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Safety First—A Critical Examination of the Lights and Shapes in COLREGs

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Abstract: According to The International Regulations for Preventing Collisions at Sea, 1972, ships can only determine their collision avoidance responsibilities in accordance with the rules of "Conduct of Vessels in Sight of One Another" if the dynamic and category of the target ship is identified to be using lights and/or shapes during encounters at sea. Then, appropriate actions can be taken, and the effectiveness of the collision avoidance actions can be checked during the subsequent maneuvering process. In order to analyze and solve the problems related to lights and shapes and to adapt to the development of ship size, speed, and intelligence, this paper firstly reviews the development history and revision process of lights and shapes. Furthermore, it explains the collision avoidance responsibility of ships in sight of one another, analyzes the role of lights and shapes in the collision avoidance process, and summarizes the lights and shapes displayed by different categories of ships. Next, through qualitative and quantitative analysis, the relationship between the visibility distance of lights and shapes and the timing of ship avoidance actions is examined. Finally, the paper points out current problems related to lights and shapes, including: (1) non-uniform visibility distance of lights, (2) insufficient visibility distance of lights, and (3) small size of shapes, and proposes solutions to these problems from theoretical and practical perspectives, including: (1) unifying the visibility distance of masthead light, sidelights, and sternlight to 6 nautical miles, (2) unifying the visibility distance of the sternlight to 3 nautical miles, and (3) unifying the diameter size of shapes and the vertical distance between shapes to 1.8 m.

Keywords: COLREGs; lights and shapes; collision avoidance; safety; suggestions

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1. Introduction

As a key aspect of maritime regulatory framework of the International Maritime Organization (IMO) [1], the International Regulations for Preventing Collisions at Sea, 1972, (COLREGs) not only provides guidance for seafarers in collision avoidance but also in resolving disputes related to ship collisions at sea. Chapter II of the COLREGs, on Steering and Sailing Rules, is the core guidance for seafarers in collision avoidance. It sets out two sets of different action rules based on whether ships are in sight of one another: "Conduct of Vessels in Sight of One Another" and "Conduct of Vessels in Restricted Visibility". Under the action rules in sight of one another, the general principles and framework for dividing collision avoidance responsibilities between ships are determined based on the category of ships and their mutual position relationship. This includes, "the vessel that is overtaking another vessel shall keep out of the way of the vessel being overtaken, the vessel with the better maneuverability shall keep out of the way of the vessel which is less maneuverable, and when vessels are of the same maneuverability, the give-way vessel shall be determined based on their mutual position."

Therefore, when ships are navigating at sea, they need to first identify the category and/or mutual position relationship of the other ship(s) to determine the collision avoidance responsibilities between them, and the ship categories and mutual position relationships are primarily determined by lights and shapes. According to the COLREGs, the minimum visibility range for lights varies depending on the type of lights and the size of the ship. For example, the masthead light used to identify the category of ship and the sidelights used to determine the mutual position relationship have a maximum range of 3 nautical miles. The size of shapes is uniformly set at a diameter of no less than 0.6 m. While these ranges and sizes may be effective for collision avoidance between small and slow-moving vessels, they may not be sufficient for large and fast-moving vessels of today, as waiting until the distance is within 3 nautical miles may already be too late for safe maneuvering, thereby posing a great risk to navigation safety. Therefore, adjusting the rules for lights and shapes to adapt to the development of larger, faster, and smarter ships has become a key issue that needs to be addressed.

As a result, this paper will first introduce the historical evolution of lights and shapes; then, according to the "Steering and Sailing Rules" and the technical characteristics of lights and shapes, it will analyze the main problems faced by lights and shapes in application. Finally, from the perspective of the navigational practices of seafarers and the ship's maneuvering characteristics, it will propose specific recommendations for adjusting the rules for lights and shapes, aiming to provide technical support for the subsequent revision of the COLREGs.

2. The Development History of Lights and Shapes

Lights and shapes are devices used to indicate a ship's position, category, and movement, facilitating recognition by other vessels [2,3]. The regulations concerning lights and shapes that ships had to comply with date back to 1838, when the United States passed an act requiring ships to display appropriate lights from sunset to sunrise to be identified by other vessels and prevent collisions. The United Kingdom followed suit in 1848 and established regulations for steamships to display lights during navigation at sea. In 1889, the United States initiated the development of international rules for preventing collisions at sea, which included requirements for lights and shapes [4]. In the 20th century, the Titanic disaster led to the establishment of the International Convention for the Safety of Life at Sea (SOLAS). At the Second International Conference of SOLAS in 1929, the revised International Regulations for Preventing Collisions at Sea were adopted as an annex to the SOLAS Convention, and the rules for lights and shapes were included as a part of the Regulations which were revised three times in 1948, 1960, and 1972, and were separated from the SOLAS Convention in 1972. Since then, the IMO, formerly known as the Inter-Governmental Maritime Consultative Organization (IMCO), has revised the Regulations seven times as amendments, including four revisions related to lights and shapes [5], as shown in Table 1.

Table 1. Revision of COLREGs concerning lights and shapes since 1972.

No.	Date of Revision	IMO Resolution No. of Revision	Date of Entry into Force	Revised Provisions Concerning Lights and Shapes
1	19 November 1981	Res.A.464(XII)	1 June 1983	Rule 22, 23, 24, 25, 27, 29, 30; Annex I
2	19 November 1987	Res.A.626(15)	19 November 1989	Annex I
3	19 October 1989	Res.A.678(16)	19 April 1991	Nil
4	4 November 1993	Res.A.736(18)	4 November 1995	Rule 26, Annex I
5	29 November 2001	Res.A.910(22)	29 November 2003	Rule 23, 31; Annex I
6	29 November 2007	Res.A.1004(25)	1 December 2009	Nil
7	4 December 2013	Res.A.1085(28)	1 January 2016	Nil

The four revisions related to lights and shapes mentioned in Table 1 mainly involved minor changes, such as adding provisions for lights and shapes for hovercraft and seaplanes. The 1981 revision had more substantial changes. However, the overall framework, visibility range, and arrangement details for lights and shapes have remained largely unchanged since the 1972 regulations and continue to be followed to this day.

