Method of Prompt Evasive Manuever Selection to Alter Ship's Course or Speed

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One of the most important challenges of modern shipping is the problem of improving the level of safety at sea and enhancing accident-free ship operation. World fleet accident rates have a direct impact on both the safety of human life at sea and on the environment. Ship collisions have a particular place in accident statistics. They are caused by increasing ship deadweight, growing speeds, dense traffic and the presence of navigational hazards, which, combined, considerably increase navigation complexity, especially in coastal and restricted waters. These factors contribute to emergencies, incidents and situations, which, in turn, are characterized by rapidly changing circumstances. The aforementioned features of the navigation process call for the development and application of modern methods of operation and flexible evaluation of the situation at hand, as well as for the development of new approaches to evasive maneuver selection, including computer and information technologies, to ensure the safety of navigation. Thus, the development of modern methods and ways of prompt selection of an appropriate evasive maneuver to alter a ship's course or speed, which is the subject of this paper, is an important research trend. The paper also proposes a method of prompt evasive maneuver selection to prevent collisions by altering the ship's course or reducing its speed by active and passive braking. Analytical expressions used to calculate the limits of unacceptable ship course and ship speed values, taking into account the braking mode, are presented. The author's recommended optimum evasive maneuver is presented, and a technique of prompt evasive maneuver selection aimed at altering a ship's course or speed by active and passive braking is developed.

KEY WORDS
~ Safety of navigation
~ Collision avoidance
~ Evasive maneuver
~ Multiple unacceptable ship course and speed values

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1. INTRODUCTION

According to the recent report by Allianz Safety and Shipping Review, there were 41 major ship losses worldwide in 2019, which is 20 % less than last year and nearly 70 % less than a decade ago. The number of shipping incidents (2,815) increased. The most common causes of accidents at sea that have the greatest impact on the occurrence of potential threats to maritime safety are human error and weather conditions. Disregarding equipment failures, collisions at sea remain a significant threat to navigational safety. Ship collision accidents are the result of crew inexperience, navigational errors, radar system malfunctions or misuse, and in particular poor decisions by navigation officers.

Nowadays, close-quarters evasive maneuvers are performed at the local-independent control level, i.e. each vessel monitors the development of its close-quarters situation, and in case of any disturbance, both vessels make evasive maneuvers, taking into account the provisions of the International Regulations for Preventing Collisions at Sea, 1972 (COLREG-72). The level of safety of a ship's evasive procedure is heavily dependent on the method of safe evasive maneuver selection. It makes particular sense when navigating in confined waters, in conditions where prompt selection of a ship's evasive maneuver is required to minimize the risk of collision.

2. LITERATURE OVERVIEW AND PROBLEM FORMULATION

A substantial number of scientific papers have dealt with the issues of ship collision prevention. The principles of local-independent and external control of evasive maneuvers of vessels at dangerous rapprochement and technical solutions for collision risk reduction are considered in (Burmaka et al., 2016; Couvat and Gambaiani, 2013; Zheng et al., 2021). The same paper also analyses the methods of their implementation and considers potential and relevant methods of navigational safety improvement and ship collision prevention. (Pyatakov et al., 2015) look into the types of interaction between ships in various dangerous proximity situations and consider methods of compensation for situational disturbance depending on the degree of danger. A flexible evasive strategy development method for situations involving several dangerous targets, relying on local-independent control methods, and taking into account the COLREG-72 requirements, the proximity of navigational hazards, ship dynamics and ship collision avoidance method was proposed in (Tsymbal et al., 2007, Huang et al., 2020, Youngjun et al., 2013). Ship collision prevention in excessive proximity situations was investigated in (Burmaka et al., 2014), which also proposed an emergency evasive strategy. (Mehri et al., 2021) propose a novel context-aware trajectory simplification method capable of predicting vessel movement. (Petrechenko, O., 2018; Burmaka, 2005; Li et al., 2019) propose a method for determining evasive maneuver parameters and ship's inertia to calculate evasive strategy parameters. (Lisowski, 2007) formalizes evasive maneuvers in terms of differential game, and points out that the Marine Geographic Information System (MGIS), as a rule, lacks the technical capabilities requisite for controlling vessel movement in congested areas, and proposes a new fuzzy collision avoidance method. An accurate prediction of collision time and position can be obtained using an analytical model of the marine geographic information system (GIS). The proposed method enables the vessel traffic service (VTS) operator to make decisions that will prevent vessel collision. A collision risk assessment method using true motion mode is considered and discussed in (Imazu, 2017). The paper introduces the line of predicted collision (LOPC) and the obstacle zone of target (OZT) into collision risk assessment. Being related to true motion, these values help identify dangerous proximity situations and ensure safe navigation in confined waters. Vessel's operational condition and the negative factors system are reviewed in (Onyshchenko et al., 2021; Onyshchenko and Melnyk, 2020). (Statheros et al., 2008; Kuwata et al., 2013; Wang et al., 2019; Volyanskaya et al., 2017) outline a theoretical justification for an autonomous ship-based collision avoidance system. Research on ship control automation is presented using mathematical models and algorithms, or computer technology using artificial intelligence. Though the above papers contribute to the theoretical basis and offer some ship collision prevention solutions, they are lacking in the development of practical solutions that would improve evasive maneuver selection which is of great practical interest. Therefore, the purpose of this study is to develop a new prompt evasive maneuver selection method that would allow the vessel to alter its course or reduce its speed using active and passive braking.

