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Empirical Ship Domain based on AIS Data

Martin Gamborg Hansen[1], Toke Koldborg Jensen[1], Tue Lehn-Schiøler[1], Kristina Melchild[1], Finn Mølsted Rasmussen[1] and Finn Ennemark[2]

[1] (*Rambøll, Hannemanns Allé 53, DK-2300 København S*)
[2] (*Femern A/S Vester Søgade 10, 1601 København V*)
(E-mail: MAGH@ramboll.dk)

In this paper the minimum ship domain in which a navigator feels comfortable is estimated. That is, we estimate the free space surrounding a ship into which no other ship or object should enter. This is very useful when estimating the maximum flow through a channel or a bridge span. The paper benefits from the introduction of Automatic Identification System (AIS) data as it is now much easier to conduct studies involving a large number of observations. Our observations are based on ships sailing in southern Danish waters during a four year period, and from the observations we estimate how closely ships pass each other and fixed objects in open sea navigation. The main result is the establishment of an empirical minimum ship domain related to a comfortable navigational distance.

KEY WORDS

1. Comfort ellipse. 2. Navigation. 3. Ship domain theory. 4. Traffic flow.

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1. INTRODUCTION. Since the 1960s, radar data has been used to study how closely ship navigators are willing to pass each other. This is of great interest when making a model of ship traffic flow or constructing a bridge or another obstacle for shipping traffic.

The ship domain concept has been used extensively in marine traffic engineering since it was first proposed in the 1970s; see Fujii (Fujii & Tanaka, 1971; Fujii et al., 1984) and Goodwin (1975). Variations of the ship domain theory have since been presented (Davis et al., 1980; Coldwell, 1983; Zhao et al., 1993; Zhu et al., 2001; Smierzchalski, 2001 and Kijima, 2001). The different proposals have different shapes and sizes due to differences in definitions and variations in the areas for which they are constructed. The different theories have mainly focused on the size and shape of the ship domain in standard situations.

Standard situations are suitable for studying traffic capacity or traffic risk in a large area, but ships may be willing to accept a smaller domain in a local area with reduced space or when passing an object. Pietrzykowski (2009) lets his domain grow with

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Figure 1. The areas in which the studies have been conducted.

different levels of safety and the awareness of the navigator. For instance, the domain is smaller in a confined situation where the navigator is very aware of restricted manoeuvring room.

A proposed bridge across Fehmarnbelt between Denmark and Germany forms the background for our analysis of the size and shape of the ship domain. In particular, the length of the bridge span is a crucial design parameter with a high impact on the bridge construction time and cost. It is therefore important to analyse the efficiency of the ship traffic through the proposed bridge span, and hence analyse the space required to allow ship navigators to pass the bridge in a comfortable and safe way.

In this paper, we establish the size of the ship domain based on a large amount of AIS data from the relevant areas. The goal is not to establish this space for the individual navigator standing on the bridge of the ship, but to establish it when considering the ships from above interacting with each other. The current paper describes how this ship domain is established. The ship domain is then used by Jensen, et al. (2013) to analyse the efficiency of a given bridge span.

The paper is based on AIS data from the following Danish waters:

- The area around the Great Belt bridge AIS data for a half year (1 June 2008 to 30 November 2008)
- The Fehmarnbelt (between Denmark and Germany), four years of AIS data (5 April 2006 to 30 April 2010)
- Drogden (a narrow channel between Denmark and Sweden), AIS data for one year (2008)

The geographical areas are shown in Figure 1.

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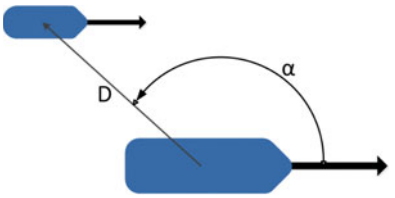


Figure 2. Definition of the angle α and the distance D between two ships.

2. SHAPE OF SHIP DOMAIN. In this section we analyse the shape of the ship domain based on data from the Fehmarnbelt area (Figure 1). This is the area in which the proposed bridge is to be constructed, and the area in which most data is available. The main commercial route, Route T, has about 20,000 annual ship movements in each direction, and the ships have an average length of 130 m. Route T has a long straight part before splitting into three routes. A ferry route between Denmark and Germany with almost 20,000 annual movements in each direction crosses Route T. The shape of the ship domain is therefore based on the distance between ships when navigating through an area where the navigator has to take different navigational issues into consideration. This makes the shape of the ship domain based on standard ship manoeuvres in an area with good space for manoeuvring.