3. Lights and Shapes in Relation to Collision Avoidance for Ships

3.1. The Collision Avoidance Responsibilities of Vessels in Sight of One Another

The Steering and Sailing Rules firstly establishes the general principles for collision avoidance at sea, which are the rules of "Conduct of Vessels in Any Condition of Visibility", and then rule of "Conduct of Vessels in Sight of One Another" and "Conduct of Vessels in Restricted Visibility" are created based on whether ships are in sight of one another. The former is the core for determining collision avoidance responsibilities between ships, with "in sight of one another" as a prerequisite. According to the General Definitions of Rule 3, vessels shall be deemed to be in sight of one another only when one can be observed visually from the other. To interpret the meaning of the term "in sight of one another", it is generally understood that the key features that can clearly indicate the other ship's basic category and movement, such as the hull, the bow and stern facing, and the lights and shapes, can be visually seen by the naked eyes with normal vision.

Based on this, the COLREGs clearly divide the collision avoidance responsibilities based on the encounter situation between ships, maneuvering capabilities, and geometric positions in relation to each other. Specifically, (1) the vessel that is overtaking another vessel shall keep out of the way of the vessel being overtaken; (2) vessels with better maneuvering capabilities shall keep out of the way of vessels with poorer maneuvering capabilities; (3) in a crossing situation, the vessel which has the other on her own starboard side shall keep out of the way of the other vessel; (4) sailing vessels on the windward or port side shall keep out of the way of sailing vessels on the leeward or starboard side; and (5) in a head-on situation between two power-driven vessels, both vessels shall alter their course to starboard. The specific collision avoidance responsibilities between vessels in sight of one another are as shown in Table 2.

Table 2. The collision avoidance responsibilities between vessels in sight of one another.

Category of Vessel	Collision Avoidance Responsibility	Category of Vessel
Vessel that is overtaking another vessel	Keep out of the way of	Vessel being overtaken
Power-driven vessel underway	Keep out of the way of	Sailing vessel Vessel engaged in fishing Vessel restricted in her ability to maneuver Vessel not under command
Sailing vessel underway	Keep out of the way of	Vessel engaged in fishing Vessel restricted in her ability to maneuver Vessel not under command
Vessel engaged in fishing	Keep out of the way of	Vessel restricted in her ability to maneuver Vessel not under command
The port side vessel in crossing situation	Keep out of the way of	The starboard side vessel in crossing situation
The sailing vessel with the wind on port side or windward	Keep out of the way of	The sailing vessel with the wind on starboard side or leeward
Power-driven vessel in head-on situation	Have same responsibility to	Power-driven vessel in head-on situation

3.2. The Role of Lights and Shapes during the Process of Collision Avoidance

According to Rule 7 on "Risk of Collision" and Rule 8 on "Action to Avoid Collision" of the COLREGs, the whole encounter process between vessels can be divided into five stages respectively that includes:

Stage 1: free movement with long range.
Stage 2: risk of collision exists.
Stage 3: close-quarters situation.
Stage 4: immediate danger situation.
Stage 5: collision.

As shown in Figure 1.

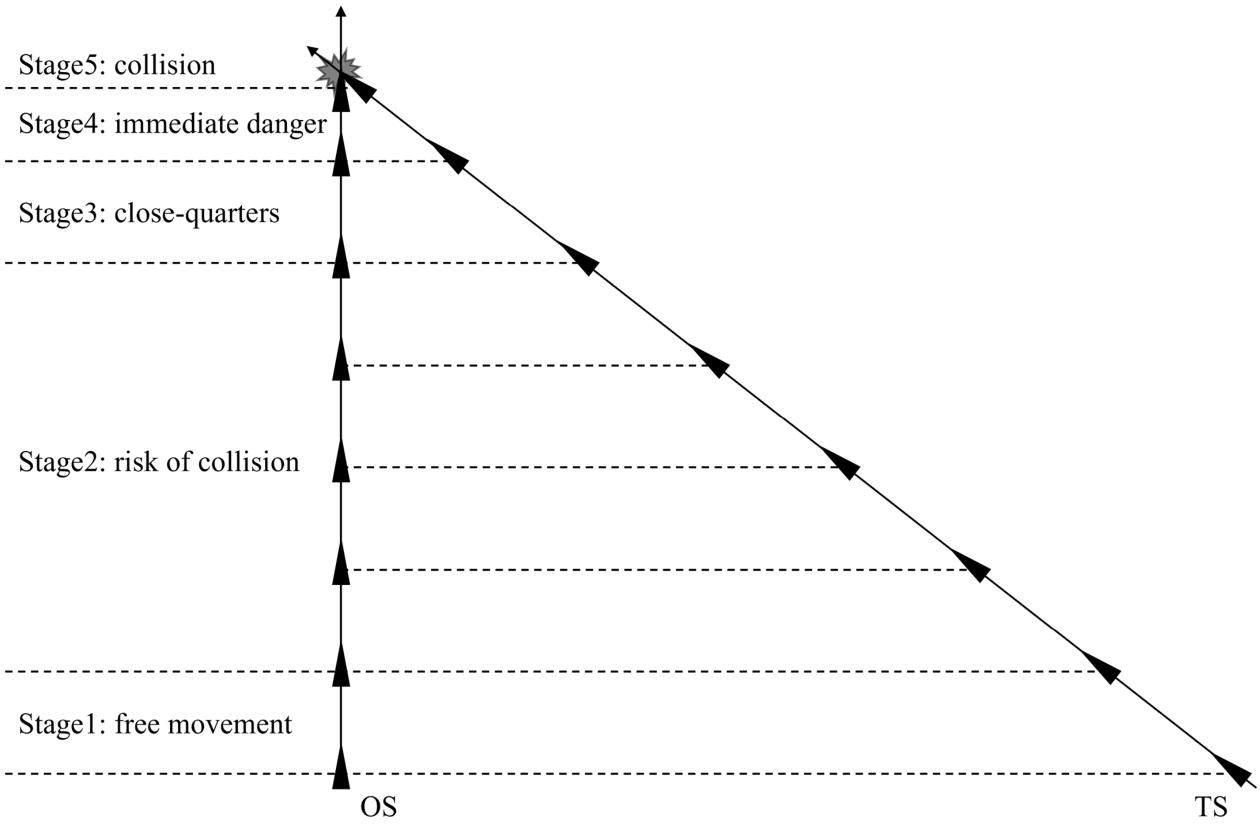


Figure 1. The developing stages of ship collision process.

