ORIGINAL RESEARCH (AR) DOI: 10.4274/jems.2022.52386

Journal of ETA Maritime Science 2022;10(1):39-46

Data-driven Ship Domain for Open Water Navigation

Ülkü Öztürk

Turkish Naval Academy, İstanbul, Turkey

Abstract

Navigation is a significant part of shipping safety as it directs and delivers the physical mass of commercial assets. In addition to navigation, ship domain is a frequently used navigation safety concept in mariner's terminology. However, the perception of ship domain lacks the terse representation because of multidimensional factors of the sea environment. This study has proposed not only a data-driven ship domain that can be compared with theoretical counterparts to validate navigation safety understanding in open waters but also a unique minimum distance passage representation for ship domain. This study proposes ship domain visualization for ship-ship encounters only in the closest passages rather than all ship trajectories. Results show that ship domain boundaries are consistent with former studies, but such results provide in-depth inference.

Keywords: Ship domain, AIS, Visualization

1. Introduction

Navigation safety is a fundamental necessity in each technological update in the maritime industry. These technological transformations are inevitable, and they may contain a number of shifts in traditional shipping behavior. The shipping industry is a great ecosystem with its subsystems and stakeholders such as mariners, shipping companies, ports, shipyards, insurance firms, training centers, regulatory bodies, and unions. These contributors aim to achieve the safe transportation of goods because seaborne transportation is safer and more economical than other transportation types. Although maritime transportation is the best transportation type in international trade, the seaborne trade has many risks. According to the European Maritime Safety Agency [1], among ship accidents from 2014 to 2020, 12.8% are collisions and 17.2% are contacts. Furthermore, de Vos et al. [2] have presented that among ship accidents from 2000 to 2018 worldwide, 20% are collisions, 6% are contacts, and 43% are hull-machinery damages. In addition, they have presented that 44% of the accidents worldwide are navigation related and assumed that autonomous ships will reduce the number of navigation-related accidents in the future.

These maritime-related accidents have been analyzed by many researchers [3-5], and the community has proposed a number of indicators [6-12] that can reveal the degree of ship-to-ship collision. The main source of these studies is simulation logs and automatic identification system (AIS) data. Furthermore, activity data measures such as numbers of port calls, numbers of vessel days, and nautical miles sailed have been presented by some researchers [13]. Among these indicators, the ship domain is of utmost importance because it is the fundamental perception of sea environment for the officer on watch (OOW). The ship domain is a navigation safety structure abstraction model since its introduction by Fujii and Tanaka [14] as "a two-dimensional area surrounding a ship which a navigator must avoid-it may be considered as the area of evasion." After Fujii and Tanaka [14], the ship domain was described as "the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary obstacles" by Goodwin [15]. The ship domain is a fundamental navigation safety indicator that most of

Address for Correspondence: Ülkü Öztürk, Turkish Naval Academy, İstanbul, Turkey
E-mail: ozturkul@itu.edu.tr
ORCID ID: orcid.org/0000-0003-0737-151X

Received: 23.11.2021
Accepted: 01.02.2022

To cite this article: Ü. Öztürk, "Data-driven Ship Domain for Open Water Navigation." *Journal of ETA Maritime Science*, vol. 10(1), pp. 39-46, 2022.

the researchers used in their problem. Collision avoidance, collision risk assessment, and path planning studies have already used ship-domain-based approaches in navigation analysis.

However, no consensus has been found on how a ship domain should be. Despite the theoretical [16-18] and empirical ship domain proposals [19], the open sea environment perspective of the ship domain has not been emphasized with empirical data. The open sea is an unbiased environment because all congested waters have their own specific characteristics such as shallow waters, buoys, current, land obstacles, and local traffic. Thus, this study proposes a novel empirical ship domain exploration for open waters from AIS data. The novelty of the study is based on the utilization of AIS data with minimum passing distance data instead of all ship trajectories. In addition, this study aims to reveal ship domains in open waters with the minimum passing distance approach rather than all trajectories of ship traffic.

In this study, open waters refer to a navigation area that differs from congested waterways (port entrance and coastal waters) and narrow channels and provides more free navigable space to ships. Open waters may substitute for international waters, which start from the end of contiguous zones [24 nautical miles (NM)]. The main contribution is revealing the ship domain structure of each vessel type in open waters using a novel minimum passing distance approach. This has been achieved with only one ship-ship encounter that has the closest distance rather than all ship trajectories [19].