The shape of the ship domain is analysed by visualising the distances between all ships in the area in special intensity plots. All distances are measured from each ship to all other ships, and are normalised with the length of the current ship. The normalisation makes it possible to include ships of different sizes in the analysis. The method can be repeated in any area and is not just useful for the Fehmarnbelt area or for the estimation of the ship domain proposed in this paper. The idea of the intensity plot is described in more detail below.

In the areas considered each ship has an AIS registration at a time interval between 3 seconds and 3 minutes. Generally, the AIS registrations are saved with small time intervals when a ship is turning and longer time intervals when sailing straight ahead. All AIS registrations in the area of interest are linearly interpolated such that all ships in the area are assigned an approximate registration of the location every 30 seconds. The registrations are displaced to the centre of the ships, taking into account the actual location of the Global Positioning System (GPS) signal on the ships. The distance D and the angle α between each ship and all other ships in the area are then calculated as illustrated in Figure 2 for each time stamp.

The calculations are restricted to include only distances between ships below a certain threshold $D_{\text{considered}}$. We use $D_{\text{considered}} = 3{,}500$ m as this ensures that distances up to ten ship lengths from the longest ship in the area (which is around 350 m) are included. For each ship the distance to all other ships is calculated relative to the length of the current ship. This proved to give the best results; especially when considering a bridge passing. We note that this is unlike Fujii (Fujii and Tanaka, 1971), who measured the distance between two ships relative to the sum of the length of the two ships. The latter means that overlapping ship domains are not allowed, whereas we only require that ships do not enter each other's ship domains. The effect of allowing ship domains to overlap is shown in Figure 3. In Fujii's terminology, both cases in Figure 3 would result in violation of the ship domains.

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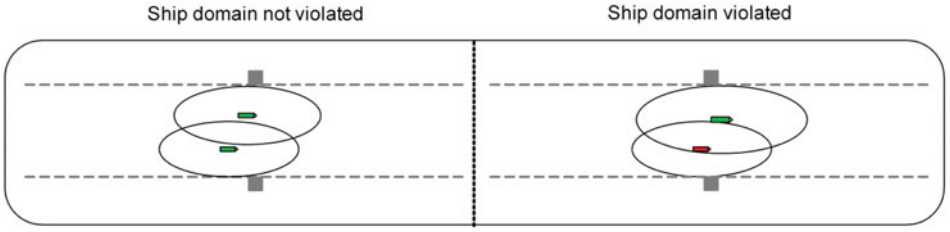


Figure 3. Examples of ships not violating/violating the ship domain for two ships sailing concurrently between two bridge pylons.

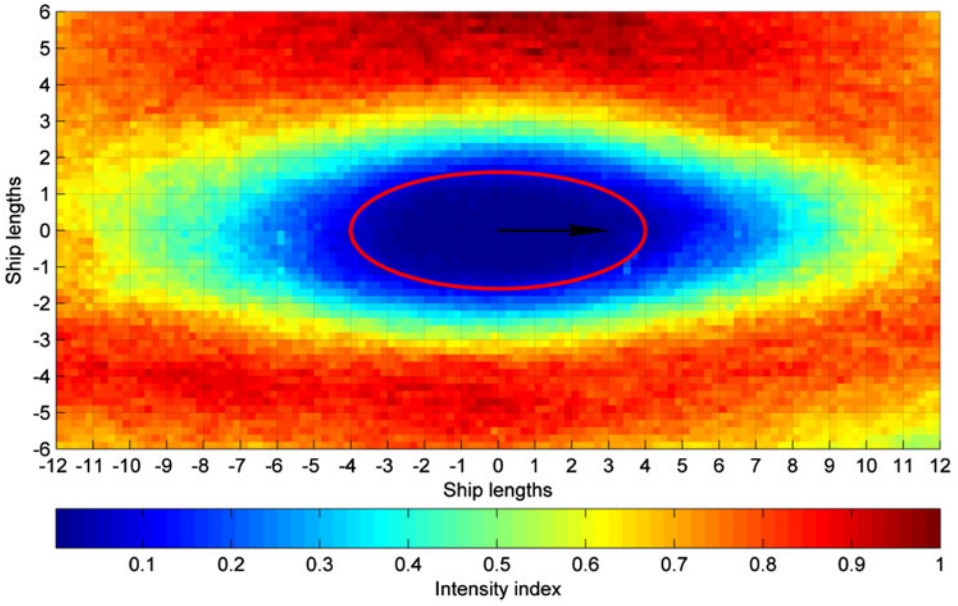


Figure 4. Intensity plot for all AIS registrations in the Fehmarnbelt area together with a plot of the ellipse predicted by the ship domain as established in this paper.

