Marine Traffic Behaviour in Restricted Waters

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This paper, which was presented at an Ordinary Meeting of the Institute held in London on 26 January 1983, outlines the development and analysis of the ship domain in restricted waters and illustrates some of its uses in a buoyed channel.

1. INTRODUCTION. The analysis of marine casualties raises the question of how casualties occur, and may indicate the circumstances most likely to lead to a casualty. In addition, information may be gained as a basis for estimating the risk of a casualty and for assessing the effectiveness of proposals for improving the safety and efficiency of navigation in the area.

The use of casualty statistics as a measure of marine risk has distinct limitations. In most areas a casualty is a reasonably rare occurrence, so that any systematic analysis of casualties will normally have to take place over a period of a few years; and, if improvements are made, a further period of time is necessary to measure their effectiveness.

This paper describes how planning a seaway can be undertaken using alternative methods for assessing marine risk, and goes on to show how marine traffic usage of a seaway can be made more efficient. It shows analytically how the potential risk to marine traffic can be reduced.

The Humber was used for analysis as this was an area where data were readily available. The area is interesting as it comprises a seaway to the third largest shipping complex in the UK; further, it is an area where no major marine traffic study has ever been undertaken. The study area is from the Humber light-vessel to No. 10 buoy between Grimsby and Immingham (Fig. 1).

The primary analytical concept in the study was the development of the ship domain theory for use in restricted waters. The paper considers how this concept can be used to improve navigational safety within such waters.

2. SHIP DOMAIN FOR USE IN RESTRICTED WATERS. The concept of ship domain was introduced to this country by Fujii,[1, 2] and further work by Goodwin[3] established the existence of a ship domain. Their approaches, have however, some important differences which are reflected in the definitions which they use.

Fujii *et al.* defined the 'effective domain' as 'a two-dimensional area surrounding a ship which other ships must avoid – it may be considered

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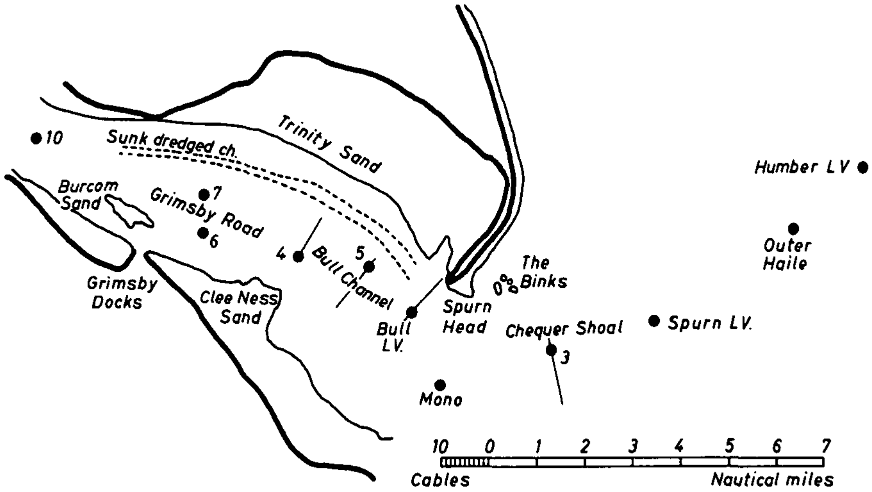

Fig. 1. Humber light-vessel to No. 10 buoy (some buoys ommitted and positions approximate)

as the area of evasion'. The dimensions of the effective domain boundary were defined as the distance from the central vessel at which the density reaches a local maximum. The dimensions of the effective domain were separated by situation types, that is, by overtaking, meeting and crossing encounters.

Goodwin defined 'ship domain' as 'the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary objects'. The dimensions of the domain boundary were defined as the distance $x_{A}1$ in Fig. 2 such that for all $x < x_{A}1$ the number of

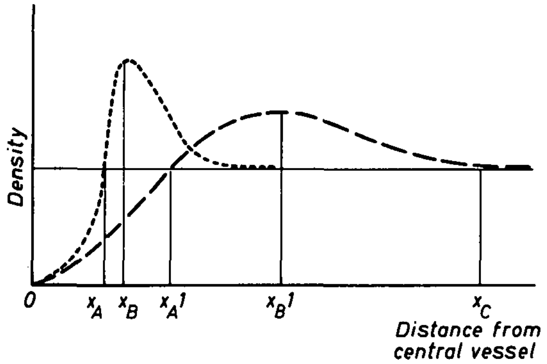

Fig. 2. Distribution of vessels around a central vessel. ——, Expected distribution assuming a domain does not exist. – – –, Expected distribution in the presence of a domain in restricted waters. — —, Expected distribution in the presence of a domain in open waters. x_B, Distance of the domain boundary as defined by Fujii for restricted waters. $x_B{}^1$, Distance of the domain boundary as defined by Fujii in open waters. x_A, Distance of the domain boundary as defined by Goodwin in restricted waters. $x_A{}^1$, Distance of the domain boundary as defined by Goodwin in open waters.

