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ANALYSIS OF TWO SHIPS' CLOSE-QUARTERS SITUATION

АНАЛІЗ ЗБЛИЖЕНЬ ДВОХ СУДЕН З РИЗИКОМ ЗІТКНЕННЯ

L.L. Vagushchenko, DSc, professor; **A.J. Kozachenko**, senior lecturer

Л.Л.Вагущенко, д.т.н., професор; **О.Ю. Козаченко**, ст. викладач

National University "Odessa Maritime Academy", Ukraine

Національний університет «Одеська Морська Академія», Україна

ABSTRACT

The development of autonomous ships has marked the beginning of a phase in which both conventional ships and unmanned ships will be sailing on the same water simultaneously. In this new phase, the basic mechanism for coordinating collision avoidance actions of ships will remain the COLREGs (International Regulations for Preventing Collisions at Sea), after being revised to take into account the changed shipping conditions. In such a revision, the principles underlying the COLREGs should be retained and provisions that do not meet the new requirements should be corrected. This study is aimed at identifying such provisions in Section II of Part B of COLREGs, and clarifying the encounter situations affecting the choice of evading actions. Since the subject of the study was two ships approaches that lead to close quarters, the first thing analyzed was the criterion established by COLREGs to identify the risk of collision and the criterion used for this purpose in seamanship. It is recognized that these criteria are different, which may be a prerequisite for incorrect decisions. The work also revealed inconsistencies between COLREGs and used in good seamanship criteria for identifying encounter situations. Recommendations are made to eliminate these inconsistencies. Logical rules for identifying two ships key encounter situations (overtaking, head-on, crossing) and their subtypes influencing the effectiveness of evading actions are given. To define the boundary between head-on and crossing situations and to choose the action in crossing situation depending on the difference between own ship and target courses without using head-on sector are suggested. Classification of non-extreme two ships approaches with risk of collision is proposed, allowing to clearly distinguishing types of encounter situations, which is required for further automation of collision prevention processes.

Keywords: collision avoidance, COLREGs, risk of collision, encounter situation, classification.

АНОТАЦІЯ

Розвиток автономних суден ознаменував початок етапу, на якому конвенційні судна і безпілотні судна плаватимуть по одній і тій самій акваторії одночасно.. На цьому новому етапі основним механізмом, що координує дії суден під час уникнення зіткнень, залишаться МПЗЗС-72, після їхнього переопрацювання для врахування змінених умов судноплавства. При такій переробці покладені в основу МПЗЗС-72 принципи мають бути збережені, а положення, що не відповідають новим вимогам, відкориговані. Це дослідження спрямоване на виявлення таких положень у розділі II частини B МПЗЗС-72, і уточнення ситуацій зближення суден, що впливають на вибір дій щодо запобігання зіткненню. Оскільки предметом дослідження були зближення з ризиком зіткнення двох суден, то, насамперед, було проаналізовано встановлений МПЗЗС-72 критерій для виявлення ризику зіткнення і критерій, використаний з цією метою в морській навігаційній практиці. Зазначено відмінність цих критеріїв, яка може стати передумовою неправильних рішень. Під час виконання роботи також виявлено невідповідності критеріїв для ідентифікації ситуацій зближення суден із ризиком зіткнення. Вироблено рекомендації для усунення цих невідповідностей. Запропоновано визначати межу *між ситуаціями зближення суден, що йдуть прямо один на одного, і перетинання курсів, та обирати дію в ситуації перетинання курсів тільки залежно від різниці між курсами суден без використання носового сектора курсових кутів. Наведено логічні правила для визначення ключових ситуацій зближення суден (обгін; зближення суден, що йдуть прямо один на одного; перетинання курсів) та їх видів, що впливають на ефективність анти-колізійних дій. Запропоновано класифікацію не екстремальних ситуацій зближення суден з ризиком зіткнення. Це дає змогу чітко виділяти види цих ситуацій, що необхідно під час подальшої автоматизації процесів запобігання зіткненню.*

Ключові слова: уникнення зіткнень, МПЗЗС-72, ризик зіткнення, ситуація зближення, класифікація.

Problem formulation

The ships collisions prevention is one of the main problems in maritime navigation, as collisions are accompanied by significant economic, environmental damages and even loss of human life. Mechanisms for coordinating the conduct of ships play an important role in solving this problem. Of particular importance is binary coordination, which regulates the actions of two approaching vessels and is also the foundation for determining measures to avoid collisions with multiple vessels. At the base of coordination lays the concept of a ship's "obligations", which postulates the need for the ship to perform actions that lead to the achievement of a predetermined objective in the interests of the own ship and other vessels. The second important concept is "situation", which specifies the conditions under which obligations are fulfilled, and the circumstances in which a ship may or must refuse to behave as prescribed. A distinction is made between statutory and non-statutory coordination. The first is a set of international and national regulations and guidelines. The main of these documents are COLREGs (International Regulations for Preventing Collisions at Sea). These documents also include local regulations established by individual states for their waters.

Non-statutory coordination, referred to in maritime navigation as good seamanship (GSMS), serves to fill gaps in COLREGs which do not provide an answer for all encounters. This coordination is based on the ability of bridge personnel to solve collision prevention problems in encountered situations, both represented and not represented in COLREGs. It is based on the standardized qualification of ship officers, which means the precise definition of the level of competence required to operate and control the ship.

Good seamanship is the fundamental concept from which all other rules, including COLREGs, have been derived. Today, the obligations for mariners to take into account the requirements and recommendations of good seamanship are strongly coined by international conventions such as COLREGS and the STCW. COLREGs are a binary coordination mechanism. They represent a small part of good seamanship and contain only basic, broadly applicable, coordinating provisions. These rules are subject to statutory implementation.

Analysis of changes in shipping shows that the time has come to revise the acting COLREGs [1]. Attention is drawn to this in a number of publications, in which the drawbacks of these rules are examined in detail, and methods of their improvement, clarification and concretization are proposed. It is noted that the lack of proper COLREGs increases the risk of ships collisions at sea. The development of Maritime Autonomous Surface Ships (MASS) and their constituent Unmanned Surface Vessels (USV) is also one of the reasons to improve COLREGs.

