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Polygonal Type Fuzzy Ship Domain-Based Decision Support System for Collision Avoidance Route Planning

Remzi Fışkın[1], Efendi Nasibov[2], Mehmet Oğuz Yardımcı[3]

[1]Ordu University Faculty of Marine Sciences, Department of Marine Transportation Engineering, Ordu, Türkiye
[2]Dokuz Eylül University Faculty of Science, Department of Computer Science, İzmir, Türkiye
[3]Amazon Ads, Software Development Engineer, Washington, USA

Abstract

This study presents a methodology for a decision support system based on a polygonal fuzzy ship domain, which takes into account the Convention on International Regulations for Preventing Collisions at Sea. A user interface has been created for the decision support function of collision avoidance (CA) at sea by designing a C# form application using the Microsoft Visual Studio platform. Numerical experiments and case scenarios have demonstrated that the proposed model can provide a reasonable and practical solution. Additionally, the results indicate that the developed model can accurately manage the CA action, and the planned CA trajectory can ensure safe navigation. This study is an excellent example of an algorithm structure that combines fuzzy logic and a deterministic approach. The developed methodology is anticipated to effectively guide vessel traffic services operators and navigators and contribute to ship automation, e-navigation strategy, and navigational safety at sea.

Keywords: COLREG, Ship domain, Fuzzy logic, Collision avoidance, Optimization

1. Introduction

Maritime transportation plays a crucial role in global trade and the world economy. As international trade volume continues to grow, so does the demand for maritime transportation, resulting in more intense and crowded maritime traffic [1]. According to the United Nations Conference on Trade and Development, world maritime trade volume increased by 3.2% in 2021 compared to the previous year [2]. This situation places an even greater burden on navigators and operators and increases the likelihood of maritime accidents. Therefore, a decision support system can help alleviate this burden by assisting navigators and operators in effectively mitigating collision risks during decision-making [3].

In practice, navigators often make subjective decisions regarding collision avoidance (CA) maneuvers, with support from bridge navigational aids, such as electronic chart display and information system (ECDIS), automatic identification system (AIS), and automatic radar plotting aid (ARPA) radar. The ARPA radar is particularly important for assessing collision risks but cannot suggest the best route for CA planning. Likewise, although the trial maneuver mode of radar can provide data on ship movements, it cannot provide information on the best CA maneuvers.

According to Convention on International Regulations for Preventing Collisions at Sea (COLREG), head-on, crossing, and overtaking are the main types of encounters at sea, as shown in Figure 1. Additionally, COLREG identifies and regulates these encounters, as shown in Table 1.

Figure 1 shows different encounter types as other ships approach the ship under our control (OS) from various angles. Each ship has different responsibilities according to COLREG for each encounter. For instance, when the target ship (TS) approaches from an angle between 5° and 112.5° (the light grey area in the figure), the OS is the give-way vessel, and the other ship must maintain its current movement as a stand-on vessel by keeping its course and speed constant.

Address for Correspondence: Remzi Fışkın, Ordu University Faculty of Marine Sciences, Department of Marine Transportation Engineering, Ordu, Türkiye
E-mail: remzi.fiskin@gmail.com
ORCID ID: orcid.org/0000-0002-5949-0193

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Table 1. *COLREG rules for encounter situations*

Rule	Encounter situation	Own ship (OS)	Target ship (TS)	Rule description
R13	Overtaking	Give-way or stand-on	Give-way or stand-on	"any vessel overtaking any other shall keep out of the way of the vessel being overtaken"
R14	Head-on	Give-way	Give-way	"when two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision, each shall alter her course to starboard so that each shall pass on the port side of the other"
R15	Crossing (dark grey) Crossing (light grey)	Stand-on Give-way	Give-way Stand-on	"when two power-driven vessels are crossing to involve risk of collision, the vessel which has the other on her starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel"

COLREG: Convention on International Regulations for Preventing Collisions at Sea

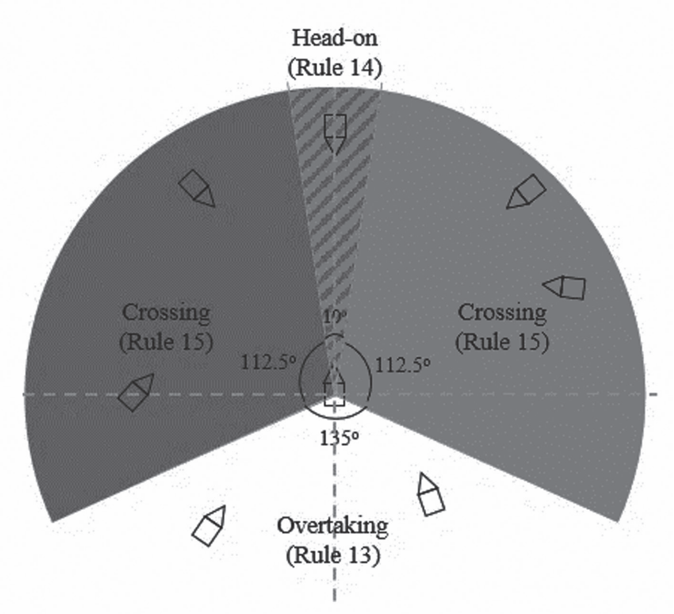


Figure 1. *Encounter situations of ships at sea (OS is on the centre while TS is approaching from different angles)*