In the collision avoidance process shown in Figure 1, vessels do not need to take specific collision avoidance actions during the free maneuvering stage. During the risk of collision stage, the vessel's category and relative position must be determined to clarify the collision avoidance responsibilities between the two vessels and take corresponding actions accordingly. Subsequently, the effectiveness of the collision avoidance actions between vessels must be checked until pass and clear. During the five stages mentioned above, the role of lights and shapes mainly includes:

(1) To determine the category of vessel and thus astern the collision avoidance responsibilities by means of light and shape.
(2) To determine the relative position and the movement of the target vessel, as well as the encounter situation applicable by analyzing the location and the arc of lights, and then the collision avoidance responsibilities be considered.
(3) To check the effectiveness of the collision avoidance action by observing changes in the type, location, and arc of the lights on the approaching vessel.

3.3. The Lights and Shapes Displayed by Different Categories of Ships

As mentioned above, whether determining the categories of vessels, judging the relative position and movement of the target vessel, or verifying the effectiveness of collision avoidance actions, it is necessary to confirm through the lights and/or shapes displayed by vessels. According to the COLREGs, different categories of vessels have their own exclusive identifying lights and/or shapes, as shown in Figure 2.

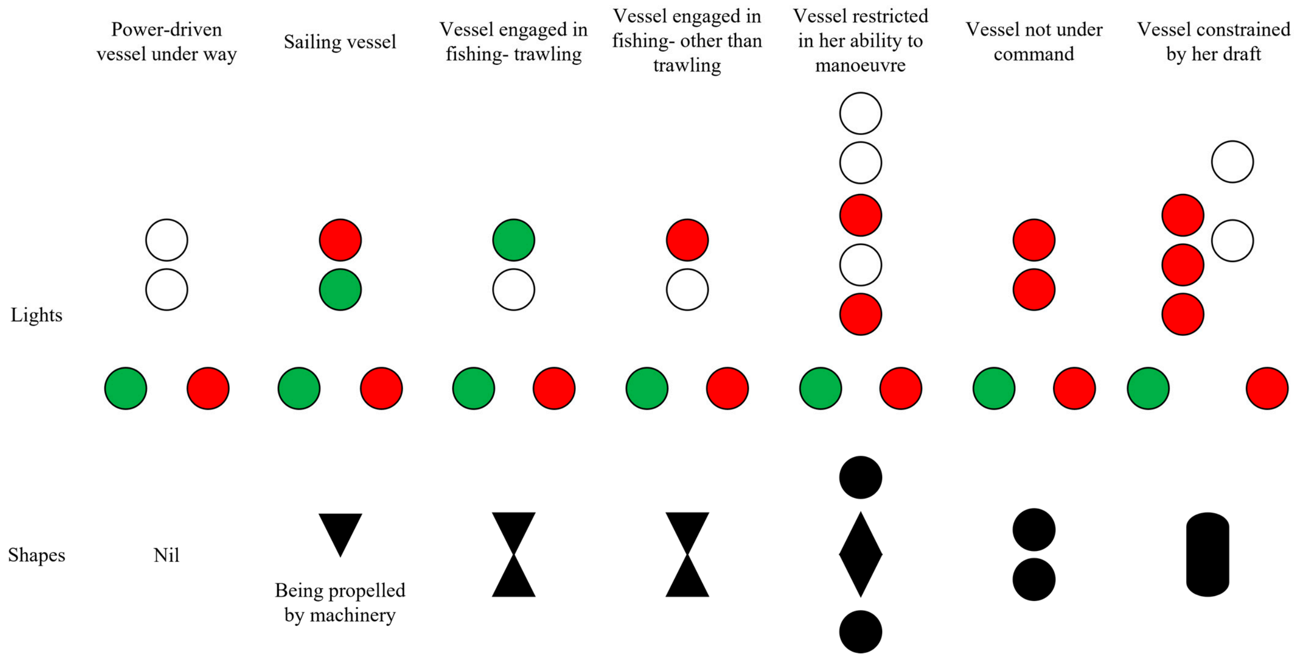


Figure 2. The specific lights and shapes of different categories of vessels. Note: Lights in Figure 2 show the vision from ahead of the vessel where the sternlight cannot be discovered, and all vessels are making way through the water. Considering that the lights displayed depend upon not only the vessels' categories but also their navigational status, it is not necessary to show all kinds of lights for vessels in every condition, but only the exclusive lights for vessels defined in the General Definitions of Rule 3 in the COLREGs.

4. The Visible Range of Lights and Shapes in Relation to the Timing of Collision Avoidance Actions

4.1. The Visible Range of Lights

The main way to determine the category of the target vessel during an encounter situation is through its exclusive identifying lights. The exclusive identifying lights of vessels of different categories shown in Figure 2 are all all-round lights, except for the masthead light on power-driven vessels. According to the rules concerning the characteristics of lights and shapes in COLREGs, the minimum visible range of all-round light is related to the length of the vessel, with a maximum distance of 3 nautical miles. To determine the relative position and movement of the approaching vessel, it is necessary to comprehensively judge the masthead light, sidelights, and sternlight. The minimum visible range of sidelights and sternlight is like that of all-round light, with a maximum distance of 3 nautical miles. The minimum visible ranges of lights concerning the length of vessel are as shown in Table 3.