3. MATERIALS AND METHODS

Evasive procedure safety largely depends on the timely identification of a close quarters situation, and the prompt selection of the correct evasive maneuver depending on the reciprocal area of mutual obligations. If there is sufficient room, a vessel course adjustment evasive maneuver is preferred. However if navigational obstacles forbid this course of action, the speed reduction evasive maneuver should be used. In close quarter situations in confined waters the presence of navigational hazards can prevent the change of course and necessitate maneuvering aimed at speed reduction by active braking, i.e. by reversing the main engine to generate propeller backstop force that lasts from the moment of reversal until the ship comes to a standstill or reduces speed to a certain set value or by passive braking performed with the stopped engine to maximize the effect of water resistance. Let us consider both instances of active braking to ensure evasive maneuver safety and develop a method for the prompt selection of the correct evasive maneuver that will change course or reduce speed by active and passive braking.

As a rule, an operating vessel in a standard evasive situation will use a maneuver that will alter one motion parameter: course or speed, keeping the second parameter unchanged. Therefore, selecting the correct maneuver for an operating vessel by using a one-dimensional set of unacceptable ship maneuvering parameter values makes sense.

Thus, in the case of the course adjustment evasive maneuver, the boundary courses of the set of unacceptable values of evasive courses M_K are determined by using the expression given in [1], taking into consideration the constant value of the ship's speed V_1:

$$K_{yp} = g^{(1)} + arcsin \frac{V_2 sin\,(K_2 - g^{(1)})}{V_1}$$
$$K_{ys} = g^{(2)} + arcsin \frac{V_2 sin\,(K_2 - g^{(2)})}{V_1} \quad (1)$$

where: K_{yp}, K_{ys} - limit values of evasive courses, V_1 - ship's speed constant value; K_2 - ship's course points; $g^{(1)} = a - arcsin \frac{d_d}{D}$ и $g^{(2)} = a - arcsin \frac{d_d}{D}$ - bearing and distance between ships.

Consequently, the $M_K = [K_{yp}, K_{ys}]$ set, and course adjustment selection K_y depend on condition $K_y \neq M_K$.

In case of a speed reduction evasive maneuver, the set of unacceptable speeds M_V limited by speeds V_1 and V_{1y}, and V_{1y} is calculated using the expressions given in [1].

In case of active braking:

$$V_{1y} = \sqrt{\frac{P}{\mu}}\, tg\,\{ arctg\,(\sqrt{\frac{\mu}{P}} V_1) - \rightarrow$$
$$- \frac{\sqrt{\mu P}}{(1+k)\, mV_2\, sinK_2} \{ X_1\,(t) - [\, sin\,(\, K_{otp} + Arcsin \frac{d_d}{DD_P})] \,/\, D_p \}\} \quad (2)$$

where:

$$X_1\,(t) = S\, sin\, K_{1y} = \frac{(1+k)m}{2\mu} ln \left| \frac{V_1^{\,2} + \frac{P}{\mu}}{V_{1y}^{\,2} + \frac{P}{\mu}} \right| sin\, K_{1y} \quad (3)$$

$$D_P = \sqrt{(X_1\,(t) - X_2\,(t))^2 + (Y_1\,(t) - Y_2\,(t))^2} \quad (4)$$

and

$$Y_1\,(t) = \frac{(1+k)m}{2\mu} ln \left| \frac{V_1^{\,2} + \frac{P}{\mu}}{V_{1y}^{\,2} + \frac{P}{\mu}} \right| cos\, K_{1y} \quad (5)$$