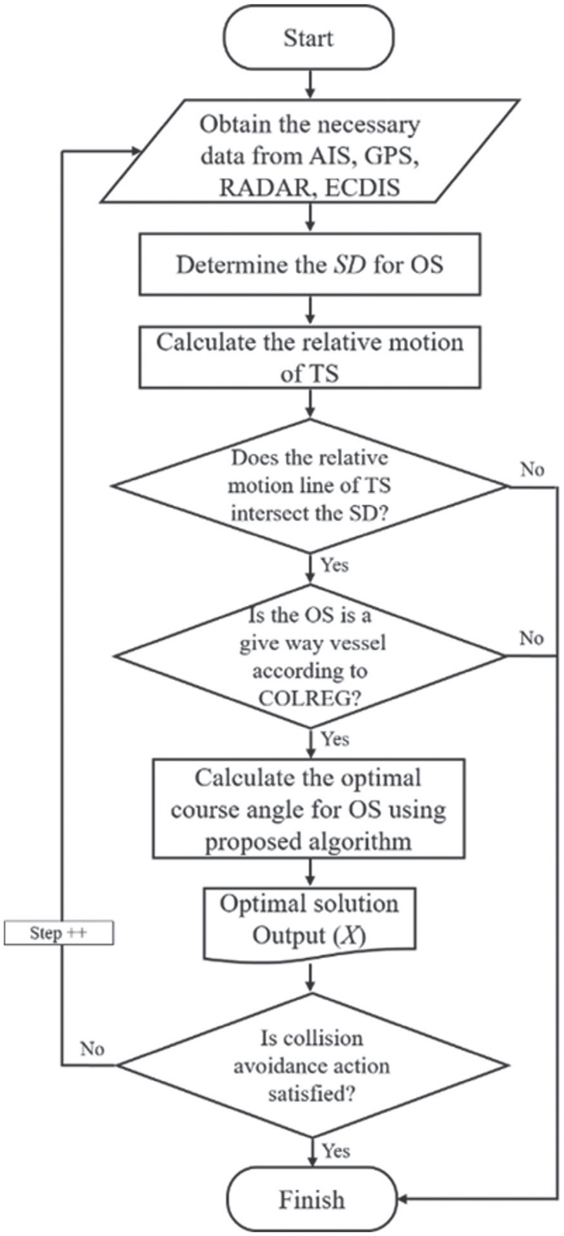


Figure 2. *Methodological flowchart for model development*

The COLREG rules define encounter situations on a one-to-one basis, so this study primarily focuses on such situations and does not consider encounters involving multiple ships. To solve maritime encounter situations and propose the optimal CA route, this study introduces a deterministic-based approach that accounts for the requirements of COLREG. Unlike similar studies in the literature, this methodology uses a polygonal fuzzy ship domain (SD) surrounding the ship for collision risk assessment. Figure 2 depicts the methodological flowchart of the presented approach. Initially, data is gathered from relevant instruments, such as AIS, Global Positioning System, and ECDIS to determine the current state of the encounter situation. The collision risk assessment is then conducted by determining the SD for OS. Next, the relative motion of TS is calculated and checked to see if it violates the SD. If there is a violation, it indicates a risk of collision. In such a scenario, OS, as the give-way vessel, should take evasive action. The proposed model determines the optimal course alteration degree and provides the optimal solution. If the CA action is unsatisfactory, the system reverts to the initial step to improve the solution.

The study is divided into several sections: Section 2 contains a literature review summarizing contemporary works. Section 3 provides information about the model definition of the methodology introduced. Section 4 presents the findings of numerical experiments. Section 5 discusses the study's findings in comparison with other works. Section 6 outlines the limitations of the study. Finally, Section 7 concludes the study and makes recommendations for further research.

2. Literature Review

Encounters that involve collision risk are crucial for ensuring navigational safety at sea [4]. Consequently, this topic is one of the most widely discussed areas in the field and is frequently studied by researchers.

Kim et al. [5] have developed a method based on the Distributed Stochastic Search Algorithm (DSSA) that allows for stochastic alteration of a ship's route by detecting the movement intentions of TS. The experimental test results showed that DSSA is more efficient than previously developed distributed algorithms, such as the distributed local search algorithm and distributed tabu search algorithm. The authors suggested that their system takes into account both safety and efficiency.

Liu et al. [6] have introduced a model that offers CA route planning based on the particle swarm optimization algorithm. The model uses the fuzzy quaternion SD to assess the collision risk. Simulation tests were implemented to demonstrate the performance of the model.

It has been shown that the model can effectively address the CA problem. Lazarowska [7] developed another algorithm for route planning using Artificial Potential Field (APF) to suggest a safe route for ships. The author claimed that this model can provide a close-to-real-time solution, taking into consideration obstacles (static and dynamic). Experimental tests were conducted to demonstrate the effectiveness of the model under various scenarios, and the results confirmed its effectiveness.

Fiskin et al. [8] proposed a model based on deterministic features, allowing the vessel to change course deterministically to eliminate the risk of collision using the shortest safe route. The system was tested experimentally and was found to be applicable and outperform Artificial Intelligence (AI)-based methods. Lyu and Yin [9] also presented a deterministic-based method that returns a real-time solution in different environments. In their study, an APF-based system was developed to address encounter situations, including emergencies.

Huang et al. [10] developed an interpretable and interactive CA system for practitioners by modeling the CA process on ships through human-machine interaction. The applicability of the proposed model was supported by scenario tests performed with an Unmanned Surface Vehicle (USV). Zaccone and Martelli [11] introduced a model for CA in open waters based on the Rapidly exploring Random Tree algorithm. The authors stated that the proposed approach was designed to function as the top layer of the control structure of autonomous vessels navigating in open waters. The experimental tests determined that the developed model can plan an unobstructed alternative route and then alter the ship to its original route, avoiding the surrounding obstacles in almost real-time.