2. Literature Review

Ship domain is a recommended free space around a ship that no other ships/obstacles should enter. Determining the ship domain is achieved by statistical approaches based on radar [15] and AIS [19] and analytical approaches [20], [21]. However, determining the ship domain size and shape, which heavily emerge as circle and ellipse-like, is based on mariners' experience. Goodwin's [15] statistical circle ship domain, inferred from simulation results, proposes different distances for each direction (Figure 1a). However, Fujii and Tanaka's [14] elliptical model is 1.6 ship length (L) for breadth and 4 L for longitudinal (Figure 1b). This model has been extracted from a high volume of ship position records in Japanese waters. Coldwell [22] separated breadth as 1.75 L for port and 3.25 L for starboard side. However, the longitudinal distance is 6.1 L. Despite measurement differences among these former ship domains; the understanding represents the perception of mariners.

Furthermore, Kijima and Furukawa [23] have introduced a ship domain based on the blocking area concept (Figure 2a). The watching area is a threshold that mariner should decide avoidance maneuver in the case of any invader ship, whereas the blocking area is not permitted for other ships. The parameters (R_{bf}, S_b, R_{ba}) are determined by ship length, speed, breadth, tactical diameter, and advance, which are the main characteristics of a ship. A similar work has been proposed by Dinh and Im [24], who proposes the minimum distance of the blocking area as between 2.8 and 4.6 L based on the decision of 61 experts. Fuzzy ship domain approaches are also identified. For example, Pietrzykowski [16] has proposed a fuzzy polygon-shaped ship domain for restricted waters at different safety levels. Another study with the same model has been proposed for open waters [25] (Figure 2b). Distances are not normalized, and γ refers to fuzzy memberships of the navigational environment. On the contrary, an empirically calibrated ship domain for

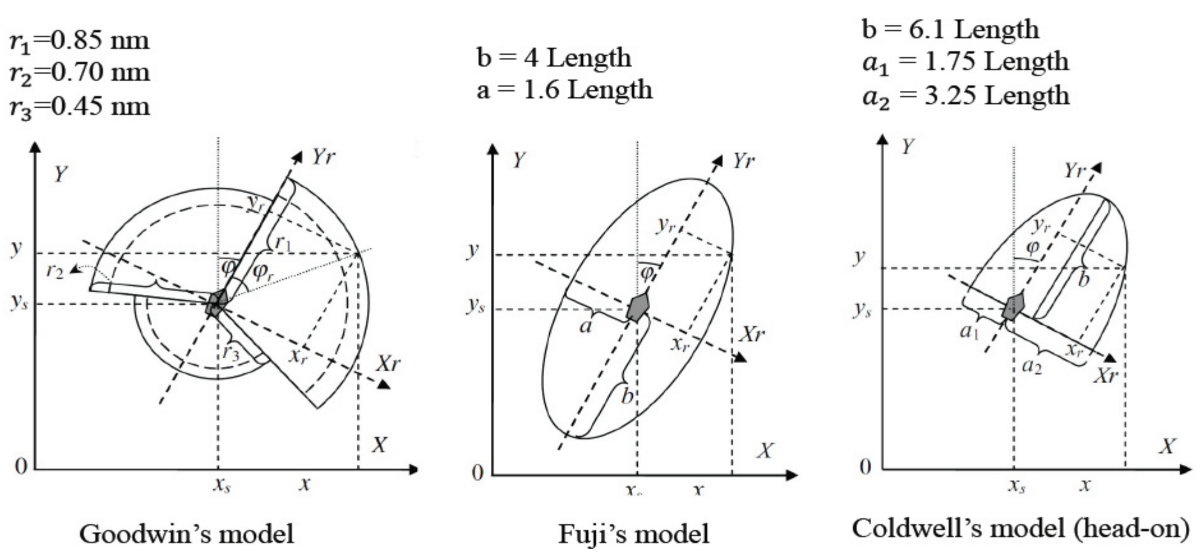

Figure 1. *Ship domains*

confined waters is provided by Wang and Chin [26], which can change with speed parameters (Figure 2c). Authors have compared this model with other models [14,16] with different scenarios and concluded that the proposed ship domain is potentially more adaptable in revealing ship separation.