Table 3. The minimum visible ranges of lights concerning the length of vessel (n mile).

Length of Vessel	Masthead Light	Sidelights	Sternlight	All-Round Light
$L \geq 50$ m	6	3	3	3
20 m $\leq$ L< 50 m	5	2	2	2
12 m $\leq$ L < 20 m	3	2	2	2
L < 12 m	2	1	2	2

This means that even without considering individual differences in human visual acuity and adverse maritime conditions, the officers on watch (OOW) can only accurately identify the lights of an approaching vessel and determine its category when the distance between the two vessels is within 3 nautical miles. For smaller vessels, the distance may need to be as close as 2 nautical miles. During the collision avoidance process, sidelights and sternlight, which are used to determine the movement of the approaching vessel and verify the effectiveness of the actions, also need to be identified accurately within a range of about 3 nautical miles.

4.2. The Visible Range of Shapes

According to the rules concerning the characteristics of shapes in Annex I of the COLREGs, the shapes displayed by vessels are comprised of four basic shapes: a ball, a cone, a cylinder, and a diamond, which can be displayed separately or in combination. The minimum size of different types of shapes are as shown in Table 4.

Table 4. The minimum size of shapes.

Shapes	Appearance	Minimum Diameter (m)	Minimum Height (m)
Ball		0.6	--
Cone		0.6	0.6
Cylinder		0.6	1.2
Diamond		0.6	1.2

When the above-mentioned basic shapes are displayed in combination, the vertical distance between them should be at least 1.5 m. Therefore, the schematic diagram of the combined sizes of shapes for different categories of vessels are as shown in Figure 3.

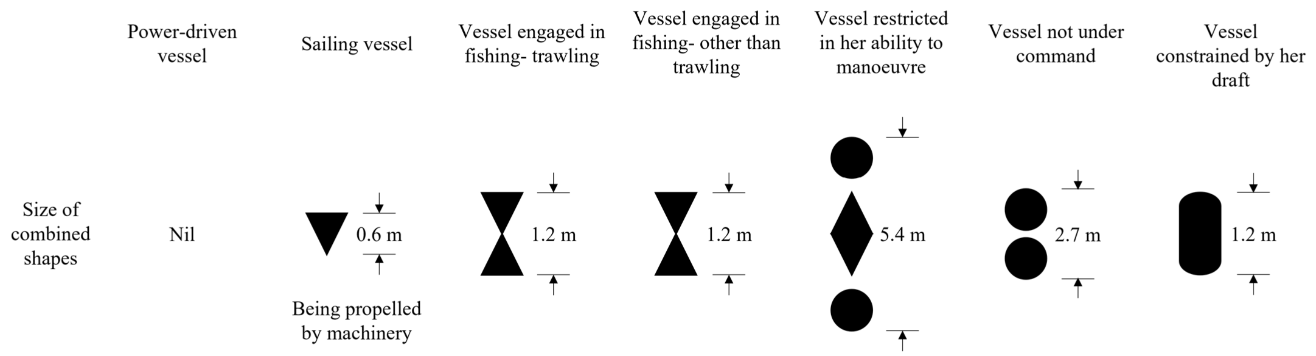


Figure 3. The size of the combined shapes of different categories of vessels.

According to the Rayleigh Criterion [6], The ideal angular resolution of the human eyes is approximately 1.35×10^{-4} rad or $0.46'$ [7], However, due to factors such as the retina, environment, and contrast sensitivity, the actual angular resolution of the normal human eyes is about 2.91×10^{-4} rad or $1'$ [8,9]. As a result, the relationship between object distance and spatial resolution is as shown in Equation (1):

$$s = R \cdot \theta_{min} \tag{1}$$

where s represents the spatial resolution between two points on an object, R represents the distance between the human eye and the object, θ_{min} represents the minimum resolvable angle.

Therefore, to identify the category of a target vessel through the shapes displayed, the OOW needs to accurately identify the characteristics of a single shape in both the horizontal and vertical directions with an angular resolution of $1'$, and be able to distinguish the individual shapes in a combination of shapes. According to Figure 3, it is necessary to identify the individual shapes that have a diameter of 0.6 m and a height of 1.2 m, respectively, and to distinguish the combined shapes with a vertical spacing of 1.5 m, as shown in Figure 4.

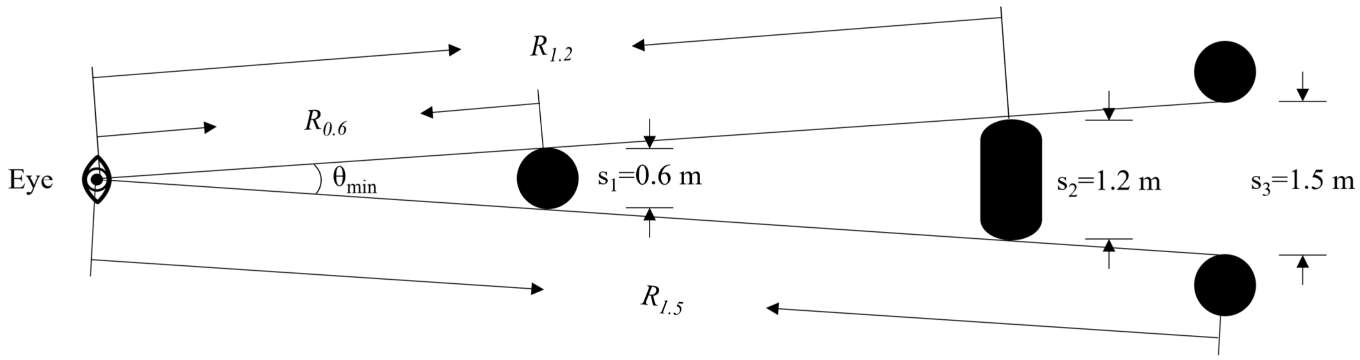


Figure 4. The visual distance of different types of shapes on board vessel.