Fiskin et al. [12] proposed a CA methodology that utilizes a genetic algorithm (GA) and fuzzy logic. The methodology included qualitative and quantitative research processes and was experimented with in a virtual environment using a bridge simulator and in the real environment with a USV through different scenario cases. The authors stated that the algorithm produced satisfactory findings and can be used as a CA submodule within the navigation module for unmanned ships and USVs.

Li et al. [13] introduced a CA route planning methodology based on deep reinforcement learning to solve the safe trajectory planning problem of autonomous surface vehicles in uncertain environments. In the developed model, the environment of the TS was divided into four level avoidance zones, and a risk assessment was carried out according to these zones. Simulation experiments were planned to test the effectiveness of the model in various environments. The experiments showed that CA route planning could be performed effectively with the model.

Szlapczynski and Szlapczynska [14] presented a novel model for collision risk assessment for near-miss detection, which mainly uses a SD concept. A total of five variables were used such as relative speed of vessels, encounter complexity, and arena violations. Additionally, case studies were provided to verify the system's suitability. The authors highlighted that the presented system deals tremendously well with early maneuvers.

Zhao et al. [15] developed an intelligent model for CA in open waters, which takes into account the ship's maneuverability. The model combines the mathematical modeling group (MMG) approach with a three-degree-of-freedom maneuvering model in various environmental conditions, taking into consideration the ship propeller characteristics. The algorithm ultimately decides to change the course and/or speed of the ship. The proposed model was tested through simulation with various scenarios. The findings showed that the optimum CA action can be achieved with the decision made by the system. Du et al. [16] introduced a collision warning system based on the risk perception of the navigator to initiate a timely CA maneuver. The proposed system was tested with various encounter cases, showing its feasibility in both one-to-one and multi-ship encounter situations. García Maza and Argüelles [17] aimed to identify and classify basic criteria for decision-making in ship encounters with respect to COLREG. The authors offer insights into ship CA considering COLREG.

In conclusion, the problem of CA route planning is a hot topic that attracts the interest of researchers. Many approaches to the solution of the problem have been introduced so far. Some recent studies, detailed in Table 2, are provided in the previous paragraphs. It is revealed that the SD is commonly used for collision risk assessment in most studies. Similarly, this study uses the SD method for collision risk assessment. However, unlike most studies, which generally use a circular or elliptical SD, a polygonal SD is used in this study. The proposed model in this study also has a deterministic algorithm structure in addition to a polygonal SD with a fuzzy structure. Since no similar approach exists in the literature, this study fills the gap in the related field.

3. Materials and Methods

SD, traffic flow theory, and closest point of approach are methods in the literature used for collision risk assessment [18]. If a vessel violates the free area of another vessel in the vicinity, it is considered at risk of collision, and the give-way vessel should take CA action [19,20]. SD is defined as "the area surrounding a ship where a navigator aims to keep free with respect to other ships or obstacles" [21]. Although the circular SD is commonly used in practice, this study utilizes a polygonal, fuzzy SD (as illustrated in Figure 3 and introduced by Fiskin et al. [20]) for collision risk assessment.

The introduced model has several advantages. The size and shape of the domain are determined by expert interviews and literature, taking into account factors that affect them:

a) ship length (L),

b) ship speed (V),

c) maneuverability (M),

d) traffic state (T),

e) navigator experience (N),

f) daytime (daylight or night) (D),

Table 2. *Current models proposed by various authors*

Reference	Approach type	Action type	Risk assessment method	Domain type	Complex environment	Method type	Obstacle characteristic
Kim et al. [5]	AI	Route change	Ship domain	Circular (around the OS)	Yes	DSSA	Dynamic
Liu et al. [6]	Deterministic	Route change	Ship domain	Elliptic (around the OS)	No	Analytical	Dynamic
Lazarowska [7]	AI	Route change	Ship domain	Hexagon (around the TS)	Yes	APF	Dynamic
Fiskin et al. [8]	Deterministic	Route change	Ship domain	Circular (around the OS)	No	Analytical	Dynamic
Lyu and Yin [9]	AI	Route change	Ship domain	Circular (around the OS)	Yes	APF	Dynamic
Huang et al. [10]	Deterministic	Route/speed change	-	-	Yes	Analytical	Dynamic
Zaccone and Martelli [11]	AI	Route change	Ship domain	Circular (around the OS)	Yes	RRT	Dynamic
Fiskin et al. [12]	AI	Route change	Ship domain	Circular (around the OS)	No	GA, fuzzy logic	Dynamic
Li et al. [13]	AI	Route change	Ship domain	circular (around the OS)	No	DRL	Dynamic
Szlapczynski and Szlapczynska [14]	Deterministic	Route change	Ship domain	Elliptic (around the OS)	Yes	Analytical	Dynamic
Zhao et al. [15]	Deterministic	Route/speed change	Ship domain	Elliptic and circular (around the OS)	Yes	MMG	Dynamic
Du et al. [16]	Deterministic	Route change	Ship domain	-	Yes	Analytical	Dynamic
Proposed model	Deterministic	Route change	Ship domain	Polygonal (around the OS)	No	Analytical	Dynamic

g) sea state (W),

h) visibility (I),

ı) relative bearing (RB) of the TS (E).

Their values were defined based on literature. For instance, ClassNK and Kao et al. [22] analyzed ship length using AIS data, while ship speed was determined by considering the ship speed categorization in the ITU-R M 1371-1 report [23]. Additionally, the navigator's experience was taken into account by considering the promotion periods in Türkiye.