Liu et al. [27] have extended Fujii and Tanaka's [14] model with a dynamic model for restricted waters by considering the ship behavior and waterway structure to apply capacity analysis. Furthermore, Rawson et al. [28] present a ship domain model based on AIS data for river basins with 22 h of data. Unlike the abovementioned studies, Du et al. [29] provide available maneuvering margin, which indicates a proximity measure to reflect the dynamic nature of encounters in Baltic Sea. On the contrary, Hansen et al. [19] have provided an empirical ship domain based on AIS data in busy waters by integrating ship positions below 3500 m. They have revealed a comfort ellipse (Figure 3) that has a length of 8 L and a breadth of 3.2 L, which is consistent with Fujii and Tanaka's [14]. As they focus on restricted and busy waters, they recommend studying other areas such as open waters in the future. In Hansen et al.'s [19] study, intensity analysis includes all ships around rather than the closest pair. Intensity analysis has been conducted with all other ships' geospatial positions, which may cause a biased representation of the ship domain perception. The AIS was data obtained from three particular areas such as Fehmarnbelt Channel (~9 NM wide), Great Belt Bridge (~9 NM wide), and Drogden Channel (~7 NM wide), which may not be assumed as open sea.

Furthermore, Szlapczynski and Szlapczynska [17] have reviewed the ship domain studies in detail, which can be referred to any further query about the ship domain. They have concluded that the latest ship domain research is similar to some of the classic ones. The length and dimensions are similar in each ship domain study because they are relatively a complex problem to predict ship domain. Consequently, each ship domain approach has provided sizes and shapes of free spaces from its own ship (OS) to enhance the navigation safety. However, this novel study differs from former studies because it proposes a data-driven ship domain for open waters rather than restricted/busy waters [19] and takes only the closest ship pairs into consideration rather than all ship trajectories in the sea, thereby revealing the OOW perspective rather than the maritime traffic structure.

3. Methodology

The methodology used in this study has been presented in Figure 4. Raw AIS data contain an insurmountable volume of data segments, which should be explored and cleaned