Analysis of recent studies and publications

The results of research into the issues of improving COLREGs, of their algorithmization, of considering these rules in computer supporting the decisions of navigators and in the automatic control of the anti-collision process are reflected in many publications. In the paper [2] the requirements for a fuzzy interface system are defined, taking into account COLREGs. An original solution is proposed to solve the multi-ship collision avoidance problem. The paper [3] contributes to the development of algorithmic rules and in particular algorithmic COLREGs. The focus is on the codification of COLREGs into a machine-executable system applicable to MASS. COLREGs are modeled as a fuzzy expert system based on ordinary seamanship practice. A review of existing research on COLREGs and recent improvements in maritime education was conducted in paper [4]. In study [5], a three-layer hybrid collision avoidance system for autonomous vessels compliant with COLREGs rules 8 and 13-17 is presented. The system consists of a high-level planner, an algorithm based on model predictive control, and an algorithm that handles emergency situations according to COLREGs. The study [6] presents the results of a questionnaire of licensed deck officers on the potential future of COLREGs with regard to the implementation of MASS. In [7], an algorithm for USV to avoid collisions with ships based on COLREGs is suggested. The proposed algorithm predicts hazardous situations using DCPA and TCPA. The solutions are based on the dynamic window method improved to meet the COLREGs requirements. The study [8] focuses on crossing situation recognition. A comparative analysis between an autonomous collision avoidance algorithm and the procedure used by a navigator to identify the crossing situation is performed. In the paper [9], an approach to COLREGs-compliant ship navigation is considered. System architecture for autonomous and unmanned surface vessels is proposed. Attention is paid to software for collision avoidance and reducing the associated risks. The paper [10] contains a model to analyze the risk of two common marine accidents: collision and grounding. The model uses a formula for calculating risk that takes into account both the probability of occurrence of an undesirable event and its consequences. In [11], a simulation model for ship navigation in collision situations is established. According to the general COLREGs requirements and navigation rules, the definition of collision situations is quantified. Multiple genetic algorithm and linear extension algorithm are used for trajectory planning to avoid collisions. In paper [12], scenarios in which both conventional and unmanned ships will simultaneously sail in the same water area are considered. It is noted that such hybrid scenarios will remain relevant for quite a long period of time until conventional ships are completely replaced. A literature review on maritime collision avoidance systems is given in [13] to verify their compliance with COLREGs. Shortcomings are identified and solutions are suggested. The paper [14] presents the results of the development of a method for determining, systematizing and displaying ship collision avoidance information based on the Collision Threat Parameters Area technique. The method allows visualizing navigational threats as well as possible collision avoidance maneuvers. It is noted in [15] that collision risk assessment is usually based on the concept of danger domains. An alternative method for such evaluation is presented that is consistent with COLREGs from different points of view. The paper [16] discusses the responsibility for ship collision avoidance and the effect of High Ship Speed Ratio on it. Proposals for modeling anti-collision actions based on intelligent platform are developed. In paper [17], the main COLREGs accounting methods proposed for use in collision avoidance systems are discussed and critically analyzed. The paper [18] proposes a coordination system which consists of two algorithms for avoiding collision risk and returning to scheduled waypoint. The first algorithm is based on the VO (velocity obstacle) method and the second algorithm is derived from LOS (light of sight) guidance.

In unmanned vessel equipment, methods shall be used to automatically perform planning of effective anti-collision maneuvers, to control the realization of these plans, and, if necessary, to correct these plans during the realization process. The provisions of good seamanship, which include those of COLREGs, should be considered when planning maneuvers. COLREGs, in the past, present, and foreseeable future, are destined for humans. On manned vessels, anti-collision decisions are made by the captain or officer on watch, taking into account COLREGs and GSMS. Decisions are prepared using ARPA (Automatic Radar Plotting Aids) and/or ECDIS (Electronic Chart Display and Information System) or CASS (Collision Avoidance Support System), which recommends a collision avoidance maneuver taking into account to a certain amount the COLREGs and GSMS provisions.

Changes in shipping conditions over time and the introduction of scientific and technological achievements on ships necessitate certain changes in the control of anti-collision processes and in the mechanisms for coordinating ships' actions. These demands of practice relatively quickly lead to refinement of the good seamanship provisions. In COLREGs, on the other hand, they are not counted for long period of time. As a result, differences between the COLREGs and good seamanship provisions appear which may be a prerequisite for incorrect decisions. It should be noted that the updating of COLREGs does not imply that they should be greatly expanded to include non-mainstream GSMS provisions. COLREGs should remain compact and responsive to the requirements of shipping. One of COLREGs updating tasks is to detect inconsistencies between the provisions of these rules and those of GSMS and to resolve them. It determined the purpose of the study, the results of which are described in this paper.

Formulating the objectives of the paper

The objective of the study is analysis of the two ships key encounter situations allocated by COLREGs, detection of differences between COLREGs and GSMS criteria for identifying these situations, development recommendations for eliminating such differences, division key situations into subtypes and determination a classification and coding system for key situations and their subtypes.

Presentation of work results

Abbreviations, denotations, suppositions. In Table 1 the abbreviations (Abr.) and denotations (Den.) more than once used below are presented.

Table 1. The abbreviations and denotations

Abr.	Den.	Concept	Abr.	Den.	Concept
OS	A	Own ship	-	D	Distance between ships
TS	B	Target ship	-	K_A, V_A	OS course and speed
BCR	S	Bow/stern crossing range	-	K_B, V_B	TS course and speed
Course	K	Course through water	-	K_{AB}, V_{AB}	OS course and speed relative to TS
CD	θ	Course difference (K_B-K_A)	-	K_{BA}, V_{BA}	TS course and speed relative to OS
CPA	-	Closest point of approach	-	P_A	OS point at closest approach to TS
CRS	-	Collision risk situation	-	P_B	TS point at closest approach to OS
DCPA	δ	Distance at CPA	-	P_C	TS point at OS course line crossing
GWV	-	Give way vessel	-	γ^H	Head angles limit
NM	-	Nautical mile	-	γ^S	Stern angles limit (112,5°=10 points)
RB	γ	Relative bearing	-	$\delta^\wedge$	Safe DCPA limit
SOV	-	Stand on vessel	-	$\delta^\vee$	DCPA contact zone limit
Speed	V	Speed through water	-	Δ	$K_{AB}-K_A$
TA	ψ	Target angle (aspect)	-	$\theta^\vee$	Limit of negligible CD
TCPA	τ	Time to CPA	-	$\tau^\wedge$	Safe TCPA limit

The following suppositions are used in solving the task at hand:

- The course and speed of the ships remain unchanged during the considered approach intervals.
- Parameters of positions, motion, mutual positions of OS and TS refer to the centers of mass of these ships.
- DCPA values are positive/negative when at the time of closest approach TS will be to the right/left of the line of OS course relative to TS.
- TCPA values are considered positive/negative when the OS is moving before/after CPA.

- Target relative bearing and angle are measured from the heading within the range of 0° to 180° clockwise (right) and counterclockwise (left). According to the first/second direction, these parameters are called "right-handed"/"left-handed" and are considered positive/negative. Target angle is the relative bearing of own ship from a target vessel.
- A course is considered to be a course through water so that the course reference system will be compatible with the relative bearing and target angle reference system,
- The angles $\theta=(K_B-K_A)$ and $\Delta=(K_{AB}-K_A)$ are measured from K_A and are taken from 0° to 180° clockwise (right) and counterclockwise (left). According to the first/second direction of reference, these parameters are called "right-handed"/"left-handed" and are considered positive/negative.
- It is considered that the separation of ship encounter situations should meet the requirements of the hierarchical classification method.

According to hierarchical classification method:

- The basis for the division must be defined by a feature essential to the task to be solved.
- The elements of division should exclude each other.
- The division at each of its stages should be performed on only one basis.
- The division should be proportional, i.e. the initial set size should be equal to the union of the subsets obtained by division.

We will denote positive/negative DCPA, relative bearing, and angle between courses by pDCPA/nDCPA, pRB/nRB, and pCD/nCD, respectively.

The Rules referenced below in the text are part of the COLREGs.