$$X_2\,(t) = D_0\, sina_0 + V_2\, sin\, K_2 \frac{(1+k)m}{\sqrt{\mu P}}$$
$$[arctg\, (\frac{\sqrt{\mu}}{\sqrt{P}} V_1\,) - arctg\, (\frac{\sqrt{\mu}}{\sqrt{P}} V_{1y}\,)] \quad (6)$$

$$Y_2\,(t) = D_0\, cosa_0 + V_2\, cos\, K_2 \frac{(1+k)m}{\sqrt{\mu P}}$$
$$[arctg\, (\frac{\sqrt{\mu}}{\sqrt{P}} V_1\,) - arctg\, (\frac{\sqrt{\mu}}{\sqrt{P}} V_{1y}\,)] \quad (7)$$

In case of passive braking:

$$V_{1y} = \frac{V_1}{1 + \frac{\mu V_1}{(1+k)mV_2 sinK_2} \{X_1\,(t) - [sin\,(K_{otp} + Arcsin \frac{d_d}{DD_p})]/D_p\,\}} \quad (8)$$

where:

$X_1\,(t) = \frac{(1+k)m}{2\mu} ln \left| \frac{V_1^{\,2}}{V_{1y}^{\,2}} \right| sin\, K_{1y}$, Dp is defined by expression (3)

$$Y_1\,(t) = \frac{(1+k)m}{2\mu} ln \left| \frac{V_1^{\,2}}{V_{1y}^{\,2}} \right| cos\, K_{1y} \quad (9)$$

$$X_2\,(t) = D_0\, sina_0 + V_2\, sinK_2 \frac{(1+k)m}{\mu V_0} (\frac{V_1}{V_{1y}} - 1)$$

$$Y_2\,(t) = D_0\, cosa_0 + V_2\, cosK_2 \frac{(1+k)m}{\mu V_0} (\frac{V_1}{V_{1y}} - 1) \quad (10)$$

The following designations are used in the above expressions: K_{YP} , K_{YS} - limit values of evasive courses, KV_1 - ship's speed constant; K_2 - ship's course points P - propeller thrust; m - mass of the ship with attached water masses; μ - resistance coefficient and evasive course value:

$$K_{otp} = \arcsin \frac{V_{1y} \sin K_{1y} - V_2 \sin K_2}{[V_{1y}^{\,2} + V_2^{\,2} - 2V_{1y} - V_2 \cos(K_{1y} - K_2)]^{½}} \qquad (11)$$

Since $M_V = [V_{1y}, V_1]$ is set, evasive maneuver speed is selected by applying the $V_y \neq M_V$ requirement. Note that optimum evasive maneuver speed is achieved at the value of $V_{1y} = V_1$.

A computer program was developed for this purpose that displays sets of M_K и M_V, allowing us to select the optimal evasive maneuver and verify its correctness. For example, let us consider a dangerous approach situation with parameters α= 88°, miles, K_1= 45°, V_1 =23 kn, K_2 =315°, V_2 =20 kn.

After entering the parameters of a dangerous proximity situation, the monitor displays graphical representations of unacceptable sets M_K и M_V (red) at a given point in time (Figure 1), and the set M_K illustrated by a horizontal red line on the ship's course axis, in this case from 23˚ to 76˚.