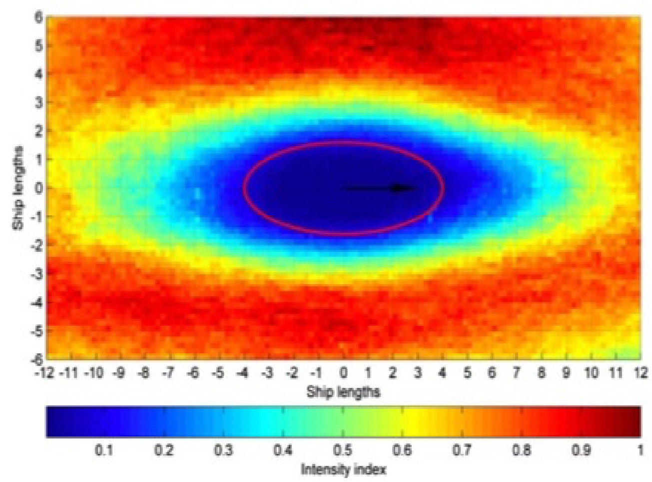

Figure 3. *Hansen et al. [19] ship domain model*

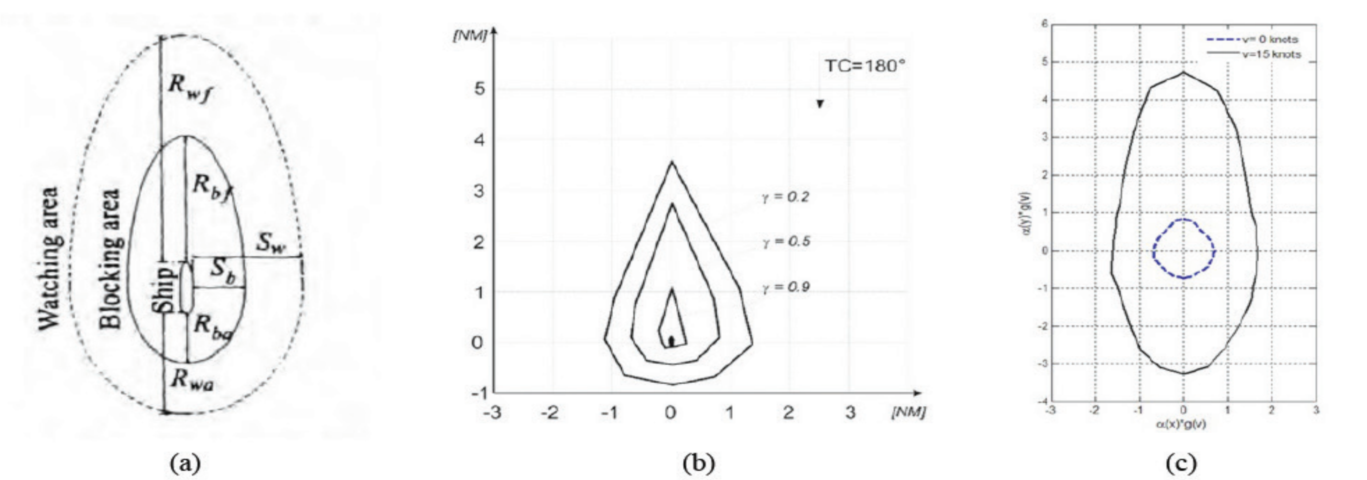

Figure 2. *Further ship domains*

before further analysis. Therefore, raw data have been clustered, and new features such as the relative position of other ship, number of ships in 5 NM, number of ships in 10 NM, day/night, and minimum passing distance have been obtained. The filtering and data cleaning steps along with features will be extensively explained in the next subsection. This methodology, containing relative positions and distances, provides a visual ship domain structure for open waters, which pave the way for detailed correlation analysis of parameters with ship domain.

After obtaining data, visualization has been achieved with relative bearing and distances. Correlation analysis, ship domain parameters, and density visualization outputs provide foundations for detailed analysis of ship domain perception in an open sea environment.

3.1. Data Analysis

The AIS data of the Mexican Gulf has been used in this study. The dataset contains 3 years (2015-2017) of AIS transmission from merchant vessels in open sea environments between contiguous zones (24 nautical miles) and the exclusive economic zone (200 nautical miles) obtained from marinecadastre website. All data analysis steps have been implemented in the Python environment. In addition, the raw dataset contains around 47 million observations, and after filtering by geographical aspect and cleaning, 1,814,863 unique observations have been obtained for detailed analysis. For example, only the observations that are outside the contiguous zone (24 NM) have been taken into consideration. Relative position of other ship, number of ships in 5 NM, number of ships in 10 NM, day/night, and minimum passing distance have been obtained after feature engineering of the raw dataset. All these features are obtained after the encounter situation with minimum distance has been detected. Only the minimum distance of all distance measurements is considered. A brief algorithm of how to obtain minimum passing distance has been shown in Figure 5.

The number of ships are the other ship numbers in the respective range at the time of minimum passing distance. Furthermore, minimum passing distance is the distance of another ship from its OS when the time to the closest point of approach (TCPA) is zero. The visual representation of the minimum passing distance has been shown in Figure 6.

The minimum passing distance (y) is the distance when TCPA is zero, which indicates the moment of the closest distance between two encountered ship pairs. The previous trajectories have not been considered to distinguish the closest encounter. Otherwise, the number of trajectories out of the real ship domain may be excessive than expected, which in turn may affect density analysis. In fact, this moment is of utmost importance for mariners because the

Algorithm 1 Minimum passing distance pseudocode

```
function MP-CPA(shipID, shipCorr, time)
    D ← Group all shipCorr by ShipID                        ▷ First grouping
    D ← Eliminate groups below 20 ▷ Eliminate low sampled observations.
    D ← interpolate by D[time]
    S ← Divide by two hours period
    For each divided S execute:
    for each ShipCorr in S do
        for each ShipCorr in S do
            S[Distance] ← Distance between ships            ▷ Get all distances
            S[MinimumPD] ← minimum S[Distance]              ▷ Get minimum
distance
        return S
```