In Figure 4, $R_{0.6}$ and $R_{1.2}$ represent the distance between a naked eye to the object with dimensions of 0.6 m and 1.2 m, respectively, and $R_{1.5}$ represents the distance at which two shapes with a vertical spacing of 1.5 m can be distinguished by the naked eye. According to Figure 4 and Equation (1), the distance required to identify different types of shapes can be calculated, as shown in Table 5.

Table 5. The optical distance of different types of shapes on board vessel (n mile).

Type	θ_{min}	Optical Distance
$R_{0.6}$	$1'$	1.11
$R_{1.2}$	$1'$	2.23
$R_{1.5}$	$1'$	2.78

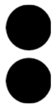
This means that even without considering individual differences in human visual acuity and adverse maritime conditions, the OOW can only distinguish between the two vertical shapes when the vessels are approaching within 2.78 nautical miles. To accurately identify whether the shape displayed by a vessel is a ball, a cone, a cylinder, or a diamond, the vessel needs to be as close as 2.23 nautical miles or even within 1.11 nautical miles. When a combined shape is displayed by a vessel, the distinguishable distance depends on the smallest shape in the combination. The distinguishable distances of shapes for different categories of vessels are as shown in Table 6.

4.3. The Timing of Collision Avoidance Actions

During the whole process of encounter, any vessel that has the responsibility to avoid collision shall, so far as possible, take early and substantial action to avoid a close-quarters situation and ultimately ensure that both vessels pass at a safe distance. There are multiple interpretations of the term "close-quarters situation" [10–12], and the widely accepted one is that a situation in which two vessels are approaching so close that the most effective evasive action of one vessel alone is insufficient for passing at a safe distance [13]. Neither the COLREGs nor the interpretation provide specific numerical values for close-quarters situations or safe distance, but in navigation practice, there are corresponding reference standards for both.

In terms of safe distance that varies with the navigational circumstances and the ship's maneuverability, it is generally 0.3–0.5 nautical miles in coastal and congested waters, while in open seas, it is usually 1–2 nautical miles. In adverse weather or restricted visibility, 2 nautical miles is recommended. The safe distance can be reduced if the vessel has good maneuverability [14–16].

Table 6. The minimum distinguishable distance of different types of shapes (n mile).

Category of Vessel	Shapes	Distinguishable Distance
Power-driven vessel	Nil	--
Sailing vessel (being propelled by machinery)		1.11
Vessel engaged in fishing		2.23
Vessel restricted in her ability to maneuver		1.11
Vessel not under command		1.11
Vessel constrained by her draft		2.23

Similarly, the applicable distance for close-quarters situation also depends on various factors such as vessel size, maneuverability, speed, and so on, making it difficult to quantify with a specific value. Generally, when using radar observation from a long distance and considering radar errors, the minimum applicable distance for close-quarters situation is 3 nautical miles; In open seas with restricted visibility, for approaching vessels crossing the bow of the observer's vessel, this distance should not be less than 2 nautical miles. In congested waters, when the vessel is moving slowly or in an overtaking situation, this distance can also be less than 2 nautical miles [17,18].

In addition to the reference standards in navigation practice, using mathematical methods and considering vessel maneuverability, it is possible to calculate the distance of a close-quarters situation related to factors including vessel size, speed, bearing, and distance between vessels [19]. For two vessels of approximately 330 m in length, considering the target vessel maintaining its course and speed, and assuming that the own vessel can turn at full rudder with a maximum advance of four times its length, the close-quarters situation distance at which the own vessel could avoid the target vessel by using the rudder is approximately 2.2 nautical miles [20]. The close-quarters situation distance obtained using simulation methods based on ship's domain and Maneuvering Modeling Group (MMG) indicate that the close-quarters situation distance for stationary objects is about 2.01 nautical miles, while for moving objects, it is about 3.20 nautical miles [21,22]. Using the method proposed by Captain Zajone to estimate the critical collision avoidance distance based on the time required for one vessel to turn 90 degrees and the speed of both vessels, the close-quarters situation for own vessel with 330 m in length and a target vessel with 290 m in a head-on situation is approximately 2.1 nautical miles [23].

In summary, whether in navigation practice or theoretical calculations, the distance at which two vessels in a close-quarters situation on the sea is typically between 2–3 nautical miles. This distance is also known as the point of the latest minute action [24] or the last moment maneuver [25]. It refers to the latest time that the vessel with the duty to avoid collision can take action in an encounter situation, considering the maneuverability of the vessel. If the action is taken later than this time, the vessels may not be able to pass at a safe distance [26].

5. The Main Problems and Suggestions Regarding Lights and Shapes

5.1. The Main Problems of Lights and Shapes

It was early in the 1st meeting (NAV/I) of the IMCO sub-committee on navigation held in 1966 that three substantive issues were raised regarding the technical details of lights and shapes specified in the 1960 International Regulations for Preventing Collisions at Sea. At the 1972 COLREGs amendment conference, some suggestions on lights and shapes were adopted, such as integrating the technical details into an annex. However, some obvious problems and reasonable revision proposals were not discussed and adopted, and deep-seated issues, such as the insufficient clarity of shape size, were not thoroughly explored [27]. These issues regarding lights and shapes have not been completely resolved in the subsequent seven amendments, and with the development of larger, faster, and smarter ships, these problems have become increasingly apparent.

5.1.1. An Inconsistent Visibility Range of Lights

As stated in Table 3, the visibility range of lights for ships of different sizes is not the same, with larger ships having a significantly greater range than smaller ones. It means that larger ships need to be closer to detect the smaller ships, which violate the rules of "early detection of approaching vessels"; Additionally, for ships of the same size, the visibility range of different types of lights is also not the same. Take the cargo ship with a length of 50 m or more for example, the visibility range of masthead light is 6 nautical miles, while of the sidelights, sternlight, and all-round light is only 3 nautical miles, which means that it is necessary to approach 3 nautical miles more to find the sidelights, sternlight, and all-round light after detecting the masthead light, and then the category and movement of the vessel detected can be determined, and a subsequent action can be taken. This is obviously unsafe and does not comply with the "take early and substantial action" requirement in the COLREGs.