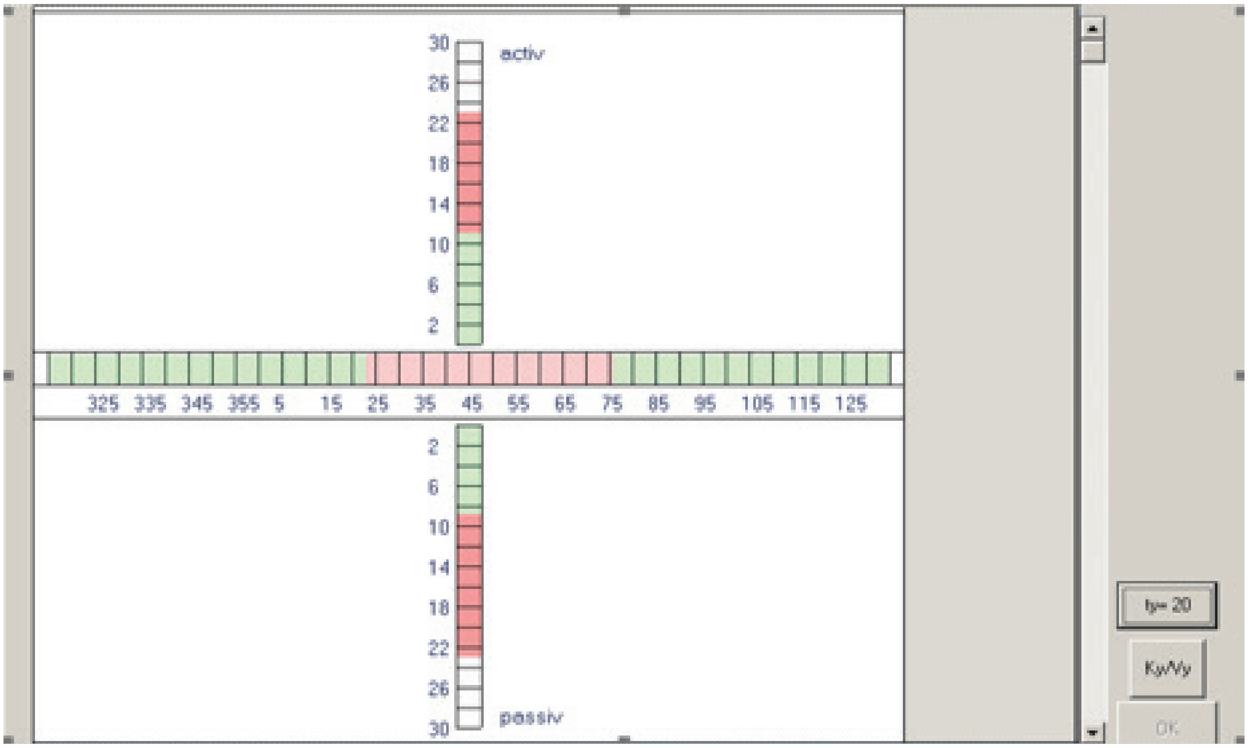

Figure 1.
Mapping of M_K and M_V sets.

The remaining set of allowed evasive trajectories is depicted in green. The M_V set for active braking is shown by the vertical red segment at the top of the screen. In the case considered, limits of the set are 23 and 11 knots, thus $M_V = [\,11, 23\,]$. The vertical red bar at the bottom of the screen represents the M_V set in case of passive braking. Limits of the passive braking M_V set are 23 and 9 knots, $M_V = [\,9, 23\,]$.

In Figure 2, the evasive maneuver selected is course adjustment. The optimal course determined using the scroll bar is turning left, i.e. towards the left boundary of the M_K set, equaling $K_Y = 23\,^{\circ}$.

Figure 3. illustrates true and relative evasive trajectories, designated as red and green, respectively, for the given evasive course. The relative evasive trajectory is tangential to the circular domain, which confirms the optimality of the selected evasive trajectory.

Figure 4 shows the right-turn evasive maneuver to optimal course $K_Y = 76\,^{\circ}$, on the right boundary of the M_K segment;