Collision risk situations. Of the methods proposed for collision risk assessment [19], we will consider only the methods used in marine navigation practice. When solving collision avoidance tasks using the maneuvering board chart and in onboard collision avoidance systems [20, 21], the collision risk is identified applying pre-defined limits ($\delta^\wedge$ and $\tau^\wedge$) of DCPA and TCPA, using a logical expression IF (ABS(δ)$\le\delta^\wedge$) AND ($0<\tau\le\tau^\wedge$) THEN CRS. Call this condition the δτ-criterion. Depending on $\delta^\wedge$, $\tau^\wedge$ and the boundary ($\delta^\vee$) of the DCPAs at which there will be ship-to-ship contact at the end of the approach, the situations presented in Table 2 can be allocated.

Table 2. Division of situations depending on DCPA and TCPA

No	Situation type	Existence condition
Not CRS		(ABS(δ)$>\delta^\wedge$) OR ((ABS(δ)$\le\delta^\wedge$) AND ($\tau>\tau^\wedge$))
1	Safe situation	ABS(δ)$>\delta^\wedge$
2	Expected CRS	(ABS(δ)$\le\delta^\wedge$) AND ($\tau>\tau^\wedge$)
CRS		(ABS(δ)$\le\delta^\wedge$) AND ($0<\tau\le\tau^\wedge$)
3	Non-contact CRS	($\delta^\vee<$ABS(δ)$\le\delta^\wedge$) AND ($0<\tau\le\tau^\wedge$)
4	Contact CRS	(ABS(δ)$\le\delta^\vee$) AND ($0<\tau\le\tau^\wedge$)

The value of $\delta^\vee$ can be calculated by taking into account the size of OS and TS, the geometry of their approach, the DCPA determination error and the Bernoulli's principle. Approximately, this boundary can be considered equal to the length of the larger of the vessels. DCPA at which there will be ships collision at the end of the approach will be called "contact DCPA" (cDCPA). The main factors affecting the value of $\delta^\wedge$ and $\tau^\wedge$ are as follows:

- type of navigation area and the density of traffic in it;
- features (size, maneuverability, speed) of the OS and TS;
- errors in determining the parameters of TS position and movement.

The $\delta^\wedge$ value is chosen so that the evading maneuver determined by it satisfies the requirements of safety and economy. These requirements are contradictory. When $\delta^\wedge$ increases, the risk of collision decreases, but the time of the evading maneuver and loss of sailing time rise. In the open sea it is recommended to avoid ships at a distance of 2÷3 NM. This recommendation was developed before automatic radar plotting aids appeared on ships. Since then the characteristics of radar equipment have improved considerably, which allowed to detect objects at a greater distance, and more accurately and more quickly determine the parameters of target movement. Significant improvement of information support of collision avoidance processes was contributed by implementation of AIS. Taking into account these achievements, many captains use in the open sea smaller recommended values of $\delta^\wedge$, most often 1.0 NM. According to the authors of the paper [22], more than 90% of their respondent seafarers will not take any evasive action when the DCPA is greater than 1.5 NM. In constricted waters, due to the limited free water area, the value of $\delta^\wedge$ is taken smaller than in the open sea.

The second criterion for detecting the collision risk is presented in Rule 7 (Risk of collision). This criterion is not used in computer systems. It is applied in the visual assessment of the risk of collision. Sections (d/i) and (d/ii) of Rule 7 specifies that such risk shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change; and, such risk may sometimes exist when bearing appreciable change, particularly when approaching a very large vessel or a tow or when other vessel is at close range. What change of bearing to consider as not appreciable and what is the close range between the ships is not numerically determined. The bearing (Π) of the target during the approach of ships can be represented as $\Pi = K_{AB} + \alpha$, where $\alpha = \mathrm{asin}(\delta/D)$. It follows that the change in bearing (Π_2-Π_1) is equal to (α_2-α_1), where Π_2, α_2 and Π_1, α_1 correspond to distances D_2, D_1. The rate of bearing change depends on the velocity V_{AB} of the own ship relative to the target. The bearing change and average rate of bearing change at V_{AB}=30 kn for intervals of distances between ships in the process of their approach, corresponding to different values of DCPA, are shown in Table 3.

Table 3. Changes of bearing and average rate of bearing change at VAB=30 kn

δ \ *D*	**12-10** NM	**10-8** NM	**8-6** NM	**6-5** NM	**5-4** NM	**4-3** NM
0,25 NM	0,2°	0,4°	0,6°	0,5°	0,7°	1,2°
	0,1°/min	0,1°/min	0,1°/min	0,2°/min	0,4°/min	0,6°/min
0,5 NM	0,5°	0,7°	1,2°	0,9°	1,5°	2,4°
	0,1°/min	0,2°/min	0,3°/min	0,5°/min	0,7°/min	1,2°/min
1,0 NM	0,9°	1,5°	2,4°	1,9°	3,0°	5,0°
	0,2°/min	0,4°/min	0,6°/min	1,0°/min	1,4°/min	2,4°/min
1,5 NM	1,4°	2,2°	3,7°	3,0°	4,5°	8,0°
	0,4°/min	0,5°/min	0,9°/min	1,4°/min	2,2°/min	3,6°/min
2,0 NM	1,9°	3,0°	5,0°	4,1°	6,4°	11,8°
	0,5°/min	0,7°/min	1,2°/min	1,9°/min	2,9°/min	4,8°/min

If distances not exceeding 5 NM are considered to be small, then, in our opinion, the change in bearing (see Table 3) will be significant at $\delta \geq 0.5$ NM. Thus, for the collision risk existing under the δτ-criterion, there may be appreciable changes in bearing at distances larger than close range.

In Section (c) of Rule 7 it is noted that in determining the risk of collision "assumptions should not be made on the basis of incomplete information, especially radar information". When the TS and OS do not change course and speed, to obtain a reasonable conclusion as to whether there is a risk of collision, at a least four parameters of the target's motion must be known: coordinates or bearing and distance; true course and speed. The TS and OS motion parameters are used to obtain the relative motion parameters (DCPA and TCPA, relative bearing and aspect of the target, the difference between the OS and TS courses, the speed ratio of these vessels, etc.), which are used to assess the risk of collision and determine the type of approach.

If COLREGs take into account a large number of situations (sets of circumstances) that can lead to a collision, the volume of these rules will become very large, and there will be difficulties in their operational use by a person. Therefore, only the most important (key) such situations are introduced into the rules. Their allocation can be recognized as rational when their type is the same for OS and TS in the process of approaching.

In COLREGs, the rules for coordination of anti-collision actions for ships in sight of one another and for ships in restricted visibility are separated.

Situations of ships approaching in sight of one another allocated in COLREGs. In COLREGs for ships in sight of each other, the key situations are Overtaking, Head-on and Crossing. From Rule 13 (Overtaking), it follows that the basis for identifying the first situation is the relative bearing of TS from OS, or OS from TS (target angle). In this situation, overtaking vessel shall keep out of the way of the overtaken vessel.