The aim of the CA route maneuver is to keep the SD clear of other ships or objects. To optimize this maneuver, the relative motion vector of the TS should be tangential to the SD. The algorithm outlined below is introduced to determine the course degree (X) that will provide the optimal maneuver.

```
1. Setting of initial values;
  • $f(a,b) = \overrightarrow{(Cos(a) * b, Sin(a) * b)}$
  • U = $C_{os(initial)}$
  • L = $C_{os(initial)} - 180$
2. For IC times;
  • C = (U + L)/2
  • $\vec{S} = f(C, |\overrightarrow{V_{os}}|)$
  • $\overrightarrow{RS} = \overrightarrow{V_{ts}} - \vec{S}$
  • $d = C - C_{os(initial)}$
  • $cTheta = Cos(d)$
  • $sTheta = Sin(d)$
  • For every point $\vec{P_i}$ in SD
      ▪ $cTheta = Cos(C - C_{os(initial)})$
      ▪ $\vec{P_i}' = \overrightarrow{cTheta * \vec{P_i}.x - sTheta * \vec{P_i}.y, sTheta * \vec{P_i}.x + cTheta * \vec{P_i}.y}$
  • If a ray starting from a point $\overrightarrow{P_{ts}}$ and has the same degree with $\overrightarrow{RS}$ **intersects*** SD:
      ▪ Then:
          ○ L = C
      ▪ Else:
          ○ U = C
  • Repeat step 2
3. $U_{final}$ = U
**BigOh ($IC$ * Intersection Check)**
```

U_{final} refers to the final value for the optimal avoidance course. The U_{final} error for optimum degree X is determined by Equation 1:

$$|X - U_{final}| \leq {}^{180}/_{2^{IC}} \quad (1)$$

where U denotes the upper course bound, L denotes the lower course bound, denotes the initial course of the OS, C represents course on check, IC denotes the iteration count, denotes the relative speed vector, denotes the position vector of the TS, SD denotes the SD of the OS, and P_i denotes the i. point in SD. is the OS speed vector which includes magnitude and course components of the OS speed.

*The following algorithm is applied to control the intersection of ray and polygon:

Intersection Check:

```
1. For every two consecutive points P1 and P2 in polygon SD
  • If ray **crosses between**** P1 and P2:
      ▪ Then ray intersects safety SD
      ▪ Return.
2. If ray does not cross between any consecutive points:
  • Then; ray does not intersect safety SD
  • Return.
```

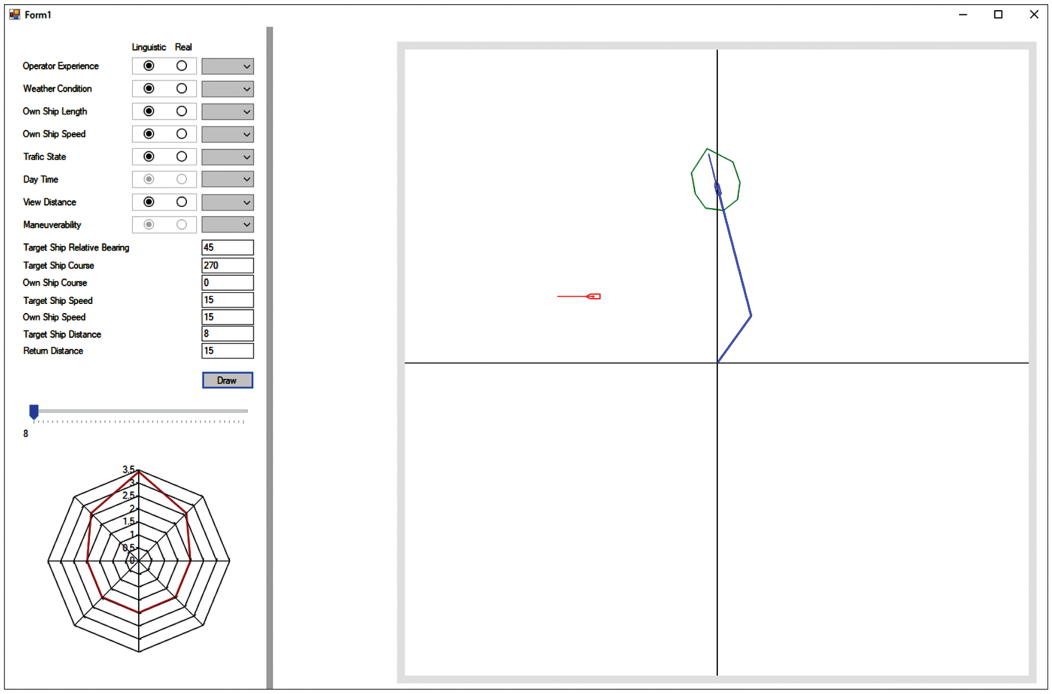
**The following algorithm is applied to determine if a ray, starting from point O and moving toward M, crosses between two points $P1$ and $P2$:

Crossing Check:

```
A = P1,B = P2,C = O,D = M ➔
1. a1 = B.y - A.y
2. b1 = A.x - B.x
3. c1 = a1 * (A.x)+ b1 * (A.y)
4. a2 = D.y - C.y
5. b2 = C.x - D.x
6. c2 = a2 * (C.x) + b2 * (C.y)
7. d= a1 * b2 - a2 * b1
8. If d= 0
  • Then:
      ▪ Ray does not cross between P1 and P2
      ▪ Return.
  • Else
      ▪ x = (b2 * c1 - b1 * c2) / d
      ▪ If ((x < A.x and x > B.x) or (x > A.x and x < B.x))
          ○ Ray crosses between P1 and P2
          ○ Return.
9. Ray does not cross between P1 and P2
10. Return.
```

4. Numerical Experiments

In numerical experiments, the results of the proposed model were observed under various scenarios, taking into account different ship encounter types, such as head-on, crossing, and overtaking. A practical user interface was created for the decision support function of CA at sea using a form application designed in the C# programming language on the Microsoft Visual Studio platform. As shown in Figure 3, the left side of the interface displays inputs provided by the system user and the SD produced by the system based on these inputs. The right side shows the spatial operation and simulation of ship motions. In the simulation, the SD of the OS represented by the green area should not be violated by other objects, and the blue line refers to the optimal trajectory suggested by the system for the OS. Experimental studies were conducted using a personal computer with an Intel(R) Core(TM) i7-9700 3.00Ghz processor and 8GB RAM. The scenario inputs of the numerical experiments and the results obtained from the scenarios are presented in Tables 3 and 4, respectively.