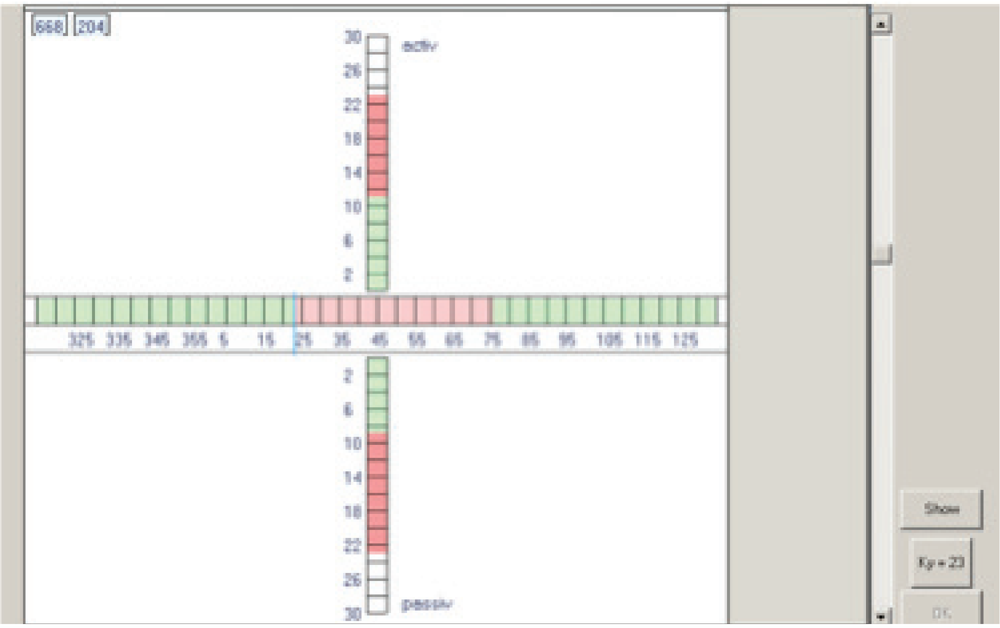

Figure 2.
Selection of a left-turn evasive trajectory.

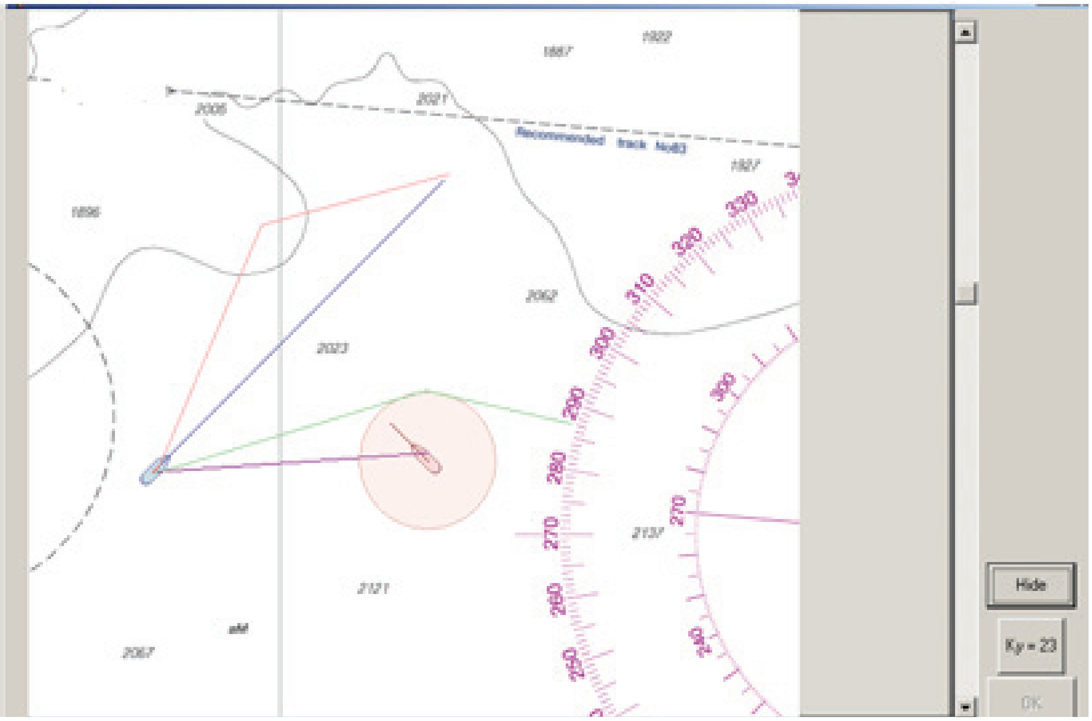

Figure 3.
Evasive trajectories by course adjustment to the left.