In COLREGs two bases are used to define a head-on situation. Under section (a) of this Rule, the first basis for distinguishing this situation is the angle between the course of one ship and the opposite direction to the course of the other ship. This angle must be small. Its limit value $\theta^{\vee}$ is normally taken in the range 5°-10°, which is in accordance with Resolution MSC.192(79) “The revised performance standards for radar equipment”. According to Annex 34 of this resolution, for non-high speed vessels, the tracking facility should present after 3 minutes steady state tracking, the course of a target with accuracy 5° (95% probability). The accuracy of data on the course of targets provided by the AIS is higher. According to Rule 14, section (b), the second indication to distinguish this situation is the relative bearing from OS to TS and from TS to OS, which must be small. Its limiting value (γ^{H}) is most often considered to be 5°. This meets the requirements of COLREGs for ships' lights with respect to their sector boundaries. According to Annex I.9 of COLREGs, the error in the display by sidelights a 0° and 112.5° boundaries of its sector should be within ±3° and ±5°, respectively. The error in the display by the masthead light and sternlight of their sectors boundaries shall be within ±5°.

Crossing situations include ships approaches that are not overtaking and head-on. Under Rule 15 “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”. In the majority of cases, the GWV uses a turn to the starboard in this situation. In the study, the results of which are presented in [23], it was obtained that to avoid collision, ferries changed course to the starboard 64.5% and to the port 23.5%, with mean amplitude of 18°, at an average distance of around 3.5 NM to the target, to cross astern of TS at a distance of 0.7 NM or ahead at a distance of 1 NM. In most cases, the ferry speed was greater than the target speed when crossing ahead of the target. The percent of maneuvers with a change in speed was 12%.

To the content of Rules 13-15 presented in Table 4 conditions of key situations existence correspond.

Table 4. Key CRSs in COLREGs

No	CRS	Existence condition
Overtaking		$(ABS(\psi)\geq\gamma^{S})$ OR $(ABS(\gamma)\geq\gamma^{S})$
1	Overtaking TS	$ABS(\psi)\geq\gamma^{S}$
2	Overtaking OS	$ABS(\gamma)\geq\gamma^{S}$
Not overtaking		$(ABS(\psi)<\gamma^{S})$ AND $(ABS(\gamma)<\gamma^{S})$
3	Head-on	$(180°-ABS(\theta)\leq\theta^{\vee})$ AND $(ABS(\gamma)\leq\gamma^{H})$
4	Crossing	NOT($(180°-ABS(\theta)\leq\theta^{\vee})$ AND $(ABS(\gamma)\leq\gamma^{H})$)

Under such conditions, approaches on opposite courses in which the TS is not in the head-on sector will be classified as a crossing situation. This drawback will not occur if the half-width (γ^H) of the head-on sector is increased to 24°. This value is obtained from the AP_1P_2 triangle (Figure 1), taking into account the distance (D_F≈5 NM) of small target detection and $\delta^\wedge$=2 NM.

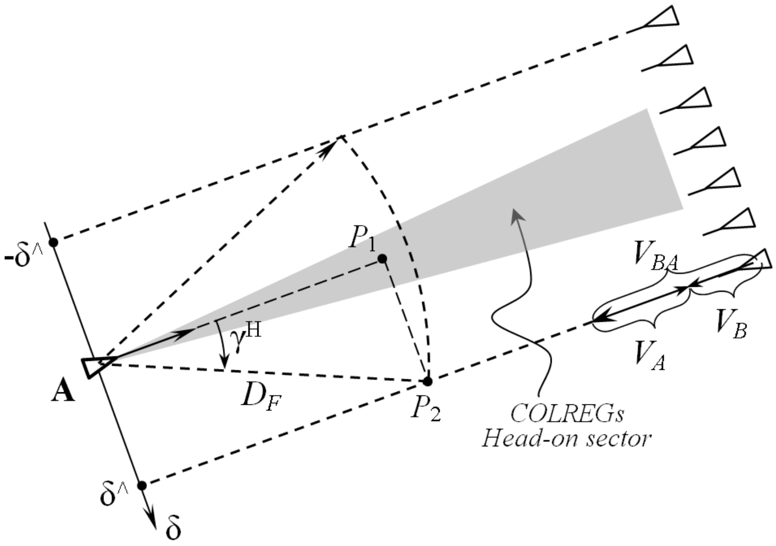

Figure 1. Toward a definition of the head-on sector

Increasing the head-on sector has been suggested before (Table 5).

Table 5. Proposals for increasing the head-on sector

Head-on situation	
γ° (Port and Stb)	**Literature**
10°	[10]
15°	[14]
22,5°	[15]
30°	[24]

Crossing CRSs can be divided into the types shown in Table 6 and Figure 2, where index B corresponds to the number of the situation in the table.

Table 6. Types of crossing CRS and their conditions of existence

No	Crossing CRS type	Existence condition
1	Starboard-to-port encounter	(γH<γ<γS) AND (−γS<ψ<−γH)
2	Port-to-port encounter	(−γS<γ<−γH) AND (−γS<ψ<−γH)
3	Port-to-starboard encounter	(−γS<γ<−γH) AND (γH<ψ<γS)
4	Starboard-to-starboard encounter	(γH<γ<γS) AND (γH<ψ<γS)

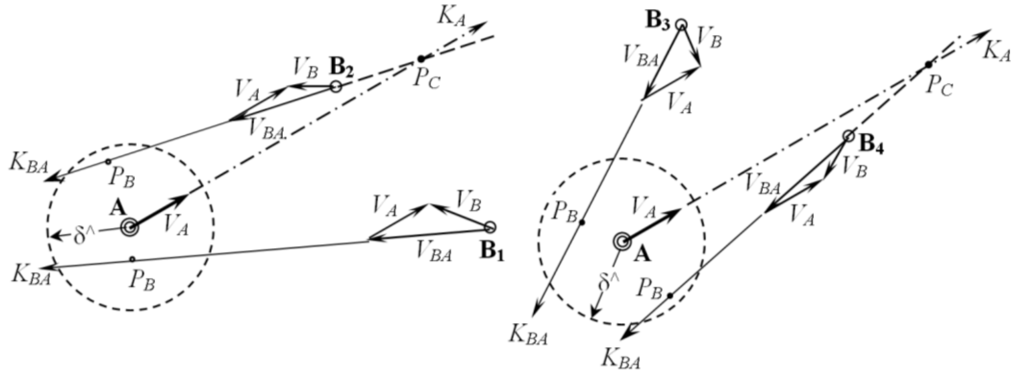

Figure 2. Types of crossing situations

The first and third types of situations are classified as ordinary and the second and fourth as special situations. In ordinary/special situations the target is detected before/after it crosses the OS course line and the relative bearing and aspect of TS have different/same sign. In Rule 15, GWV are defined only for ships in ordinary situations. COLREGs do not coordinate the ships' conduct in special situations. In the fourth situation (see Table 5) both ships have another one on their starboard side. Under Rule 15 they must take action to avoid collision. If it's a starboard turn, the vessels' actions will be similar to those in the head-on situation. In the second situation both ships have another ship on their port side. According to Rule 17 OS and TS in this case must maintain course and speed, which will result in a dangerous approach. Special crossing situations are rare but possible. They may appear when there is a small difference (Δ) between the OS course relative to TS and the OS course. The zone (A$P_C B_b B_\beta P_\beta$) of ordinary first and zone (A$P_b P_c$) of special second situation in the risk area ($B_b B_\beta P_\beta P_b$) are shown in Figure. 3.