5.1.2. The Visibility Range of Lights Is Too Small

The provisions on the visibility range of navigation lights in the COLREGs have a history of more than 50 years. At that time, ships were small and had low speed. It was safe for ships to make collision avoidance decisions and take actions at relatively close distances. After many years of development, both the size and speed of ships have significantly increased. Taking container ships as an example, since the first commercial container ship Ideal X commenced its operation in 1956 [28], the maximum cargo capacity of container ships has increased from 500–800 TEU to 21,000–24,000 TEU, and the length has increased from 137 m to 400 m [29], as shown in Figure 5.

The increase in the size of ships will inevitably bring changes to their maneuverability. According to the IMO resolution MSC. 137(76) "Standards for Ship Maneuverability", the maximum advance and tactical diameters should not exceed 4.5 times and 5.0 times of the ship length respectively, and the track reach of full astern stopping should not exceed 15 times the ship's length [30]. For a container ship that is 400 m long, the above-mentioned maneuvering characteristics are approximately 0.97 nautical miles, 1.08 nautical miles, and 3.24 nautical miles, respectively, which are twice those of ships in 1970s. Considering the extreme case where the ship can only avoid the target ship by a single turn or emergency stop, the minimum distance at which the ship can safely avoid the target ship's hull is depicted in Table 7.

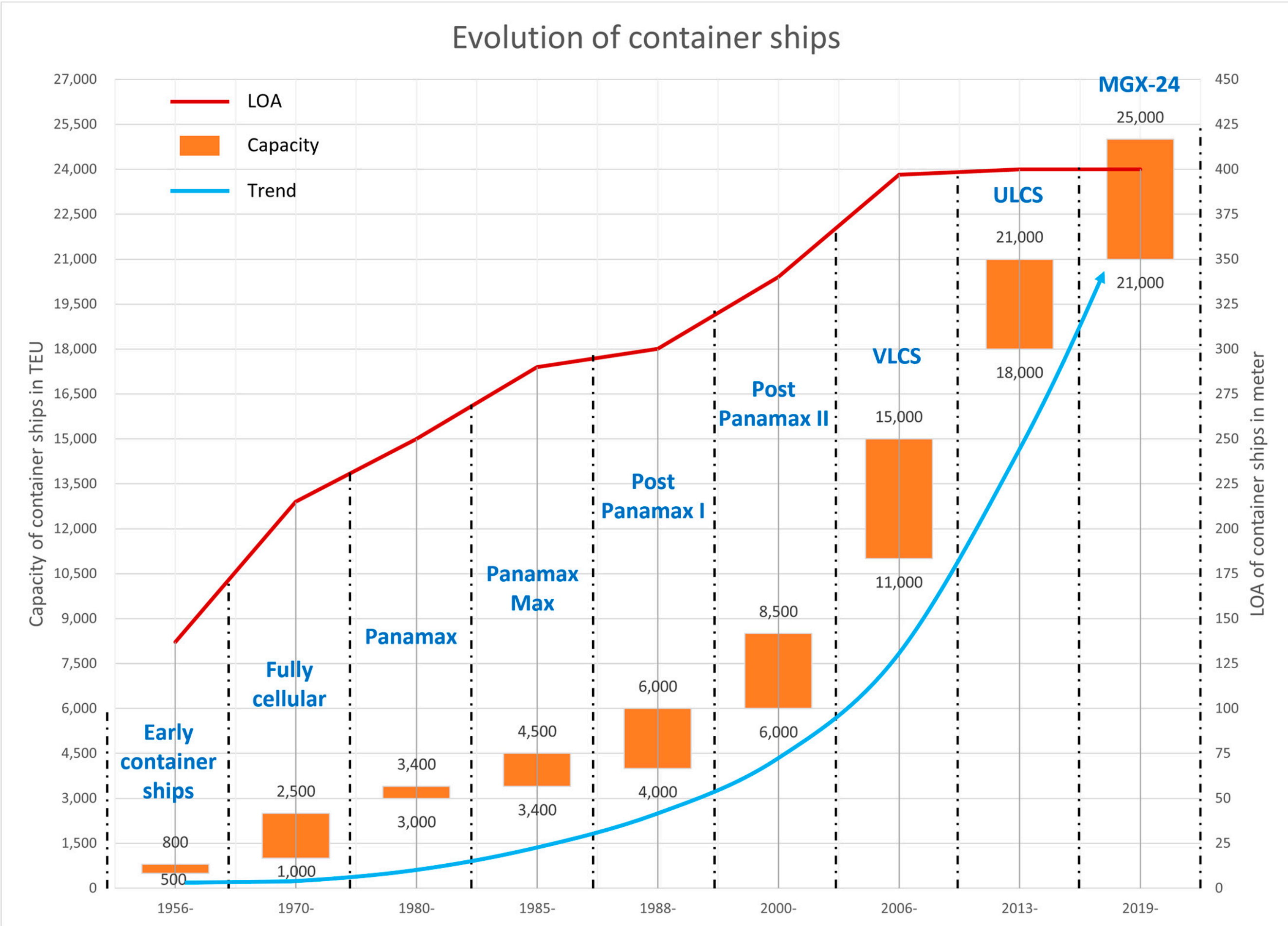


Figure 5. The evolution of container ships since 1956. Data source: https://transportgeography.org/contents/chapter5/maritime-transportation/evolution-containerships-classes/. (Accessed on 19 June 2023.)

Table 7. The minimum distance of collision avoidance with safe passage distance.

Maneuverability		Safe Passage Distance	Ship Length	Minimum Distance of Collision Avoidance
Advance	0.97′	1.0′	400 m	2.40′
Tactical diameter	1.08′	1.0′	400 m	2.51′
Track reach of full astern stopping	3.24′	1.0′	400 m	4.67′

However, the visibility range of navigation lights specified in the COLREGs is only 3 nautical miles or 2 nautical miles, except for the masthead light that has a range of over 3 nautical miles, and the sidelights of ships with a length less than 12 m have a range of only 1 nautical mile, which is an obviously inadequate visibility range according to the interpretation on close-quarters situation stated in Section 4.3. When identifying an approaching vessel through visual recognition of its navigation lights within this range, a larger vessel may not be able to act at a safe distance, which poses significant safety hazards to navigation at sea.