Figure 5. *Pseudocode of minimum passing distance calculation*

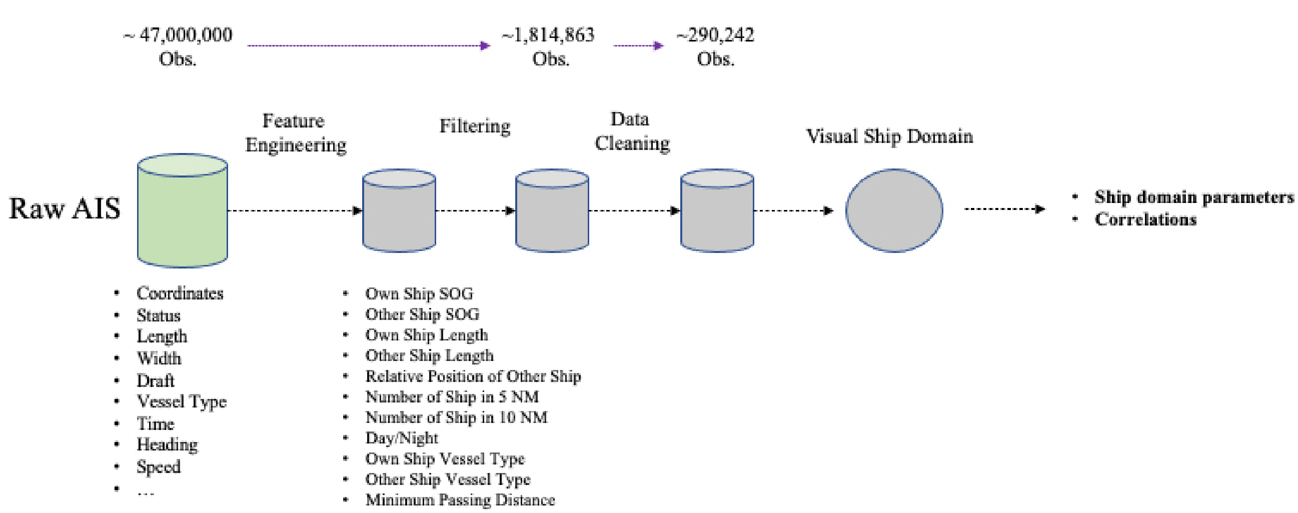

Figure 4. *General methodology of the study*

AIS: Automatic identification system, SOG: Speed over ground relative bearing and distance are important when TCPA is zero. Furthermore, it may represent the perception of mariners in any encounter situation. This unique way of representing maritime structure paves the way for in-depth understanding of mariner perception in navigation. This approach may reveal mariner's perception more than other density or statistics-based ship domain approaches because mariners deliberately prefer only the minimum passing distance out of all trajectories in most cases.

The dataset represents the ship-to-ship pair's encounter in open sea every 2 h. After geographical filtering, ships that are underway and observations below 10 NM minimum passing distances (290,242 observations) have been considered. The correlation plot of the dataset in this phase has been presented below in Figure 7.

The number of ships in 5 NM has the highest correlation with the minimum passing distance, which is the visual representation of the data-driven ship domain approach. This result indicates that OOW takes closer ships into consideration instead of far ships. However, other features such as suboesophageal ganglion, width, length of OS, and target ship (TS) have nearly no correlation with minimum passing distance with ship-to-ship pairs that are in the 10 NM range. Another crucial point must be considered, namely, the normalization of the distance with regard to ship length. Correlation analysis provides different results when the distance is interpreted with regard to ship length (DistanceSL). Therefore, the number of ships in 5 NM has more correlation with DistanceSL than the number of ships in 10 NM. However, the same case is not valid for OS length and width because ship static features such as length and width have important perception in the eye of OOW. The descriptive statistics of these variables have been provided in Table 1.