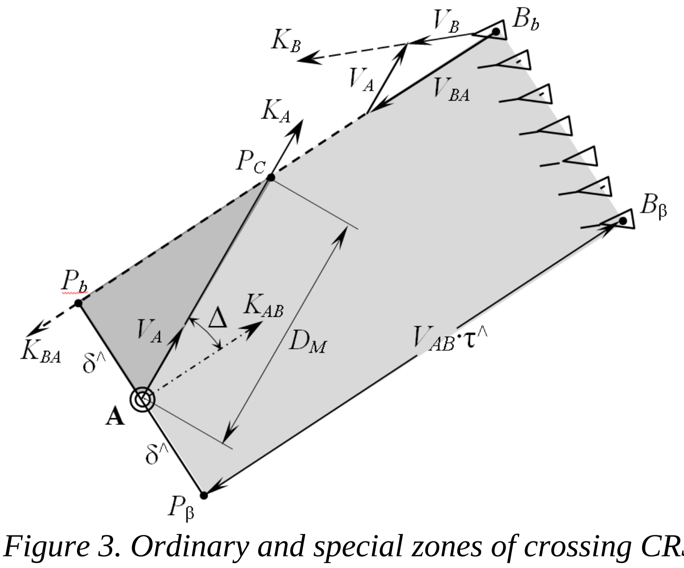

Figure 3. Ordinary and special zones of crossing CRS

As follows from Figure 5, the maximum distance (D_M) between OS and TS at which special situation can occur is D_M=δ^/sin(Δ). Table 7 illustrates the values of D_M for δ^=2.0 NM and different values of Δ.

Table 7. The D_M distance as function of Δ

ABS(Δ)	**5°**	**10°**	**15°**	**20°**	**25°**
D_M , NM (δ^=2,0 NM)	22,9	11,5	7,7	5,8	4,7

To avoid special situations at detection distances $D_F \geq 5$ NM when $\delta^{\wedge}=2$ NM, the half-width of the Head-on sector should be $\gamma^H = \text{asin}(\delta^{\wedge}/D_F) = 24°$.

When ships are in sight of one another the navigational status of the target is required to choose an evasive maneuver. Radar does not provide this attribute. The target status is determined from target shapes/lights and AIS data. According to Rule 22 (Visibility of lights), on ships of 50 meters or more in length, the visibility of lights intended to determine the status of the ship shall be at least 3 NM, and on ships of less than 50 meters, at least 2 NM. For approaching vessels on close to opposite courses such a distance can hardly be considered sufficient. On the AIS line, target data is obtained at a distance of 20-30 NM to the target.

Proposals for improving the borders between key situations. In the COLREGs modernization proposals concerning the boundaries of key situations, it is overwhelmingly considered that the boundaries between overtaking and crossing situations should remain the previous (RB=±112.5°). This is primarily due to the sectors of ships' navigation lights, by which one can visually judge the other vessel's aspect. Most of the proposals relate to correcting the deficiencies of the COLREGs boundaries separating head-on and crossing situations. Among these proposals, two types can be distinguished. In the first one, the basis for separating head-on and crossing situations is the relative bearing of the target, and in the second one, the difference between the courses of the ships.

Separation of head-on and crossing situations by relative bearing. Using such basis, the boundaries between head-on and crossing situations will be correct if the half-width of the head-on sector is increased to 24°. Division of CRS into key types in this case can be represented by the scheme shown in Figure 4. In this figure and in the situation separation schemes below, the contours of the key situation blocks are colored red.

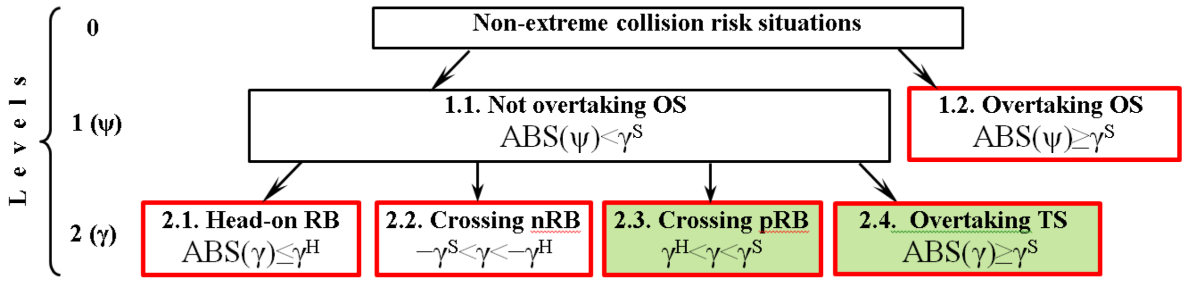

Figure 4. Division of CRS into key types depending on TA and RB

Let us call such a division of encountered situations bi-level. We will consider the level number of element with its number at this level as the code of this element. The components of block 1.1 (Not overtaking OS) can be represented as a RB-diagram (Figure 5).

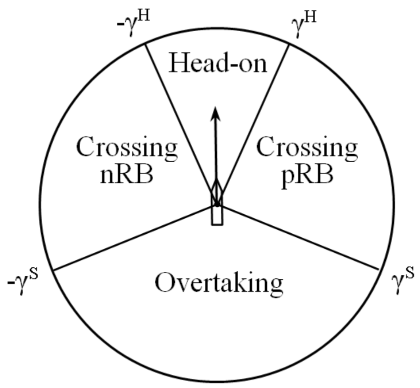

Figure 5. RB-diagram of key situations in the "Not overtaking OS" block

For the considered separation of OS and TS approaches, their possible combinations are shown in Table 8.

Table 8: CRS type of vessels in bi-level separation of situations

No	Own ship CRS	Target ship CRS
1	Head-on	Head-on
2	Head-on	Crossing, OS port
3	Head-on	Crossing, OS starboard
4	Crossing, TS port	Head-on
5	Crossing, TS starboard	Head-on
6	Crossing, TS port	Crossing, OS starboard
7	Crossing, TS starboard	Crossing, OS port
8	Overtaking OS	Overtaken TS
9	Overtaken OS	Overtaking TS

Differences in situation types for OS and TS during approaches lead to an increase in options requiring coordination. The second disadvantage is that increasing the head-on sector results in fewer situations where the OS is SOV. Accordingly, when the head-on sector increases on average per voyage, losses of sailing time due to avoiding collisions with other ships will rise.

Separation of head-on and crossing situations by the difference between the courses of the vessels. The boundary between head-on and crossing situation in this case is the difference $\theta^{\vee}$ between the course of one ship and the opposite direction to the course of the other ship. The value of $\theta^{\vee}$ is usually considered to be 5°. The division of CRS into key types in this case may be represented by the scheme shown in Figure. 6.