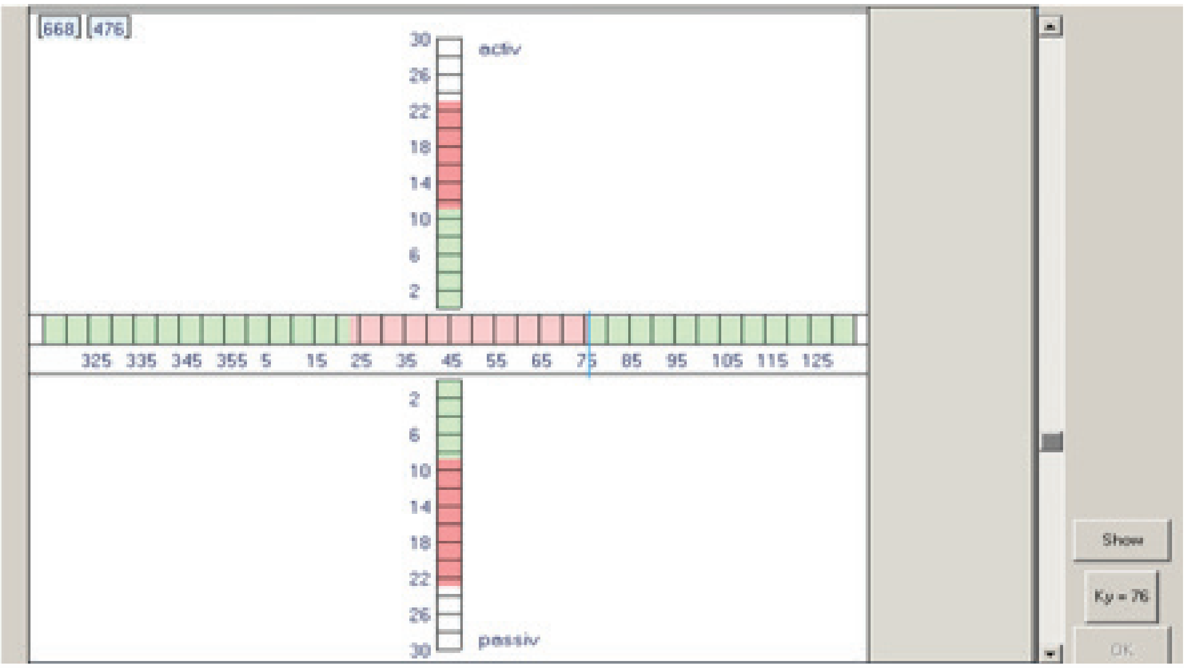

Figure 4.
Selection of a right-turn evasive trajectory.

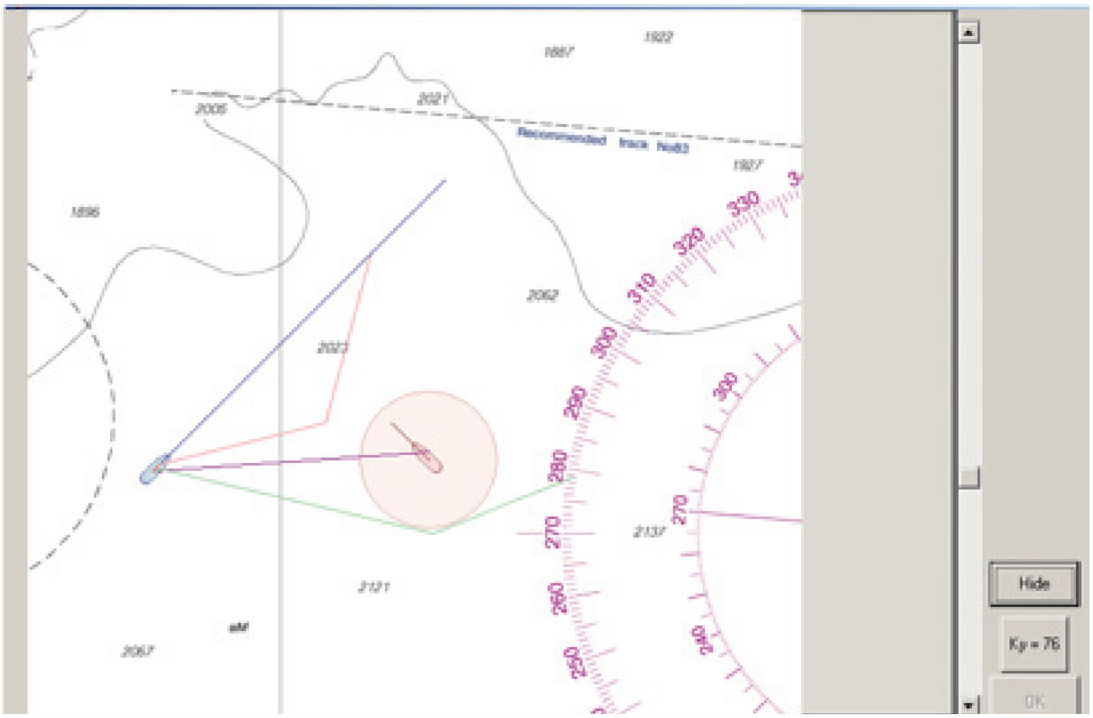

Figure 5.
Evasive trajectories by course adjustment to the right.