In addition, although visual observation is the most important means of look-out, large vessels can still use electronic navigation equipment such as radar and AIS (automatic identification system) to assist in detecting approaching vessels or being detected by them. In contrast, small boats, especially those less than 12 m in length, have a significant gap in the equipment and performance of their electronic navigation systems compared to larger vessels. Thus, large vessels can only identify small boats through navigation lights installed on them, and the small visibility range of navigation lights on small boats can lead to a close-quarters situation or even immediate danger for both vessels.

5.1.3. The Size of Shapes Is Too Small

According to the rules regarding the actions of vessels in sight of one another, vessels primarily use shapes to determine the category of vessel during the daytime and to establish the avoidance responsibility, and subsequently take appropriate action to avoid collision. However, within the current framework of shapes' size, the diameter of the light is only 0.6 m, the height is not more than 1.2 m, and the vertical distance between them is 1.5 m. The corresponding visibility range is only 1.11 nautical miles, which is obviously less than the close-quarters distance of 2–3 nautical miles, and even less than the safe passing distance of two vessels in open waters. If factors such as masts, superstructures, and cargo that may obstruct or visually interfere with shapes are considered, the visibility range of shapes may be even smaller. In such a visibility range, using visual recognition of shapes to determine the category of approaching vessel could mean that the vessels are already in an immediate danger situation, which poses significant risks to navigation safety.

5.2. The Suggestions Regarding Lights and Shapes

The lights and shapes are the foundation of the rules of "Conduct of Vessels in Sight of One Another", and are the important means for mariners to determine the categories of vessels by means of visual look-out at sea. To address the issues of inconsistent visibility range and small size of the navigation lights and shapes, it is necessary to take corresponding measures. However, it is also important to note that, according to the technical characteristics of lights and shapes stated in COLREGs, the maximum luminous intensity of navigation lights should be limited to avoid undue glare, and this shall not be achieved by a variable control of the luminous intensity.

To address the issue of inconsistent visibility range of navigation lights, it is suggested to replace the current method of dividing the visibility range based on the length of the vessel with a unified method. This will ensure that navigation lights of the same type have a consistent visibility range for vessels of different sizes and with different maneuvering capabilities, meeting the requirements of early detection and early action.

Although the distance for making collision avoidance decisions and taking actions between two vessels largely depends on the category of vessel, the navigational area, the weather condition, and the sea state, etc. The collision decision should be made when the distance between two vessels is not less than 6 nautical miles, and action to avoid collision needs to be taken before 3 nautical miles in navigation practice when navigating in open waters at sea [31]. To address the issue of navigation lights having a small visibility range, it is suggested to adjust the visibility range of sidelights to be consistent with that of masthead light, considering that the arcs of sidelights and masthead light are the same. This will enable seafarers to identify the approximate heading and movement at the same time of identifying the outline of the approaching vessel at night. Similarly, considering that all-round light is the primary means of identifying vessel's category and establishing avoidance responsibilities, it is recommended to adjust the visibility range of all-round lights to be consistent with that of masthead lights, providing more distance and time to take appropriate action. Finally, considering that the relative speed of a vessel abaft the beam is relatively slow, a visibility range of 3 nautical miles is sufficient for vessels to act and pass at a safe distance. Therefore, it is recommended to adjust the visibility range of the sternlight of vessels less than 50 m in length to be 3 nautical miles, consistent with vessels 50 m or more in length. The adjusted visibility range of navigation lights is as shown in Table 8.

Table 8. The suggested minimum visible ranges of lights (n mile).

Masthead Light	Sidelights	Sternlight	All-Round light
6	6	3	6

Regarding the issue of small visibility range of shapes that was mentioned by the International Chamber of Shipping (ICS) and Netherlands in the process of formulating the COLREGs in 1972, the IMCO Secretariat proposed a suggestion to relate the size of shape to the ship's scale and/or speed. A survey conducted by Finland showed that approximately 5–10% of respondents believed that the size of shapes should be a function of the ship's scale [27]. However, these proposals were not adopted. In fact, if the size of shapes were to be expressed as a function of the ship's scale, it would mean that larger ships would have to display larger signal shapes, while smaller ships would only need to display smaller shapes, this would not fundamentally solve the problem of not being able to identify the ship's category by shapes at a safe distance. Only by unifying the size of shapes to correspond to a certain safe visibility range can the requirements of early detection and early action be met. When deciding on the size of shapes, in addition to considering the visibility range, the adaptability of the ship's structure and the feasibility of crew operation must also be considered. The size of shapes should not be increased unreasonably beyond the height of the mast or the range of the crew's operational ability. Therefore, it is recommended to increase the size of shapes to enable them to be seen by the naked eye at a visibility range of 3 nautical miles; similarly, the vertical distance between shapes should also be distinguishable by the naked eye at a visibility range of 3 nautical miles. According to Formula (1), the diameter of the shapes should be increased from the original 0.6 m to at least 1.62 m, and considering a certain amount of redundancy, it is recommended that this value be 1.8 m. The vertical spacing between shapes should also be at least 1.8 m. The recommended combination of shapes sizes for different categories of ships is as shown in Figure 6.