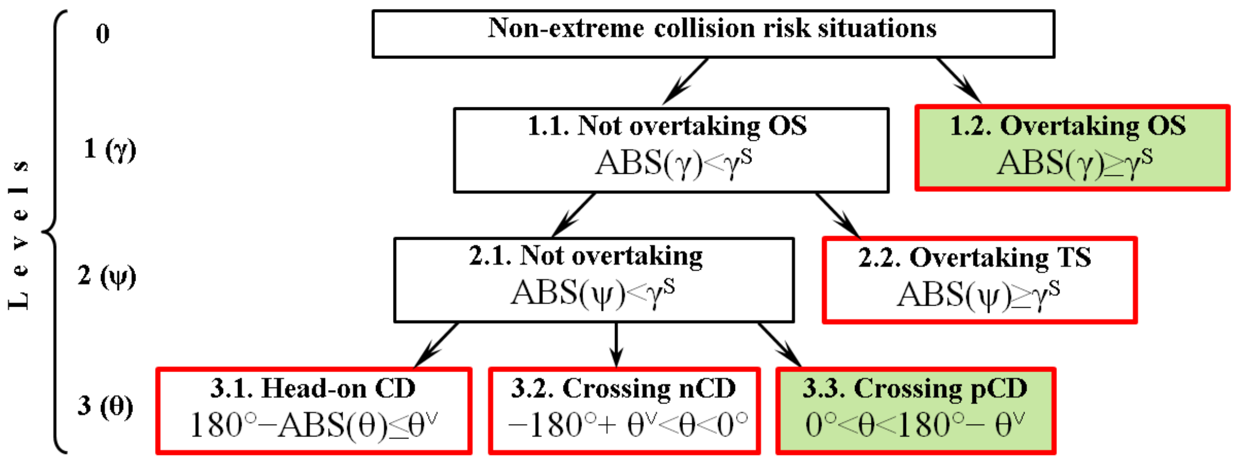

Figure 6. Division of CRS into key types depending on RB, TA and CD

We will call this way of separating situations a three-level division. Head-on sector is not being used in this case. The GWV and her conduct is determined by whether the courses of the ships are opposite or intersecting. Rule 15 corresponding to this division may be presented as follows: When two power-driven vessels are crossing so as to involve risk of collision, the vessel whose course is crossed by the other ship from starboard to port shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel. As so worded, this Rule will coordinate the actions of ships in both ordinary and special situations. CRS type and rank of approaching vessels under these conditions are presented in Table 9.

Table 9: CRS type and rank of ships under three-level separation of situations

No	**Own ship CRS**	**Target ship CRS**	**OS rank**	**TS rank**
1	Head-on	Head-on	GWV	GWV
2	Crossing, pCD	Crossing, nCD °	SOV	GWV
3	Crossing, nCD	Crossing, pCD	GWV	SOV
4	Overtaking OS	Overtaken TS	GWV	SOV
5	Overtaken OS	Overtaking TS	SOV	GWV

Here, the type of situation (overtaking, head-on and crossing) for OS and TS when they approach each other is the same. As a result, the options requiring coordination and the loss of sailing time due to avoiding collisions with other ships will be less than in two-level separation of situations. It is considered below that Head-on and Crossing situations are separated by CD.

Dividing key situations into subtypes. When solving collision avoidance tasks, not only key situations are recognized, but also their subtypes that influence the decisions adopted. The sub-types of approaches of non-maneuvering OS and TS, which can be distinguished depending on the values determined from the course and speed of these ships, are given below.

For the overtaking situation, the main subtypes of approach influencing the choice of overtaking ship's maneuver and preferred actions in them are shown in Table 10.

Table 10. Overtaking types for GWV, existence condition and preferred action

No	Overtaking types for GWV	Existence condition	Turn
1	Same courses, nDCPA	$(ABS(\theta) \le \theta^{\vee})$ AND $(\delta < -\delta^{\vee})$	To port
2	Same courses, cDCPA	$ABS(\delta) \le \delta^{\vee}$	To starboard
3	Same courses, pDCPA	$(ABS(\theta) \le \theta^{\vee})$ AND $(\delta > \delta^{\vee})$	To starboard
4	Overlapping, pCD	$\theta^{\vee} < \theta < 180°$	To port
5	Overlapping, nCD	$-180° < \theta < -\theta^{\vee}$	To starboard

Here is an example of approaching subtypes on same courses (Figure 7). From figures 7*a*/7*c*, it is easy to see that when the OS is to the starboard/port of the TS course line (nDCPA/pDCPA), it is more economical to steer the OS to the starboard/port to bypass the TS at a given distance. When the OS is on the TS course line (Figure 7*b*), overtaking the TS on its starboard and port side at a given distance is equally time-efficient.

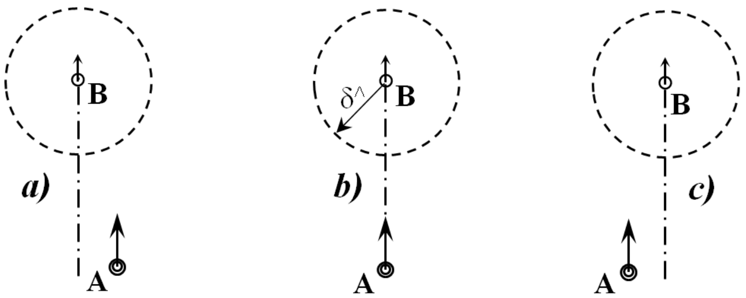

Figure 7. Subtypes of overtaking when OS and TS courses coincide

In an overtaking situation with overlapping OS and TS courses, it is possible to distinguish approaches in which the difference between the TS and OS courses is positive (Figures 8*a* and 8*b*) and negative (Figures 8*c* and 8*d*). These approaches are divided into two subtypes. In the first one (Figures 8*a* and 8*c*), the evaluation of the encounter situation is performed before the target crosses the OS course line. The second subtype (Figures 8*b* and 8*d*) includes situations whose evaluation starts at or after the moment TS is on the OS course line. Figure 8 shows that in a situation with pCD/nCD, it is more economical to bypass the TS at a given distance by evading the OS to the port/starboard

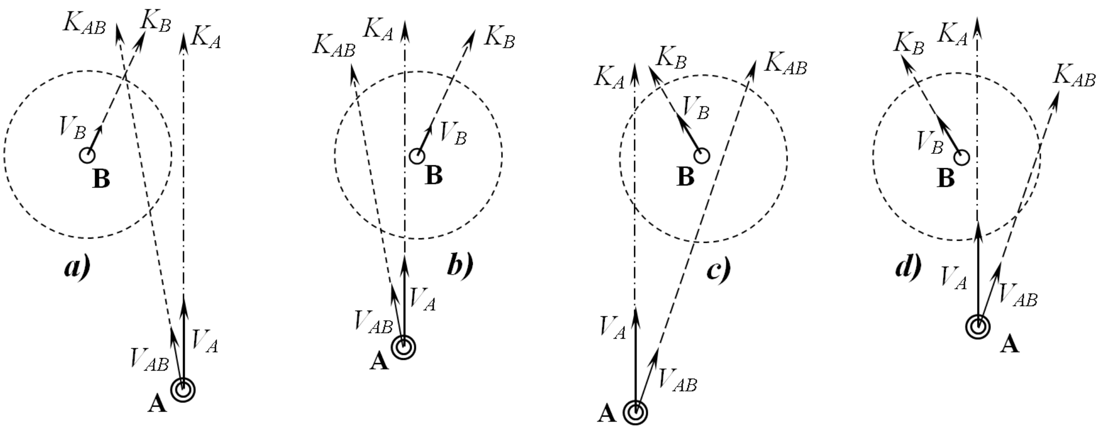

Figure 8. Subtypes of overtaking at overlapping OS and TS courses

Head-on CRSs are divided according to DCPA into subtypes, presented in Table 11 and Figure 9, in which the index B corresponds to the number of the situation in the table.