Form1

	Linguistic	Real	
Operator Experience	●	○	
Weather Condition	●	○	
Own Ship Length	●	○	
Own Ship Speed	●	○	
Trafic State	●	○	
Day Time	●	○	
View Distance	●	○	
Maneuverability	●	○	

Target Ship Relative Bearing 45
Target Ship Course 270
Own Ship Course 0
Target Ship Speed 15
Own Ship Speed 15
Target Ship Distance 8
Return Distance 15

Figure 3. *User interface (OS and TS represent with blue and red, respectively)*

4.1. Case 1: Head-on Situation

In Case 1, TS and OS approach each other on opposite courses. The initial course of OS (Φ_{OS}) is 000°, while TS's course (Φ_{TS}) is 180°. OS's speed (V) is 15 knots, and TS's speed (V_{TS}) is 10 knots. The RB of TS (E) is 5° to starboard, and the distance of TS to OS (TSD) is 15 nm. For this experiment, the 8-node approximation is used for the SD.

The following input values are set for the SD: OS's length (L) is 150 m, OS's speed (V) is 15 knots, OS's maneuverability (M) is medium, traffic state (T) is low, navigator experience (N) is 6 years, daytime (D) is night, sea state (W) is 2 forces, and visibility (I) is at least 12 nm. In this case, the optimal CA action is for the OS to change course from 028° to starboard, according to these input variables. Figure 4 shows the ships' movements that occurred in Case 1.

4.2. Case 2: Crossing Situation

In Case 2, TS is located on the starboard bow of OS. The parameters in this scenario are Φ_{OS} at 000°, Φ_{TS} at 260°, V at 12 knots, V_{TS} at 15 knots, E at 35° starboard, and TSD at 15 nm. For this experiment, the 12-node approximation of the SD is utilized.

The following input values are set for the SD: L is 200 m, V is 12 knots, M is high, T is medium, N is 10 years, D is daylight, W is 3 forces, and I is at least 10 nm. As per these input variables, the optimal CA action for OS is to change her course to starboard by 031°. Figure 5 depicts the movements of the ships in Case 2.

4.3. Case 3: Overtaking Situation

In Case 3, the OS is located at the stern of the TS. Φ_{OS} is set at 000°, Φ_{TS} at 000°, with a speed of 19 knots for V and 6 knots for V_{TS}. E is positioned at 2° starboard, and TSD is at 3 nm. The experiment utilizes the 16-node approximation of the SD.

For the SD input values, L is set at 120 m, V at 19 knots, and both M and T are low. N is set at 8 years, with D in daylight and W at 5 forces. I is set to a minimum of 11 nm. Thus, in this case, the optimal CA action is for the OS to change course 048^o to starboard. Figure 6 displays the ships' movements observed in Case 3.

5. Evaluation of Results and Discussion

The discussion section of an academic paper is crucial for presenting the performance of the developed model. In this regard, this section aims to practically compare the proposed model with other existing models. Various scenarios have been created to implement the comparison. For comparing AI-based models, the models presented by Tsou et al. [24] and Fiskin et al. [12] have been utilized, while the models presented by Lazarowska [25] and Fiskin et al. [8] have been used for comparing deterministic-based models with different parameter settings, as provided in Table 5. Furthermore, Table 6 and Table 7 present the findings of the comparison and details of the models used for discussion, respectively.

Table 3. *Scenario inputs of the numerical experiments*

			Navigational data														
			Ship domain input									**Collision avoidance route input**					**Output**
		Encounter type	L [m]	V [kn]	T [ship]	N [year]	W [force]	I [nm]	E [°]	M [γ]	D [γ]	Φ_{OS} [°]	Φ_{TS} [°]	V_{TS} [kn]	TSD [nm]	RD [nm]	$\Delta\Phi_{OS}$ [°]
Case	1	Head-on	150	15	3	6	2	12	5	Medium	Night	000	180	10	15	15	028
	2	Crossing	200	12	6	10	3	10	35	High	Daylight	000	260	15	10	10	031
	3	Overtaking	120	19	2	8	5	11	2	Low	Daylight	000	000	6	3	7	048

Table 4. *Scenario outputs of the numerical experiments*

		Encounter type	**CA route leg length 1 [nm]**	**CA route leg length 2 [nm]**	**CA route total length [nm]**	**CA course change [°]**	**Course change to back original route [°]**
Case	1	Head-on	9.27	6.13	15.40	028	(-)027
	2	Crossing	5.18	5.36	10.54	031	(-)037
	3	Overtaking	3.84	4.13	7.97	048	(-)057