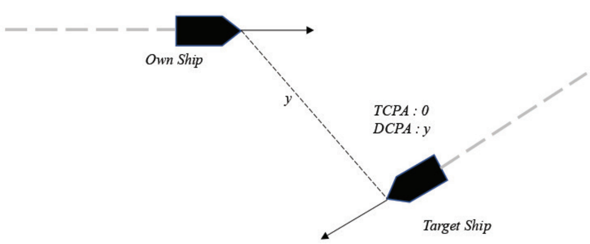

Figure 6. *Minimum passing distance representation*

TCPA: Time to the closest point of approach, DCPA: Distance at closest point of approach

Table 1. *Descriptive statistics of dataset*

Features	Mean	Std.	Min.	Max.
OS length	172.5	73.6	33	430
OS width	28.1	10.3	7	90
OS SOG	13.6	3.8	2	49.8
Number of 5 NM	0.96	0.69	0	8
Number of 10 NM	1.63	1.05	1	17
TS length	173.1	74.8	21	430
TS width	28	10.5	5	90
TS SOG	13.9	3.9	2	48.3
Minimum distance	3	2.53	0.05	10
Distance SL	48	65	0.5	588

Std.: Standard, Min.: Minimum, Max.: Maximum, OS: Own ship, SOG: Speed over ground, TS: Target ship

Figure 7. *Correlation plot of observations*

OS: Own ship, TS: Target ship, SOG: Speed over ground

The mariner perception is heavily determined by the static characteristic of the ship; thus, it is more plausible to construct an empirical ship domain approach on Distance SL rather than minimum distance [19]. The visual representation of the data-driven ship domain has been presented in the next section.

3.2. Data-driven Ship Domain

As discussed in the previous section, perceiving the distance among ship pairs with regard to ship length is important. Thus, the ship domain structure can be analyzed by visual distances with normalized distances, which in turn allows analysis of different sizes of ships. After detailed examination and processing of raw AIS data, the density of relative positions of TS based on OS with regard to OS length has been shown in Figure 8.

The density plot covers the area of 60 ship lengths, and density bins are divided into 100×100 pixels. The color of each pixel represents the number of ships in that spatial location. Although it is hard to figure out density below ~0.2, the central area is distinguishable, which can be deemed as the ship domain. The ship domain obtained from the perspective of the minimum passing distance is a circle-like domain rather than an ellipse. However, the port and aft sides seemed more comfortable for mariners in open waters because the density is high in these areas. In addition, the suitable distances are approximately 3.12 and 3.35 ship lengths from port and aft based on the density index boundary of ~0.3. Other distances are 5.28 ship lengths from the bow and 5.7 ship lengths from the starboard side. The kernel density estimation plot can show the boundaries in a more compact way. Considering that the density index and level curves have been normalized, the kernel density level curve of 0.3 corresponds to 0.08% of the observation. Based on the kernel density curves, a circle-like shape fits to the data more than an ellipse. Furthermore, the starboard-bow sector has been kept clear by most of the mariners. The reason why port and aft sectors are denser than other sectors may be the reasonable safety awareness that most of the mariners do not prefer to encounter other ships in the bow direction when TCPA is zero. This study proposes ship domain visualization based on the minimum safety distance; thus, this kind of inference could be captured (Figure 9).

Furthermore, the reason why the starboard sector is larger than the port sector as stated by [22] can be revealed in a more concise way using the proposed method. A more detailed data-driven ship domain by vessel types has been provided in Figure 10.