Table 11. Subtypes of head-on CRS depending on DCPA

No	Situation subtype	Existence condition
1	Port-to-port encounter	$\delta<-\delta^{\vee}$
2	Head-to-head encounter	$ABS(\delta)\leq\delta^{\vee}$
3	Starboard-to-starboard encounter	$\delta>\delta^{\vee}$

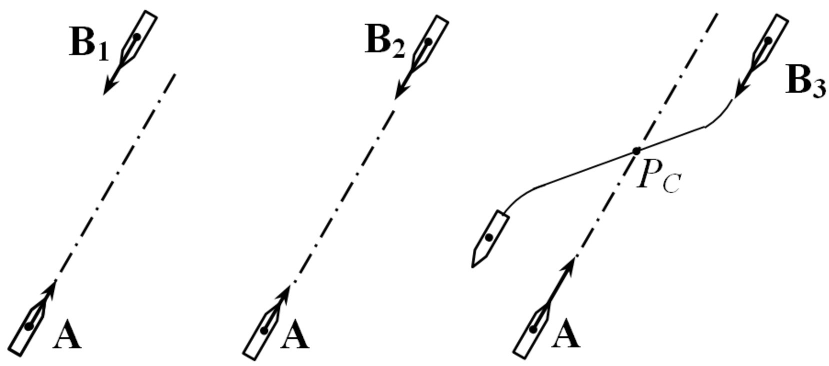

Figure 9. Subypes of head-on CRS

When ships are approaching each other, there may be cases in which one of the ships considers a collision risk to exist and fulfills the requirements of COLREGs, while the other ship believes that there is no such risk. This is particularly dangerous in starboard-to-starboard CRS. The presented division of head-on situation allows to pay attention to this kind of approach and to choose in it course changes by a larger value.

In crossing situations, one of the factors considered in collision avoidance is the BCR (*S*) - the distance from the OS to the position of the point (P_C) at which its course is crossed by another ship (TS). The bow/stern crossing distance will be considered positive/negative. Depending on the CD and DCPA in crossing situations, subtypes can be distinguished as shown in Table 12 and Figure 10, where index B corresponds to the situation number in the table.

Table 12. Subtypes of crossing CRS depending on CD and DCPA

No	Situation subtype	Existence condition
1	Bow crossing	$((-180° < θ < -θ^{\vee})$ AND $(δ < -δ^{\vee}))$ OR $((θ^{\vee} < θ < 180°)$ AND $(δ > δ^{\vee}))$
2	Contact crossing	$((-180° < θ < -θ^{\vee})$ OR $(θ^{\vee} < θ < 180°))$ AND $(ABS(δ) \le δ^{\vee})$
3	Stern crossing.	$((-180° < θ < -θ^{\vee})$ AND $(δ > δ^{\vee}))$ OR $((θ^{\vee} < θ < 180°)$ AND $(δ < -δ^{\vee}))$

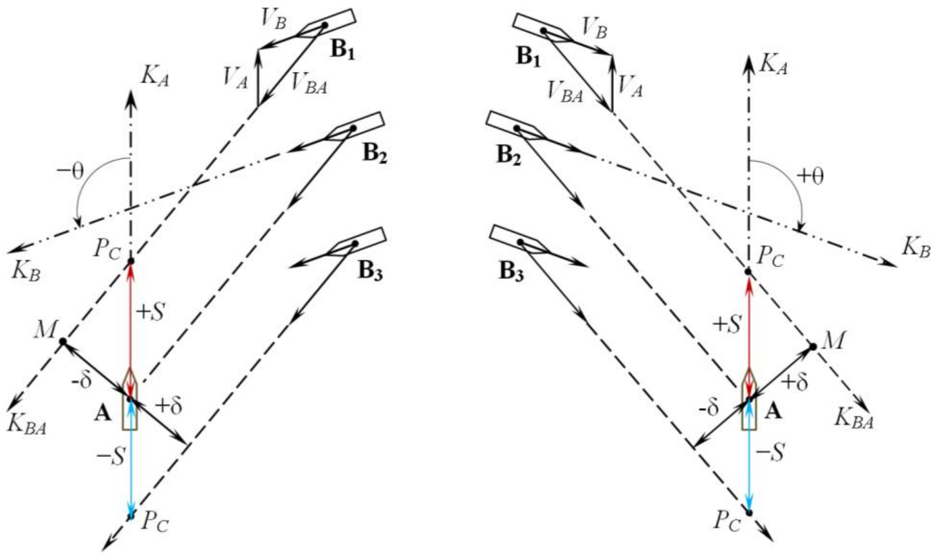

Figure 10. Subtypes of crossing CRS

From the triangle AMP_C in Figure 10 it follows that BCR can be obtained by the formula $S = δ/\sin(K_A - K_{BA})$. The BCR value for maneuver selection is usually called into account when TS relative bearing is between 67.5° and 112.5°. In this case, when BCR is negative, a turn to starboard with decrease in speed or decrease in speed may be more effective than only course change to the starboard.

Another factor influencing the choice of GWV actions in Crossing situations is the difference in vessel speeds ($VD = V_A - V_B$). Positive/negative values of VD will be denoted by pVD /nVD.

In Rule 18 (Responsibilities between vessels), the vessel giving way in head-on and crossing situations is defined according to the navigational status of the vessels, but there is no guidance as to the actions of that vessel (the requirements for overtaking, as follows from Rule 13, must be fulfilled by vessels regardless of their status). In systems for automatic collision avoidance, an algorithm for such actions should be provided. It is logical to assume that in head-on situation the vessel with lower status should change course to starboard.

It may also be considered that in a crossing situation the lower status ship should give way to the other ship and, if the circumstances of the case admit, avoid crossing ahead of the other vessel. It is not difficult to establish that fulfillment of such a condition can in most cases be achieved by changing course to the opposite direction of the CD side.

Classification of CRS in which ships are in sight of one another. One of the issues in the development of automatic collision avoidance systems is the classification of situations affecting the decisions made. First of all, it concerns the approaches of two ships that are not constrained in maneuvering by stationary and moving objects. The classification of encountered situations of non-maneuvering OS and TS, which can be distinguished depending on the values determined from the course and speed of these ships, is given below. Five levels of separation are used in its derivation. At these levels, situations are respectively separated depending on RB, TA, CD, DCPA, VD. The obtained classification is presented in Figure 11.