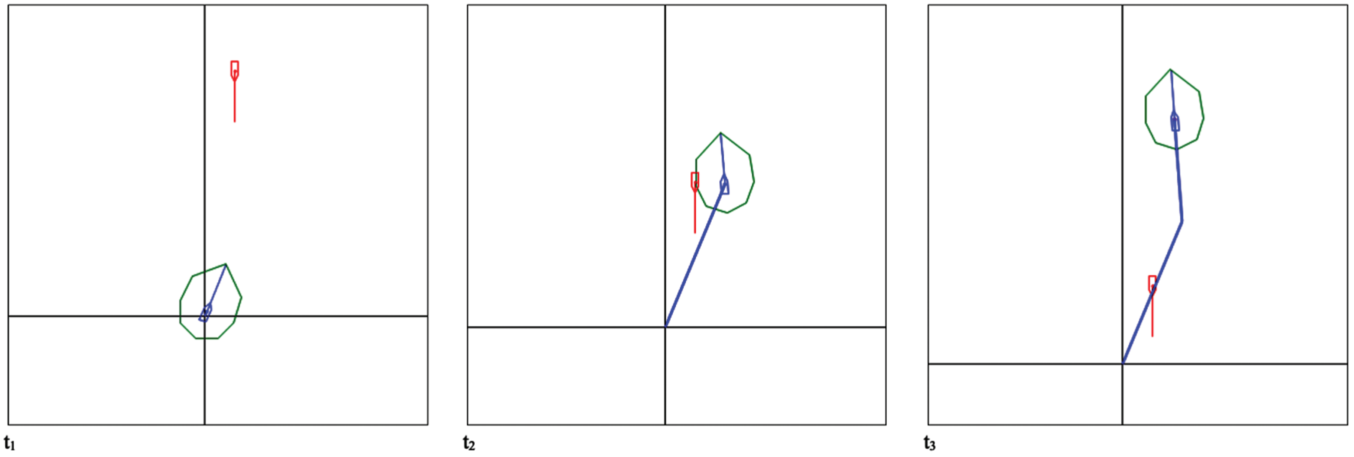


Figure 4. *Collision avoidance action of the OS in Case 1*

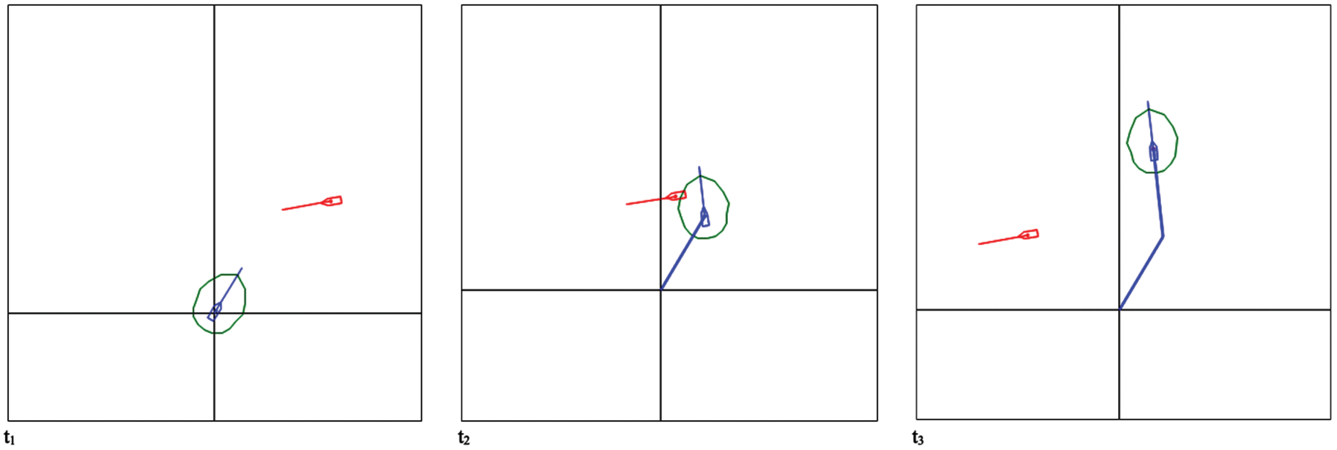


Figure 5. *Collision avoidance action of the OS in Case 2*

5.1. Numerical Comparison with AI-based Models

In Case 1, the GA-based model developed by Tsou et al. [24] is compared with the model developed in this study. The CA trajectories formed by both models are shown in Figure 7a. In the comparison scenario, the navigational input data for ships and numerical results provided by both models are shown in Tables 5 and 6, respectively. The table clearly shows that the proposed model outperforms the GA-based model in terms of total CA trajectory length and computational time. In addition, the proposed model produces considerably shorter CA trajectories and has a much shorter computational time, with the advantage of being deterministic. On the other hand, Tsou et al. [24] used a SD radius of 2 nm. To ensure a fair comparison, inputs for a polygonal SD are provided to produce a 2 nm radius for the longest node. An 8-node approximation is used in the polygonal SD.

In Case 2, the solution generated by the proposed model is compared with the solution computed by the GA and fuzzy logic-based model developed by Fiskin et al. [12]. The CA trajectories created by both models are shown in Figure 7b. In the comparison scenario, the navigational input data for ships and numerical results provided by both models are shown in Tables 5 and 6, respectively. The proposed model reaches the solution much faster. Moreover, Figure 7b shows that the trajectory computed by the proposed model is slightly shorter than the one generated by the other model. Fiskin et al. [12] used a circular domain with a radius of 2 nm. To facilitate the comparison, inputs for a polygonal SD are provided to produce a 2 nm radius for the longest node. Similar to the previous case, an 8-node approximation is used in the polygonal SD.

5.2. Numerical Comparison with Deterministic-Based Models

In Case 3, a comparison was made between the proposed model and the deterministic method known as TBA, developed by Lazarowska [25]. The CA trajectories generated by the model developed by Lazarowska [25] and the proposed model are shown in Figure 7c. In the comparison scenario, navigational input data for ships and numerical results provided by both models are shown in Table 5 and Table 6, respectively. The comparison revealed that both models produced similar results, except that the proposed model maneuvered a little later to return to the original route. Lazarowska [25] used a hexagonal SD with the longest diagonal line measuring 1.25 nm. To ensure an accurate comparison, inputs of polygonal SD were provided to produce the smallest size, which is approximately 1.5 nm. In this case, a 16-node approximation was used in the polygonal SD.