Figure 5 shows the true (red) and relative (green) evasive trajectories for the selected rightward evasive course, with the relative evasive trajectory being tangential to the circular domain, as seen in the same figure. To turn by braking, an active braking speed reduction maneuver must be selected in the upper vertical segment to obtain the optimal active braking speed of V_Y=11 knots.

The validity of optimal speed value selection is verified by checking the relative evasive trajectory on the screen, as shown in Figure 6. It should be noted that relative evasive trajectory after braking is tangential to the boundary of the vessel safety domain, which confirms the optimality of the selected evasive speed value.

In case of a passive braking evasive maneuver, evasive maneuver speed must be chosen from the lower vertical section. The optimal speed of passive braking was V_Y=9 knots.

The results of optimal evasive speed selection validation by passive braking are presented in Figure 7 that shows relative evasive trajectory, tangential to the circular domain, which confirms that the selected evasive speed is optimal for collision prevention.

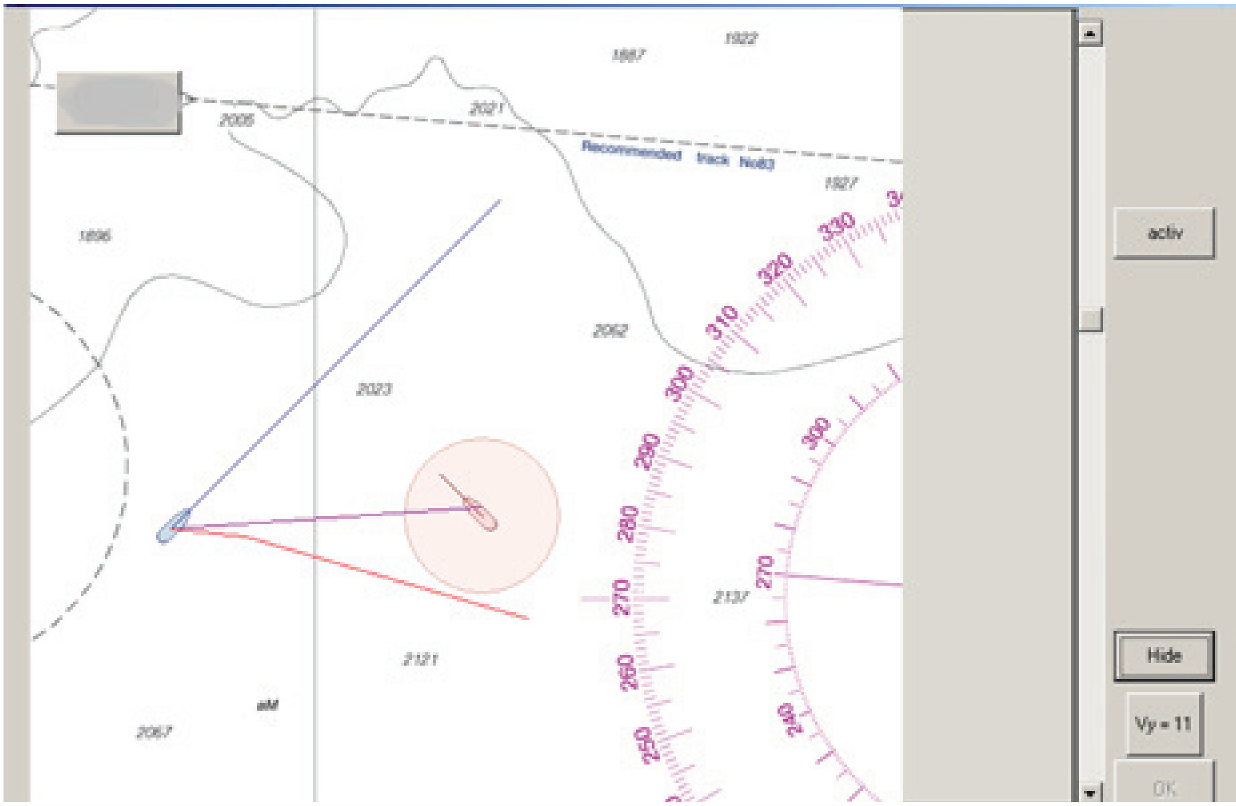

Figure 6.
Relative evasive trajectory during active braking.