The intensity plots are generated to cover an area with a length of 24 ship lengths and a breadth of 12 ship lengths. The area is discretised into elements of 0·2 by 0·2 ship lengths; i.e. a total of 120 by 60 elements. The colour of each element reflects the amount of time during which another ship is observed at the given position relative to the current ship placed in the centre of the intensity plot. The colour axis is scaled such that the element where other ships are most often observed is given index 1.

The intensity plot in Figure 4 is based on all ships travelling through the Fehmarnbelt area, and shows how close ships pass each other.

The intensity plot reveals an ellipse formed shape. However, it is difficult to distinguish intensities below index 0·25; i.e., the central part of the plot where other ships are observed less than 25% as often as for the most often observed distances. Therefore, the level curves of Figure 4 are shown in Figure 5 to give a better idea of the shape.

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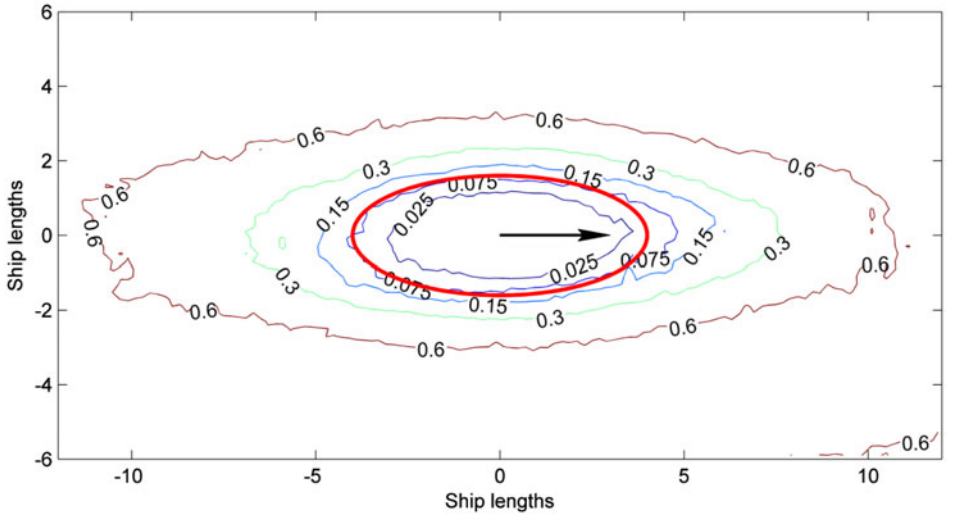


Figure 5. The level curves of Figure 4 together with a plot of the ellipse predicted by the ship domain as established in this paper.

The level curves in Figure 5 should be interpreted such that the entire area inside a corresponding curve in Figure 4 has an intensity less than the value indicated on the level curve compared to the most often observed distance. For instance, the level curve of 0·075 will surround an area in Figure 4 with an intensity less than 7·5% compared to the most often observed distance, and all squares outside this level curve have an intensity of more than 7·5% compared to the most often observed distance. When looking at the level curves in general it is clear that the ellipse shape is reasonable.

It is seen that the intensity is higher to the starboard side than to the port side, which is because larger vessels stay closer to the centre of Route T. Therefore, large ships have more ships to starboard while small ships have more ships to the port side. The intensity is higher to starboard side as a large ship will experience a given situation as relatively closer.

The shape analysis reveals that the distance maintained by navigators can be described by an ellipse. It is assumed that the minimum, preferred, comfortable distance between ships can similarly be described by an ellipse. In the following sections the length and breadth of this (minimum) comfort ellipse are analysed.

The estimate of length and breadth could be based on the same study as the shape, but in the Fehmarnbelt area the ships have a lot of space available and no reason to come close. Instead the length and breadth are established by considering situations in which the navigators are more likely to make an actual decision about the preferred distance.