In Case 4, the results achieved by the proposed model were compared with another deterministic model called the

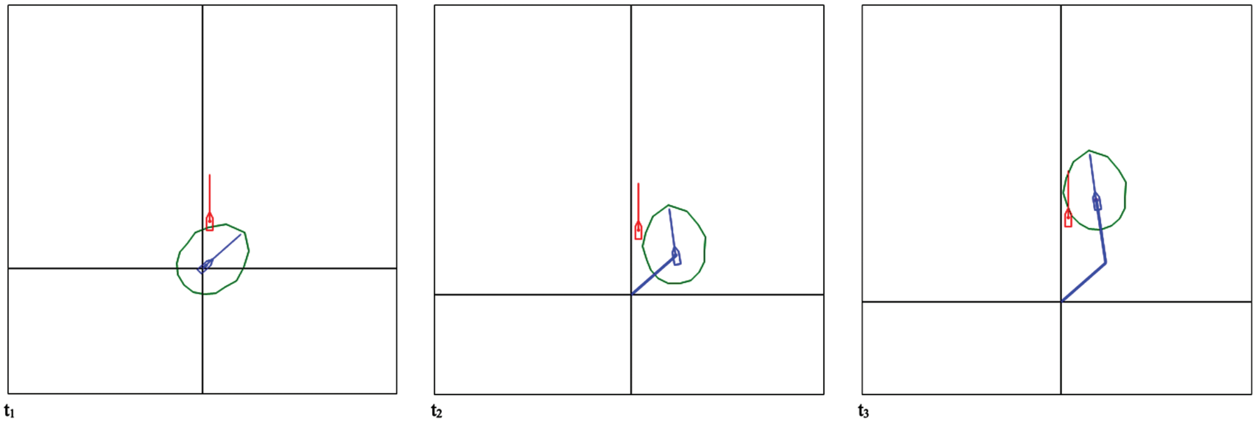


Figure 6. *Collision avoidance action of the OS in Case 3*

Table 5. *Navigational data of ships for comparison scenarios*

				Navigational input data of ships						
		Comparison with	**Encounter type**	**Φ_{OS} [°]**	**Φ_{TS} [°]**	**V [kn]**	**V_{TS} [kn]**	**E [°]**	**TSD [nm]**	**RD [nm]**
Case	1	Tsou et al. [24]	Crossing	000	240	14	15	30	4	3.8
	2	Fiskin et al. [12]	Crossing	000	240	14	15	30	4	3.4
	3	Lazarowska [25]	Head-on	000	180	14	12	0	8	9
	4	Fiskin et al. [8]	Head-on	000	180	15	15	0	10	8.14

***Table 6.** Numerical results of comparison scenarios*

		Method	CA course change [°]	Course change to back original route [°]	Total CA route length [nm]	Computational time [sec]
Case	1	Proposed model	034	(-)069	4.62	0.3
		Tsou et al. [24]	046	(-)093	5.55	14
	2	Proposed model	034	(-)078	4.38	0.3
		Fiskin et al. [12]	058	(-)088	4.53	6.8
	3	Proposed model	013	(-)026	9.23	0.3
		Lazarowska [25]	014	(-)025	9.22	0.4
	4	Proposed model	012	(-)034	8.49	0.3
		Fiskin et al. [8]	028	(-)057	9.39	0.3

***Table 7.** The discussion of models utilized for comparison*

Reference	Tsou et al. [24]	Fiskin et al. [12]	Lazarowska [25]	Fiskin et al. [8]	Proposed model
Method	GA	ColAv_GA	TBA	WBDA	Polygonal-based CA
Approach type	AI	AI	Deterministic	Deterministic	Deterministic
Type of maneuver	Course change	Course or/and speed change	Course change	Course change	Course change
Number of maneuvers	Single	Single	Single	Single	Single
Static obstacle	Not Considered	Considered	Considered	Considered	Considered
Dynamic obstacle	Considered	Considered	Considered	Considered	Considered
Ship domain type	Circular	Circular	Hexagon	Circular	Polygonal
Ship domain holding	Around the OS	Around the OS	Around the TS	Around the OS	Around the OS
Ship domain characteristic	Static	Static	Static	Static	Static
Expression of domain	Safety domain	Ship domain	Ship domain	Ship domain	Ship domain
Safety indicator	Violation of the domain	Violation of the domain	Violation of the domain	Violation of the domain	Violation of the domain
Objective function	Minimize the CA route length	Minimize the CA route length	Minimize the CA route length	Minimize the CA route length	Minimize the CA route length
TS motion	Keeps movement	Keeps movement	Keeps movement	Keeps movement	Keeps movement
Action range determination to the TS	No	Yes	No	No	Yes
Speed change option	No	Yes	No	No	No

Web-Based Deterministic Algorithm (WBDA), developed by Fiskin et al. [8]. The CA trajectories provided by the model developed by Fiskin et al. [8] and the proposed model are shown in Figure 7d. In the comparison scenario, navigational input data for ships and numerical results provided by both models are shown in Table 5 and Table 6, respectively. The table clearly shows that the result returned by the proposed model outperformed the WBDA-based model in terms of total CA trajectory length. The time to reach a solution, on the other hand, is about identical since both have deterministic features and can reach a result quickly.