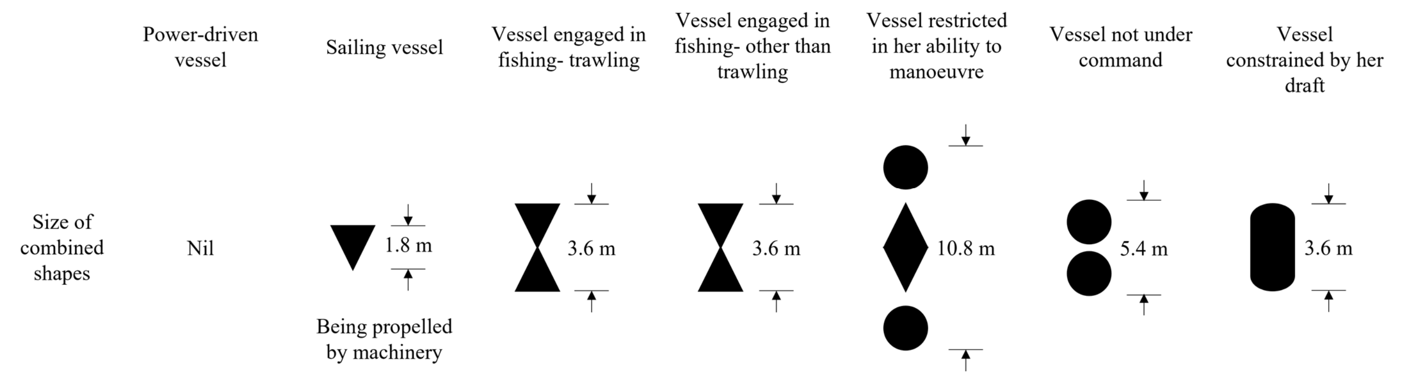


Figure 6. The suggested size of the combined shapes of different categories of vessels.

In addition to conventional approaches such as increasing the luminous intensity of lights and enlarging the size and spacing of shapes, to increase the visibility range of lights and shapes and improve the safety of collision avoidance, advanced technologies including semiconductor laser [32], BP neural network [33], and augmented reality [34] can also be employed.

6. Conclusions

The rules of "Conduct of Vessels in Sight of One Another" are the core of the COLREGs, which defines the collision avoidance responsibilities and action requirements of vessel in sight of one another. According to the definition of "in sight of one another", vessels can be deemed to be in sight of one another only if when one can be observed visually from the other. The determination of collision avoidance responsibilities depends on the categories of the two vessels and their relative positions, which are mainly determined by identifying the navigation lights and shapes.

The navigation lights mainly include masthead light, sidelights, sternlight, and all-round light. The function of masthead light, sidelights, and sternlight is to identify the outline and approximate heading of the ship at night or in restricted visibility and to check the effectiveness of collision avoidance actions. The all-around light is mainly used to identify the category of the ship and determine the collision avoidance responsibility accordingly. The visible range of these lights is inconsistent with each other but varies with the size of the ship and the type of lights. In general, larger ships have a longer visible range than smaller ships, and the masthead light have a longer visible range than other lights. It means that when a ship discovers another ship at sea through its masthead light, she still needs to continue sailing for a long time and distance before identifying the approximate dynamics of the other ship through its sidelights or sternlight or identifying the ship's category through its all-around light, which does not comply with the principle of "early detection and early action" in the COLREGs. In addition, the current visible range of lights is mainly suitable for small and slow vessels in the early days. Today, with the trend of larger and faster ships, a too small visible range can cause ships to enter a close-quarters situation or even immediate dangerous when discovering other ships, and they may not be able to act according to the COLREGs and pass at a safe distance.

The navigation shapes mainly include cone, ball, diamond, cylinder, and combination of these basic shapes. The main function of shapes is to identify the category and movement of a vessel in daylight, and thus determine the collision avoidance responsibility. However, these shapes are relatively small and have limited visible range which is insufficient to allow ships to take actions at a safe distance, especially when two vessels with corresponding shapes are not power-driven vessels with normal maneuverability. In such situation, the urgency of their movements is even more critical.

To address the issues with lights and shapes, this paper proposes to standardize the masthead light, sidelights, and all-round light of ships of different sizes to a visible range of 3 nautical miles, in order to solve the problem of inconsistent and insufficient visibility. At the same time, the shapes' size and vertical distance between shapes will be standardized to 1.8 m, ensuring that they can be detected at a visible range of at least 3 nautical miles, thus solving the problem of limited space and time for collision avoidance caused by small shapes. According to the legislative procedures of the IMO Convention, proposals for revisions to the COLREGs should be submitted to the IMO by relevant maritime contracting states. As a result, these suggestions might be developed into proposals and submitted to the IMO as part of our further research.

Although this research makes a significant contribution to existing knowledge regarding the navigation lights and shapes, there were also several limitations in this study, and future work will need to improve in these areas. Firstly, studies on the COLREGs mainly focus on collision avoidance, but there is limited research specifically on lights and shapes. As a result, the literature relating to lights and shapes are very limited, and the corresponding theoretical foundations are therefore lacking in this specific area. Secondly, the research was limited in terms of time and financial resources; thus, there has been no interviews with seafarers who implemented the COLREGs, to understand the practical application of lights and shapes in navigational practice. A long period of interviews of seafarers from different categories of vessels could have generated a more targeted and practical suggestion. Thirdly, although the suggested larger visibility range of 6 nautical miles for lights has been verified on masthead light since 1972, the suggested larger visibility range of 3 nautical miles for shapes has never been verified on a real ship; thus, differences between different types of conflicts were not analyzed in detail. Finally, the study only focuses on vessels with mankind on board and does not cover the Maritime Autonomous Surface Ships (MASS) [35] and the outcome of the Regulatory Scoping Exercise for the Use of MASS [36].

As a result, further research is needed to determine the theoretical visible range of lights and shapes and the relationship between a ship's collision avoidance actions and these signals, to determine the distance of close-quarters situation and safe passing of different categories of vessels in different navigational environments. Additionally, it is necessary to understand the common practices and good seamanship for seafarers in applying lights and shapes in navigation, as well as the issues and possible solutions for unmanned vessels in complying with the relevant regulations for lights and shapes, and to carry out experiment and data collection on real ships to verify the validity of the suggested visibility range of lights and shapes, as well as to analyze the differences between different types of conflicts in detail. Many of these questions will need to be addressed through exploratory accounts in future research.

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