3. ANALYSIS OF DISTANCE IN THE LENGTH DIRECTION.

The length of the comfort ellipse is analysed in two different studies. Both studies are conducted by constructing an intensity plot as for the shape analysis. In both studies the navigator can be forced to make a decision about which distance he will accept in

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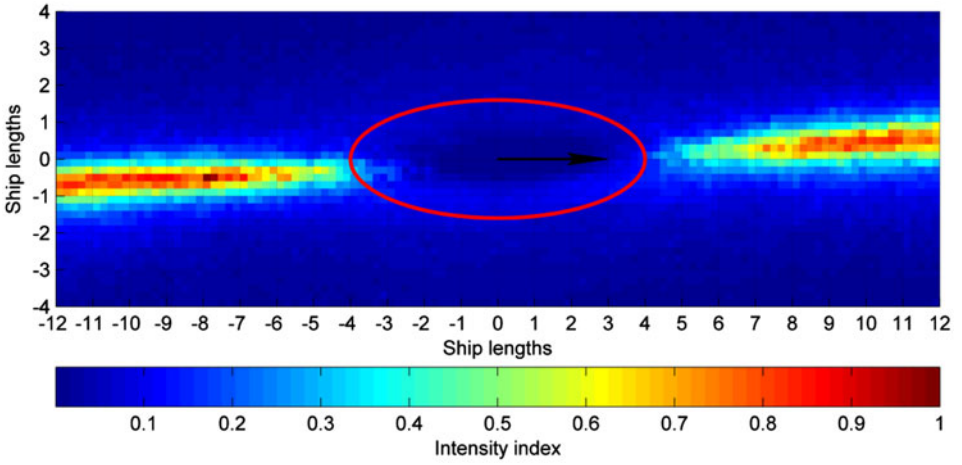


Figure 6. Intensity plot from Drogden only considering ships travelling in the same direction.

the length direction. This decision may result in a speed reduction or a rather large course adjustment to change the distance in the length direction.

3.1. *Length of the comfort ellipse in a narrow traffic separation scheme (TSS).* The first study of the length of the comfort ellipse was conducted in a narrow traffic separation scheme (TSS) in the Drogden channel between Denmark and Sweden (see Figure 1). Drogden is approximately 5·5 nm long, 300 m wide and 8 m deep with a total yearly traffic around 30,000 ship movements in 2008. The average ship length in Drogden is 110 m and the ships prefer to stay away from the borders of the channel. It is very difficult to overtake as the channel is only 300 m wide. Hence navigators have to make a speed adjustment in order to keep a comfortable distance to other vessels. It is therefore a suitable area for estimating how much space the navigators prefer in the length direction. As overtaking is very difficult in this area, the ellipse shape is not seen. When constructing the intensity plot only the distances between ships travelling in the same direction have been considered.

Based on the intensity plot in Figure 6, it seems reasonable that the navigators feel uncomfortable with another ship closer than four ship lengths.

3.2. *Length of the comfort ellipse when crossing a ferry route.* The second study of the length of the comfort ellipse is conducted by considering the distance between ships on crossing routes. In the Fehmarnbelt the main traffic on Route T crosses a ferry route between Denmark and Germany (see Figure 1). The ferry cannot be compared to a regular ship in Danish waters; it is faster and has very good manoeuvring capabilities. In order to remove some of the influence caused by the special nature of the ferries the intensity around a Route T vessel has been analysed when the Route T vessel is the give-way vessel (COLREG, 1972). In this situation we assume that the Route T vessel dictates the distance to the ferry (Figure 7).

When the Route T vessel is the give-way vessel it meets a Ferry coming from the starboard side. In the intensity plot this can be considered as a Route T vessel heading east and a ferry passing from south to north. In Figure 8 the intensities just behind and in front of the Route T vessel are illustrated.

Based on Figure 8, a comfort ellipse with a length of four ship lengths in front and behind the ship was used in the Fehmarnbelt studies, as this was sufficiently detailed