5.3. Evaluation of Discussion

In summary, the proposed model is advantageous due to its deterministic nature, allowing for faster results than AI-based models. Additionally, deterministic methods produce consistent results in every execution. The numerical analysis demonstrates that the proposed model outperforms AI-based models, producing shorter CA trajectories in less time. Comparing the proposed model to other deterministic-based methods, it is almost identical in terms of total CA trajectory length and computational time, with the exception of a slight difference in trajectory length when compared to the WBDA model.

6. Limitations and Further Improvements

Despite the results and advantages mentioned above, the developed model still has certain limitations. Therefore, additional work is required to enhance the research in the following areas:

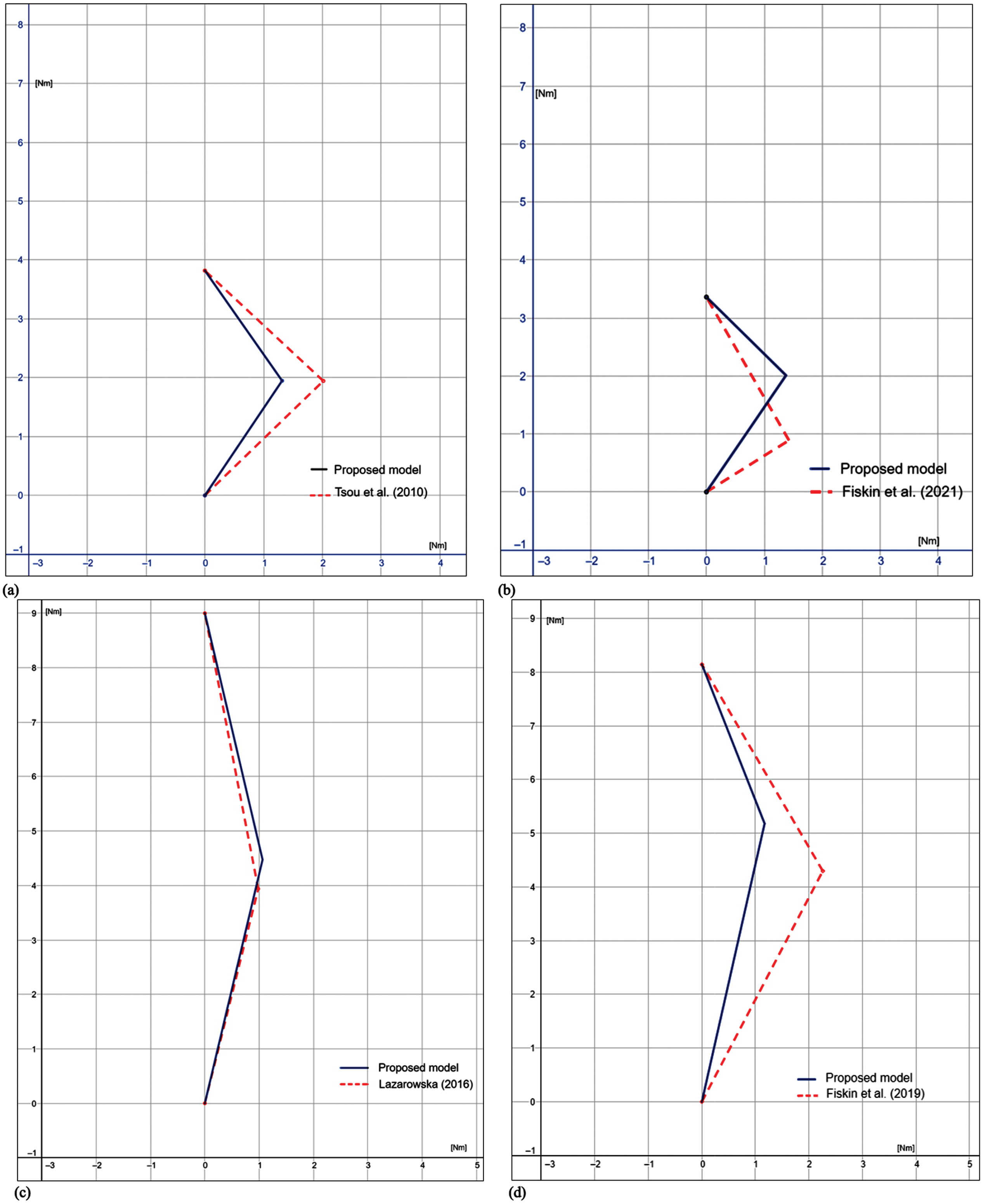


Figure 7. *CA trajectories of the OS obtained by the models in comparison*

- Variations in the motion of the TS are not considered, and it is assumed that it will maintain its current speed and course. However, if a change in course or speed is detected, recalculations must be made based on the new navigational data.

- This model is not intended for complex environments or encounters with multiple ships. Calculations should be made for each ship individually, based on its distance from the OS.

- The calculation of ship movements uses a kinematic model that does not take external forces into account.

- Speed and time losses that occur during ship turns are disregarded.

7. Conclusion

In this study, we have developed an optimal methodology for CA route planning in sea navigation, taking into consideration the COLREG rules. Our methodology involves conducting a collision risk assessment with a polygonal-type fuzzy SD. Our numerical experiments demonstrate that our system can generate a sensible solution for ship CA problems. Furthermore, our system has a deterministic algorithm structure, ensuring that it produces the same solution with each execution.

Our CA maneuver is limited to course change and does not take into account speed change. We have excluded speed change from the scope of this study since it is not frequently used to avoid collision in practical situations, except in critical or emergency circumstances. Furthermore, due to the nature of the COLREG rules, we have only considered one-on-one situations. For future research, our system can be designed and adapted for multiple ship encounters, and we can also incorporate other polygonal approximations of the SD to extend the proposed strategy. The findings from this study have the potential to contribute to ship automation and e-navigation strategy.

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Authorship Contributions

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