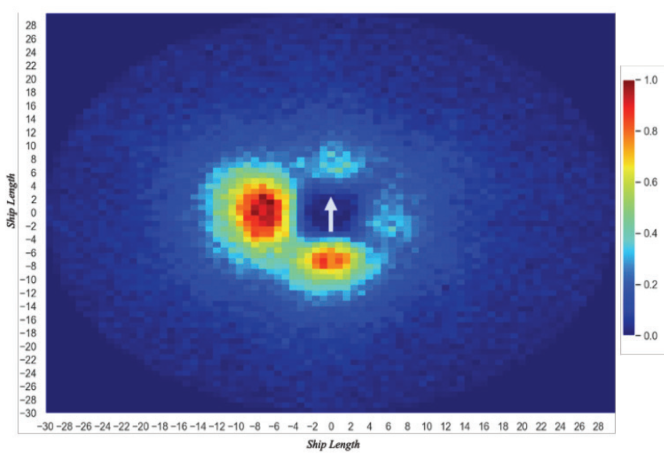

Figure 8. *Density plot for open waters*

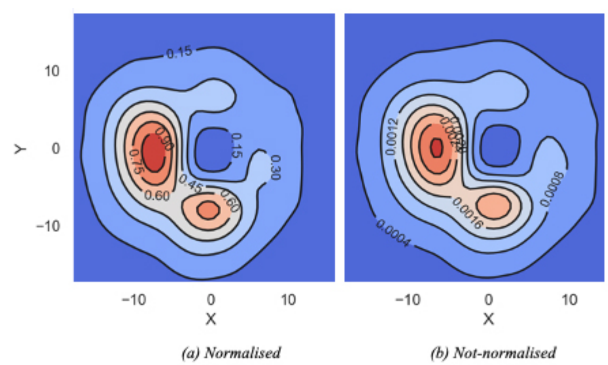

Figure 9. *Kernel density estimation of the minimum passing distance*

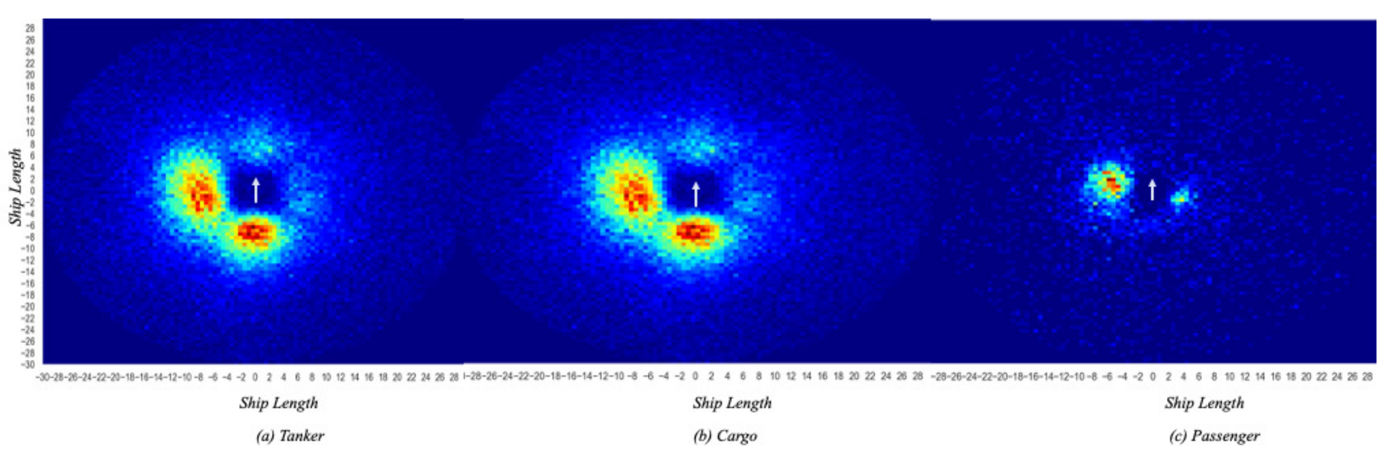

Figure 10. *Density plots for open waters by vessel types*

Figure 10 presents another aspect of density plot by vessel type. Although tankers and cargo ships have similar visual density plots, they are quite different from passenger ships. The approximate circular distances have been presented in Table 2 for a closer look into ship domain boundaries. The boundaries of passenger ships are a slightly below than other ship types. In addition, the distance in the bow sector is the highest among all sectors for all ship types. In particular, tankers have the highest distance in the bow sector. Furthermore, the port sector is more comfortable than starboard for all mariners except for passenger ships.

Former ship domain dimensions [14,22] are quite similar to the obtained results. For example, Fujii and Tanaka's [14] model proposes four ship lengths in the bow and aft direction for the ship domain, whereas the present study has obtained 3.35 and 5.28 ship lengths for the aft and bow, respectively. However, lateral radiuses are quite different. On the contrary, Coldwell's [22] model proposes 1.75 and 3.25 ship lengths for the port and starboard, respectively. The obtained results (3.12 and 4.5 ship lengths) are consistent with these measurements. Furthermore, these results support the view [19,22] that mariners would prefer larger spacing in the starboard sector in ship-to-ship encounter situations.