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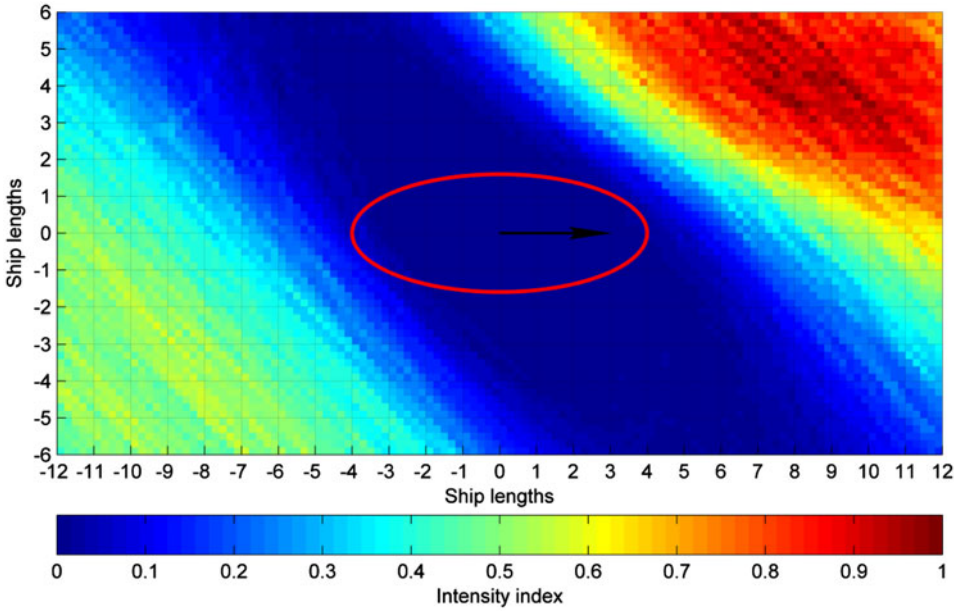


Figure 7. Intensity plot for Route T vessels when the Route T vessel is give way vessel.

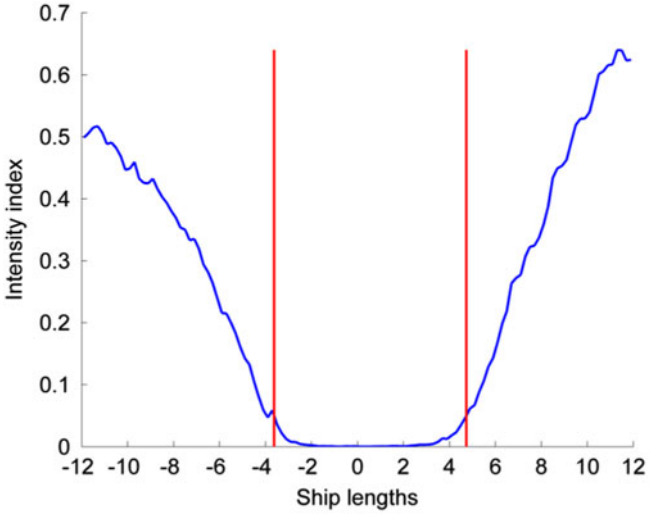


Figure 8. Plot of intensities across the intensity plot in the length direction at the location of the Route T vessel. At −3·62 and 4·68 ship lengths the intensity is 5% of the maximum observed intensity (marked with red lines).

for these studies. However, in studies where the exact position of the ellipse is important it is proposed to use an ellipse with a length of 4·5 ship lengths in front of the ship and 3·5 ship lengths behind the ship.

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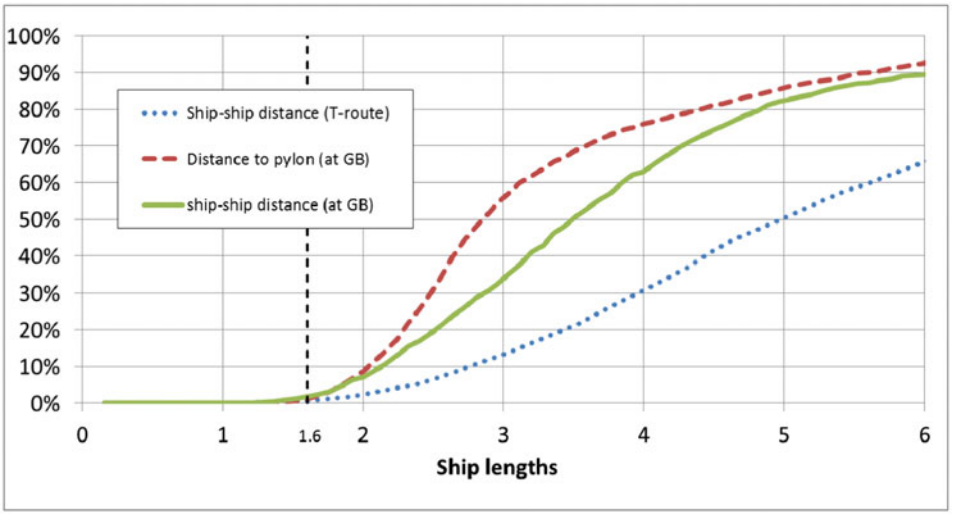


Figure 9. Distribution functions for the distances between ship-pylon and ship-ship.

