navigational equipment and COLREGs rule 19. Fujiwara, Saeko & Fujimoto, Shoji & Fuchi, M. & KOnishi, Tsukasa Trans. Navig. 2, 25–33.

Gil, M., Wróbel, K., Montewka, J., Goerlandt, F., 2020. A bibliometric analysis and systematic review of shipboard Decision Support Systems for accident prevention. Saf. Sci. 128 https://doi.org/10.1016/j.ssci.2020.104717.

Goerlandt, F., Kujala, P., 2011. Traffic simulation based ship collision probability modeling. Reliab. Eng. Syst. Saf. 96, 91–107. https://doi.org/10.1016/j.ress.2010.09.003.

Goerlandt, F., Montewka, J., Kuzmin, V., Kujala, P., 2015. A risk-informed ship collision alert system: framework and application. Saf. Sci. 77, 182–204. https://doi.org/10.1016/j.ssci.2015.03.015.

Guo, S., Zhang, X., Zheng, Y., Du, Y., 2020. An autonomous path planning model for unmanned ships based on deep reinforcement learning. Sensors 20. https://doi.org/10.3390/s20020426.

He, Y., Jin, Y., Huang, L., Xiong, Y., Chen, P., Mou, J., 2017. Quantitative analysis of COLREG rules and seamanship for autonomous collision avoidance at open sea. Ocean. Eng. 140, 281–291. https://doi.org/10.1016/j.oceaneng.2017.05.029.

Hilgert, H., Baldauf, M., 1997. A common risk model for the assessment of encounter situations on board ships. Ger. J. Hydrogr. 49, 531–542.

IALA, 2018. Report 18591.620/TECH_DOC/2. Encounter Model.

IMO, 1986a. Performance standards for automatic radar plotting aids (ARPAs). Resolut. A 823 (19).

IMO, 1986b. General provisions on ships' routeing. Resolut. A 572 (14).

IMO, 2001. Standard marine communication Phrases. Resolut. A 918 (22).

IMO, 2004. Performance standards for the presentation of navigation-related information on shipborne navigational displays. Resolut. MSC 191 (79).

IMO, 2015. Resolution A.1106. Revised Guidelines for the Onboard Operational Use of Shipborne Automatic Identification Systems (AIS).

Kemp, J., 2009. Behaviour patterns in crossing situations. J. Navig. 62, 443–453. https://doi.org/10.1017/S0373463309005293.

Li, L., Wu, D., Huang, Y., Yuan, Z.-M., 2021. A path planning strategy unified with a COLREGS collision avoidance function based on deep reinforcement learning and artificial potential field. Appl. Ocean Res. 113 https://doi.org/10.1016/j.apor.2021.102759.

Lopez-Santander, A., Lawry, J., 2017. An ordinal model of risk based on mariner's judgement. J. Navig. 70, 309–324. https://doi.org/10.1017/S0373463316000576.

Mohovic, D., Mohovic, R., Baric, M., 2016. Deficiencies in learning COLREGs and new Teaching methodology for nautical engineering students and seafarers in lifelong learning programs. J. Navig. 69, 765–776. https://doi.org/10.1017/S037346331500096X.

Montewka, J., Hinz, T., Kujala, P., Matusiak, J., 2010. Probability modelling of vessel collisions. Reliab. Eng. Syst. Saf. 95, 573–589. https://doi.org/10.1016/j.ress.2010.01.009.

Montewka, J., Krata, P., Goerlandt, F., Mazaheri, A., Kujala, P., 2011. Marine traffic risk modelling - an innovative approach and a case study. Proc. Inst. Mech. Eng. Part O J. Risk Reliab. 225–307. https://doi.org/10.1177/1748006X11399988.

Panama Canal, 2019. Regulation on navigation in Panama canal waters. Marit. Regul. [WWW Document]. URL https://www.pancanal.com/eng/maritime/regulations/index.html 9.14.21.

Perera, L.P., Carvalho, J.P., Soares, C.G., 2009. Autonomous guidance and navigation based on the COLREGs rules and regulations of collision avoidance. In: Proceedings of the International Workshop "Advanced Ship Design for Pollution Prevention, pp. 205–216.