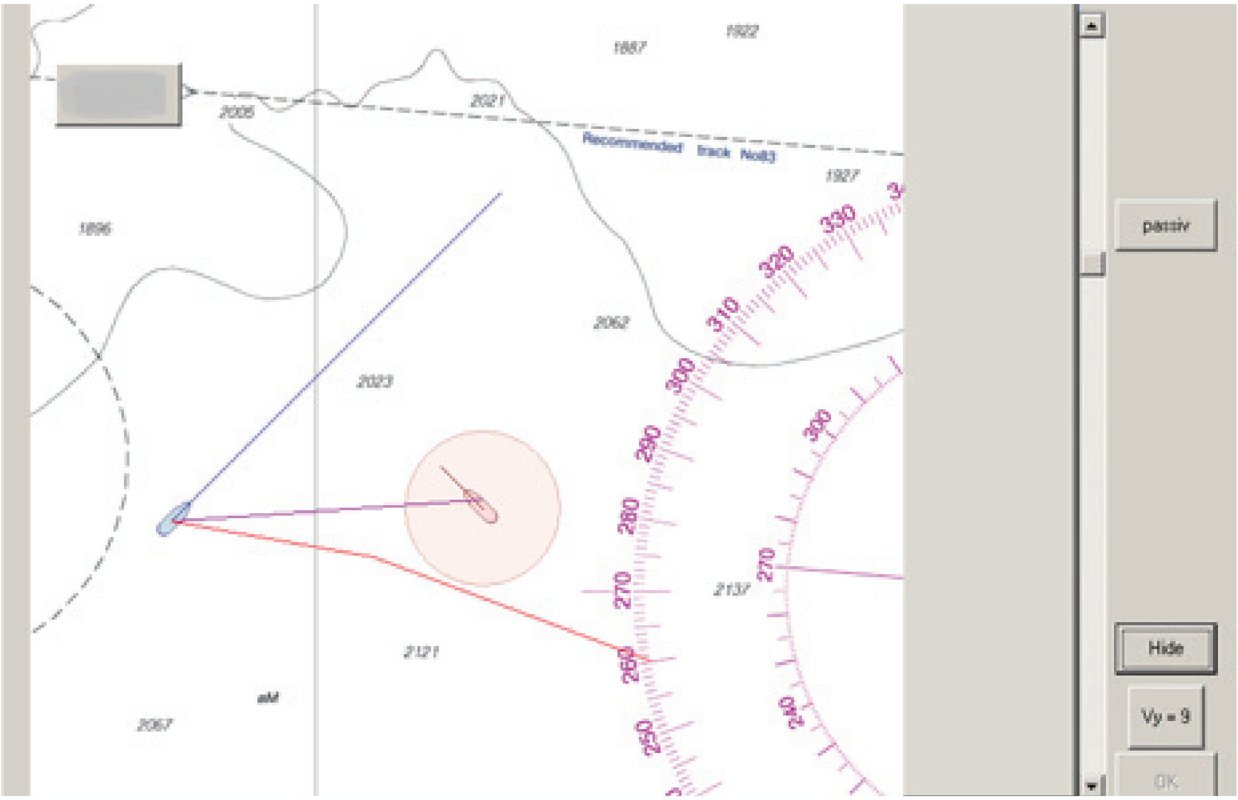

Figure 7.
Relative trajectory during passive braking.

4. CONCLUSION

This paper examines the dependence of evasive procedure safety level on the safe evasive maneuver selection method in a one-on-one situation, involving the dangerous rapprochement of two ships, and attempts to create a common collision prevention strategy for both ships. This is paramount in the presence of navigational hazards and in dense traffic conditions which significantly complicate navigation and have an impact on its safety, especially in confined waters, in congested or high traffic areas and coastal navigation, where the makings of emergency situations abound. The proposed technique is the selection of the optimal evasive maneuver involving course adjustment and speed reduction. In contrast to existing approaches, this method takes into account unacceptable ship course and speed values and allows prompt identification of the appropriate evasive maneuver to prevent collision, which minimizes the risk of ship collision in confined waters. Analytical expressions for the calculation of unacceptable ship course and speed value limits are given, which allow both the selection of the optimal evasive maneuver and the validation of its suitability in the prevailing sailing conditions. A software is proposed that gives a graphical representation of unacceptable course and speed values at any given time on the screen, as well as a set of allowable evasive courses and speed values in case of active and passive braking. The paper also provides examples of selection of optimal evasive maneuvers involving course adjustment and speed reduction, which allow the performance of the optimal evasive maneuver that will prevent collision with the target.

CONFLICT OF 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.

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