Table 2. *Approximate ship domain boundaries by vessel types*

Vessel type	Port (~ SL)	Starboard (~ SL)	Aft (~ SL)	Bow (~ SL)
Tanker	4.1	4.5	3.5	5.5
Cargo	3.5	4.6	3.6	4.6
Passenger	2.5	2.0	3.5	3.8
All ships	3.12	4.5	3.35	5.28

4. Result and Discussion

This study presents a distinguished data-driven ship domain density plot using the minimum passing distance approach. The boundaries of the ship domain presented in this study differ from other statistical and empirical ship domains in some studies. Although former empirical ship domain studies analyze ship coordinates as a whole without any further preprocessing with feature engineering, the minimum passing distance approach provides some additional clues about mariners' perception. For example, mariners not only prefer additional distance in the starboard and bow sector, but also keep their starboard and bow sector clear when TCPA is zero. Furthermore, the practical ship domain of tankers is more than that of cargo and passenger ships. The safety boundary limit of OOW on tankers seems to be higher than OOW on other ships. Thus, the safety precautions and preparedness are stricter in tanker ships.

Hansen et al.'s [19] comfort ellipse (Figure 3), which has a length of 8 L and a breadth of 3.2 L, is larger than this proposed ship domain. However, the aft and bow radius should be different. Furthermore, the open water ship domain should be larger than the busy channel. Therefore, all ship trajectories may result in biased ship domain representation.

Another critical point of the analysis is the negative correlation between ship length and the minimum passing distance. For example, correlation between OS Length and DistanceSL is -0.56, which indicates that as the ship size becomes larger, the distance between ships becomes smaller. Thus, the opposite could be expected. However, the reason for this negative correlation is that as the ship size increases, the possibility of following traffic lanes in open sea increases, which result in close passing distance. The basic understanding of a ship domain is to reveal the minimum area (blocking area etc.) that other ships enter. As other ships get closer, a general pattern may be observed, that is, they do not enter into ships area anymore. A more detailed look into this issue can be seen in Figure 11.

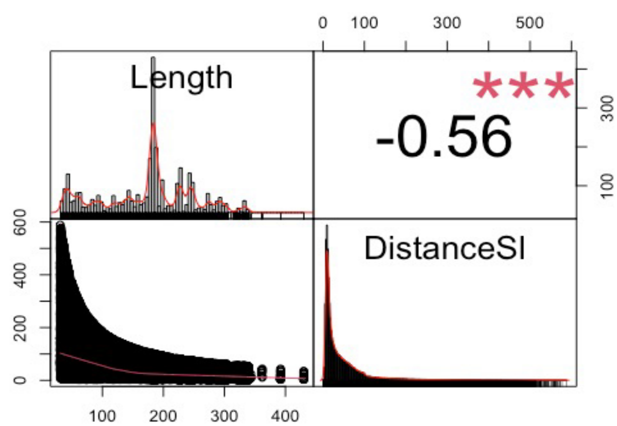

Figure 11*. Scatter plot of OS Length and DistanceSL*

OS: Own ship

The minimum DistanceSL is 0.55 among observations above 300 m ship length, whereas it is 3.48 among observations above 400 m ship length. The critical point for this threshold is 335 m ship length. Notably, more than 1000 observations can be made above this threshold. This finding indicates that the minimum passing distance does not decrease after some point, which is consistent with the ship domain concept. The fitted curve with a red line shows this understanding well. The mean value of the fitted curve after 335 ship length is 12 ship length. Finally, this study proposes that the main determinants of ship domain boundaries are ship length and the number of ships around as their correlations are the highest with a minimum passing distance.

5. Conclusion

This study presents a novel approach to determine ship domain boundaries by using the minimum passing distance approach. The AIS data obtained from Mexican Gulf have been filtered, cleaned, and examined before feature engineering steps, and the unique dataset has been obtained for further analysis. Visualization of minimum passing distance spatial point density provides a data-driven ship domain that indicates the concise perception of OOW rather than the basic density plot of maritime traffic around a ship. The result of the study provides a similar but more in-depth understanding of ship domain boundaries. This study focuses on open waters; thus, other regions such as narrow channels and busy waters can be analyzed using this approach in future studies. Furthermore, as the number of ships around is highly correlated with the minimum passing distance, this parameter can be designed using different thresholds other than 5 and 10 nautical miles in further research.

Funding: The author declared that this study received no financial support.

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