Perera, L.P., Carvalho, J.P., Guedes Soares, C., 2010. Fuzzy-logic based parallel collisions avoidance decision formulation for an Ocean Navigational System. In: IFAC Proceedings Volumes, pp. 260–265. https://doi.org/10.3182/20100915-3-DE-3008.00044.

Perera, L.P., Carvalho, J.P., Guedes Soares, C., 2011. Fuzzy logic based decision making system for collision avoidance of ocean navigation under critical collision conditions. J. Mar. Sci. Technol. 16, 84–99. https://doi.org/10.1007/s00773-010-0106-x.

Rong, H., Teixeira, A.P., Guedes Soares, C., 2021. Spatial correlation analysis of near ship collision hotspots with local maritime traffic characteristics. Reliab. Eng. Syst. Saf. 209 https://doi.org/10.1016/j.ress.2021.107463.

Salinas, C.F., 2006. Restricted visibility: in search of a solution. J. Navig. 59, 352–363.

Silveira, P., Teixeira, A.P., Figueira, J.R., Guedes Soares, C., 2021. A multicriteria outranking approach for ship collision risk assessment. Reliab. Eng. Syst. Saf. 214 https://doi.org/10.1016/j.ress.2021.107789.

Smart-Alexandra1, Ever, 2015. Report on the investigation of the collision between the container ship Ever Smart and the oil tanker Alexandra 1 [WWW Document]. URL. https://assets.publishing.service.gov.uk/media/5665aff8e5274a0367000010/MAIBInvReport-28_2015.pdf, 9.14.21.

Smeaton, G.P., Coenen, F., 1990. Developing an intelligent marine navigation system. Comput. Control Eng. J. 1, 95–103.

Szlapczynski, R., Krata, P., 2018. Determining and visualizing safe motion parameters of a ship navigating in severe weather conditions. Ocean. Eng. 158, 263–274. https://doi.org/10.1016/j.oceaneng.2018.03.092.

Szlapczynski, R., Krata, P., Szlapczynska, J., 2018. Ship domain applied to determining distances for collision avoidance manoeuvres in give-way situations. Ocean. Eng. 165, 43–54. https://doi.org/10.1016/j.oceaneng.2018.07.041.

Tam, C., Bucknall, R., 2010. Collision risk assessment for ships. J. Mar. Sci. Technol. 15, 257–270. https://doi.org/10.1007/s00773-010-0089-7.

Tsai, C.-C., Chang, J.-R., Chen, C.-L., 2017. Manoeuvrability-based critical time for preventing close-quarters situations. J. Mar. Sci. Technol. 25, 249–258. https://doi.org/10.6119/JMST-016-1207-2.

Tsou, M.-C., Kao, S.-L., Su, C.-M., 2010. Manoeuvrability-based critical time for preventing close-quarters situations. J. Navig. 63, 167–182. https://doi.org/10.1017/S037346330999021X.

Wang, X., Liu, Z., Cai, Y., 2017. The ship maneuverability based collision avoidance dynamic support system in close-quarters situation. Ocean. Eng. 146, 486–497. https://doi.org/10.1016/j.oceaneng.2017.08.034.

Wróbel, K., 2021. Searching for the origins of the myth: 80% human error impact on maritime safety. Reliab. Eng. Syst. Saf. 216 https://doi.org/10.1016/j.ress.2021.107942.

Xu, Q., Wang, N., 2014. A survey on ship collision risk evaluation. Promet - Traffic & Transp. 26, 475–486. https://doi.org/10.7307/ptt.v26i6.1386.

Zhang, W., Goerlandt, F., Montewka, J., Kujala, P., 2015. A method for detecting possible near miss ship collisions from AIS data. Ocean. Eng. 107, 60–69. https://doi.org/10.1016/j.oceaneng.2015.07.046.

Zhang, G., Thai, V., Yuen, K.F., Loh, H.S., Zhou, Q., 2018. Addressing the epistemic uncertainty in maritime accidents modelling using Bayesian network with interval probabilities. Saf. Sci. 102, 211–225. https://doi.org/10.1016/j.ssci.2017.10.016.

Zhang, X., Wang, C., Chui, K.T., Liu, R.W., 2021. A real-time collision avoidance framework of MASS based on B-spline and optimal decoupling control. Sensors 21. https://doi.org/10.3390/s21144911.