4. ANALYSIS OF DISTANCE IN THE BREADTH DIRECTION.

The distance in the breadth direction has been considered in two situations in which the ships pass each other closely but still with enough room to let the navigator choose the distance. Intensity plots are not used for these studies. The main reason for using another approach is that only certain situations are considered, and that the available data is too limited to construct intensity plots. Instead we analysed distribution functions for the distance in ship lengths towards other ships or objects. The approach is described below.

All AIS registrations in the area of interest are interpolated such that each ship has a registration of the location every 30 seconds. The registrations are displaced to the centre of each ship, taking into account the actual location of the GPS signal on the ship. Only ships overtaking or passing another ship are considered, and the Distance at the Closest Point of Approach (DCPA) towards other ships or bridge pylons is estimated for the ships of interest. A distribution function for DCPA is constructed.

The first study of the breadth of the comfort ellipse was conducted by considering ships overtaking in Danish waters. This analysis has been done for Route T in Fehmarnbelt between Denmark and Germany (see Figure 1). Here we have a fairly long and straight sailing path where the ships come close, but the navigator is still free to choose the distance. The analysis was performed for data from the period 5 April 2006 to 12 January 2007. We have considered all 2,990 ships involved in an overtaking manoeuvre. The average length of the vessels considered is 125 m.

The second study of the breadth of the comfort ellipse was conducted for ships passing the Great Belt Fixed Link (see Figure 1). In a bridge passing the distance will almost always be governed by the breadth of the ellipse. A traffic separation scheme (TSS) is present at The Great Belt (GB). This means that the northbound and southbound ships are not allowed to sail in the same area. The fixed link has a span of 1624 m and every year around 20,000 ships pass the bridge. The average ship length at the fixed link is 150 m. We only considered situations where two ships pass each other. Situations with other ships influencing their navigation are excluded. Owing to this

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approach and the very large bridge span, it is assumed that ships are able to freely choose the desired distance in the breadth direction. A passing between two ships is only included in the analysis if it is within 1·4 nm of the bridge which is just about the size of the TSS. A total of 2,218 situations were analysed. For both studies the distribution functions for the distances between ship-ship (and ship-bridge pylon at GB) are illustrated in Figure 9.

The comfort ellipse should describe how close a situation we can allow between two ships or a ship and an obstacle while still maintaining a reasonable comfort level. The plots show that a distance between ships or ship and pylon of 1·4 to 1·8 ship lengths would be reasonable as almost 5% of the ships at GB keep a distance smaller than 1·8 ship lengths and almost no ships go closer to each other than a distance of 1·4 ship lengths. At Route T the ships have plenty of space, and very large distances therefore make the distribution function more flat. Based on the above we have chosen a minimum comfortable distance between ships or ship and pylon of 1·6. This leads to a comfort ellipse with a breadth of 3·2 ship lengths.

5. CONCLUSION. The comfort ellipse is presented as an estimate of the minimum domain in which a navigator feels comfortable when passing a bridge or a narrow channel. The shape and size of this comfort ellipse is estimated based on a large amount of AIS data from different parts of Danish waters. The comfort ellipse is found to have a length of eight ship lengths and a breadth of 3·2 ship lengths. This has the same dimensions as the ship domain proposed by Fujii (Fujii & Tanaka, 1971; Fujii et al., 1984), although the definitions of the ship domains vary. The comfort ellipse is designed to describe the minimum comfortable distance between two ships. The individual navigator is most likely to keep a larger distance towards a ship on his right because he, according to COLREG (COLREG, 1972), is the give-way vessel with respect to this vessel. Further, he will be focused on the traffic in front of him and will therefore keep a longer distance from vessels in front of him compared to vessels behind him. Finally, some navigators will feel uncomfortable even though no ships or objects are inside their comfort ellipse. However, the proposed comfort ellipse is found suitable when considering the ships in the Fehmarnbelt area from above interacting with each other.

For further work it could be interesting to conduct the same study in another area to see if the results are similar.

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