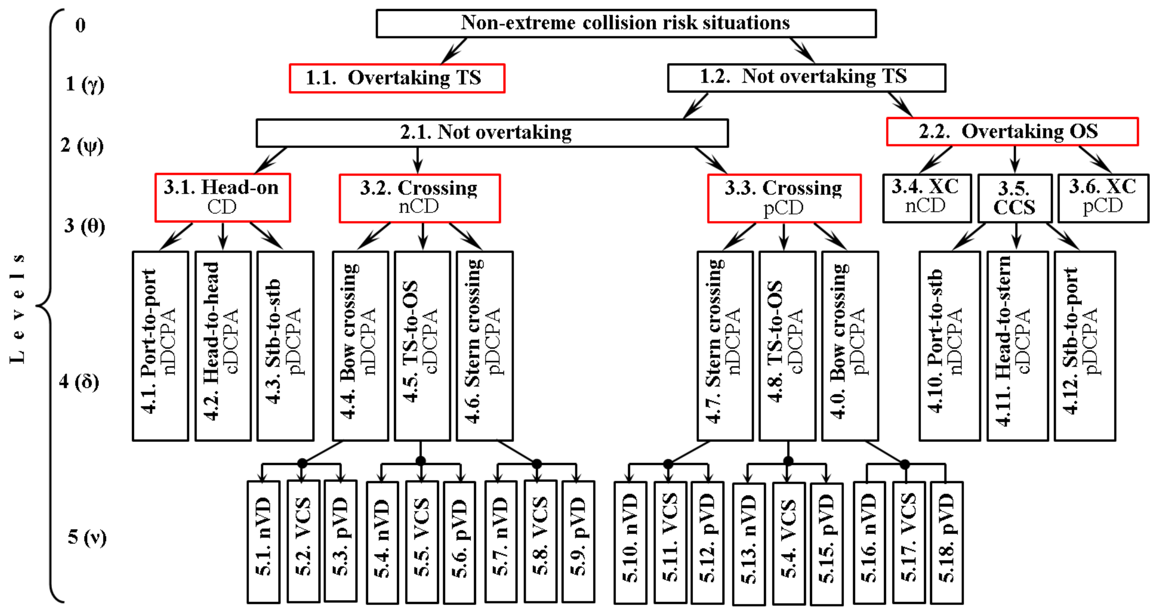

Figure 11. Classification of non-extreme CRS:
XC – overlapping courses; CCS – courses counted the same; VCS – velocities counted the same.

For situations coding, the levels of classification and the elements at those levels are numbered. The level number of element with its number at that level is the code of that element (e.g., 3.5).

Collision risk situations of ships in restricted visibility. In Rule 19 (Conduct of ships in restricted visibility), attention should be drawn to the term "abeam", which in navigation means the direction along a line approximately at right angle to the ship's keel opposite the middle part of a ship. But in considering Rule 19, the meaning of this term is a subset ($\gamma^F < ABS(\gamma) < \gamma^S$) of the lateral course angles, the boundaries of which are usually taken to be γ^F=67.5°=6 points and γ^S=112.5°=10 points. Accordingly, "forward of the beam" and "abaft the beam" denote subsets ($0° \leq ABS(\gamma) \leq \gamma^F$) and ($\gamma^S \leq ABS(\gamma) \leq 180°$).

The content of Section (d) of Rule 19 relates to a ship that uses radar equipment to monitor the motion parameters of a target. Section (e) of this Rule defines how to respond to the occurrence of an audible signal from a target with unknown motion parameters. The types of vessel approaches defined in Rule 19 can be represented as the result of a two-level division of the CRS (Figure 12). In this scheme, the term "overtaken" in Rule 19 section (d/i) is not used because Overtaking is defined only for vessels in sight of one another, and it is not noted in COLREGs that it is among the encountered situations in restricted visibility.

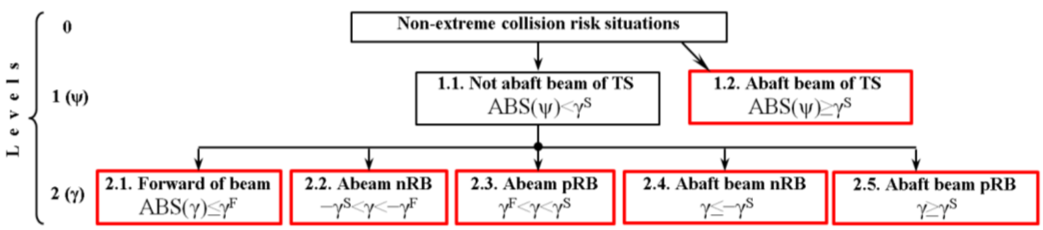

Figure 12. Scheme of the CRS types allocated in the Rule 19

This division is two-level and similar to the one given in the section "Proposals for improving the borders between key situations" (Figure 4). It has the disadvantages noted in this section. It should be noted that when the target motion parameters are known, it is possible to use the most rational variant of situation separation, in which the type of approaching for OS and TS is the same, and apply the more rigid type of coordination used for ships in sight of one another. In our opinion, it should be analyzed whether this option may be more appropriate for ships in restricted visibility. In particular, in this case it would not be necessary to change the algorithm of actions when ships are in sight of each other in a patch of degraded fog.

In this rule, no divisions of situations according to their navigational status and vessels into GWVs and SOVs apply. Measures to avoid a collision must be taken by both ships. Limitations on these actions are provided in section (d) of Rule 19. It should be noted that under Rule 35 (Sound signals in restricted visibility) in or near an area of restricted visibility, whether by day or night, the signals prescribed in this Rule for a power-driven vessel making way through the water; for power-driven vessel underway but stopped and making no way through the water; for vessels with a status other than a power-driven vessel, a vessel not under command, a vessel restricted in her ability to maneuver, a vessel constrained by her draught, a sailing vessel, a vessel engaged in fishing and a vessel engaged in towing or pushing another vessel) are different. For ships of length 200 meters or more the whistle should provide audibility at a distance of up to 2 NM in the direction of maximum intensity of the sound (COLREGs, ANNEX III: Technical Details of Sound Signal Appliances).

Conclusions

The following results were obtained in solving the set task.

It is determined that under the COLREGs relevant conditions for the existence of a head-on situation, only encounters in which the TS is in a narrow head-on sector will be classified as head-on situation. Other approaches on opposite courses will be considered as crossing situation, even though the courses of ships do not cross in this case.

It has been established that in crossing situations, when choosing actions according to COLREGs depending on the target relative bearing, only targets detected before they cross the OS course line are taken into account. The behavior of ships in possible, though rare cases, in which a dangerous target is detected after this moment, is not coordinated. That may be the reason for not taking necessary actions.

It is specified that when an extended head-on sector is used to identify a head-on situation without taking into account the restrictions on the angle between ships' courses, this situation will include targets that have the same or different approach type as OS. In such a case, OS and TS would have to be allowed to determine actions depending only on their type of approach. This fact is not considered to be positive. Increasing the head-on sector also results in an increased loss of sailing time due to collision avoidance.

It is proposed to define the boundary between head-on and crossing situations and to choose the action in crossing situation only depending on the difference between OS and TS courses without using head-on sector. It is shown that this does not increase the need for anti-collision maneuvers and takes into account dangerous targets detected after they cross the OS course line.

The bases are chosen and depending on them the division of the key situations into subtypes that affect the effectiveness of anti-collision actions is carried out. Logical rules are given for identifying the key encounter situations and their subtypes.

A classification system of non-extreme situations is defined, in which the set of possible two ships' approaches is divided into non-intersecting subsets with clear boundaries.

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