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ship points is less than would have been expected given no ship domain, and for $x = x_{A1}$ the situation is for the first time equivalent to a situation of uniform traffic density. The dimensions of the domain boundary were separated into the three sectors coinciding with a ship's side- and stern-lights.

The basic differences between the Fujii and Goodwin concepts arise because of the differences in their respective survey areas. Fujii was concerned with the channels of Tokyo Bay, where most of the traffic is between 20 and 100 gross tonnes, and the Uraga Strait, where the majority of traffic is between 100 and 500 gross tonnes. By contrast, the work of Goodwin was concerned with the relatively open waters of the southern North Sea covering an intersection of routes converging from all directions where the traffic mix by size is quite wide.

Operationally, the difference between the two approaches may be emphasized by noting that the boundary of the Goodwin domain encloses an area which a navigator would like to keep clear of other ships and that, in order to achieve this minimum clearance, the majority of navigators aim for something rather greater. This majority behaviour accounts for the increased density of ships between points x_{A1} and x_C in Fig. 2. The modal value, at x_{B1}, which corresponds to the Fujii domain boundary, may be considered as the clearance for which a typical ship aims in order that the Goodwin domain shall generally be kept free of other ships. Analytically, the radius of the Fujii domain is always greater than that of the Goodwin domain.

Another important factor emphasizing the difference between the Fujii and Goodwin concepts emerges from a consideration of the situation within restricted and open waters (Fig. 2). In open waters the curve will be such that the maximum is not well defined, particularly if the data are 'noisy', as Goodwin found[3] in her work on the ship domain. By contrast, in restricted waters the curve will be such that the maximum is well defined. In restricted waters the initial slope of the expected distribution in the presence of a domain will be steep, thus reducing the numerical difference between x_A and x_B.

The choice between using the Fujii or the Goodwin approach will depend on the purpose of the analysis. If channel capacity and safe navigation is the main interest, then the Fujii approach will be appropriate, since it defines a spacing between ships with which the majority of navigators will feel comfortable. If, on the other hand, a critical danger factor is of interest, then the Goodwin approach could be more appropriate, especially for open-water situations.

For the purpose of the present study the definition of the domain will be reworded 'the effective area around a vessel which a typical navigator actually keeps free with respect to other vessels'. The dimensions of the effective domain boundary will be defined as the distances from the central vessel at which the density reaches a local maximum, similar to to that used by Fujii (distance x_B in Fig. 2).

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If the domain as defined above corresponds to the movement of a typical ship then, for practical purposes, when that domain is encroached by another vessel there is a need for a close examination of the navigational circumstances under which such encroachments or encounters occur. It is assumed that the passage of a vessel within a restricted seaway will be, so far as possible, unimpeded by the passage of other vessels.

It was possible to obtain radar coverage from the Humber light-vessel to about two nautical miles south-east of Immingham by using the harbour radars at the Spurn pilotage control station. The area of the study is basically a buoyed channel of about 19 n.m. where broad crossing situations will not normally arise. Vessels within this area must have the intention of being either inward-bound or outward-bound, and therefore the situations of interest between two vessels can be considered as a meeting or overtaking encounter.

3. THE SHIP DOMAIN FOR USE IN RESTRICTED WATERS. To find the distance at which the number of vessels is maximized, the density of marine traffic per unit area over a given period of time is observed around a central vessel. To do this, data from 64 hours of radar survey were converted into Cartesian coordinates at 3-minute time intervals and stored in a computer for analysis. For a selected central vessel it is possible to calculate the relative bearings and ranges of all other vessels in the vicinity at any given interval of time so that a distribution of ships around a central vessel can be plotted. This procedure is then repeated for each 3-minute time interval during which the central vessel is within the area, and the distribution of ships around the central vessel for each time interval is superimposed one over the other. After repeating this process for a given number of chosen vessels, each vessel's distribution of other vessels is in turn superimposed one over the other. By this manner a distribution of ships around a chosen group of central vessels is derived.

For restricted waters and narrow channels, it was decided to array the distribution of ships around a central vessel in Cartesian coordinates. This would capitalize on the fact that the traffic flow would run in a path roughly parallel with the buoyed channel and Cartesian coordinates could be made to coincide with it. The distribution was subdivided into units of 0·05 n.m. in both the fore-and-aft and athwartship lines of the central vessel to produce units of area of 0·0025 n.m.^{2}.

As stated the two situations of interest, in restricted waters are the meeting and overtaking encounter situations, which are analysed separately. The calculation of the domain boundary was separated into athwartship and fore-and-aft components for both encounter situations. The full calculation and determination of the domain boundary is given elsewhere,[4] but the following example shows the determination of the athwartship domain dimension for the meeting encounter.

Information from the computer printout of the distribution of ships is not very instructive. What is needed is not so much the actual distribution of ship points about a central ship but rather the way in which the

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ambient cross-channel distribution is affected by the presence of a central ship.

An area 3 n.m. ahead and astern of the central vessel was chosen as the area of interest, and this was restricted to 0·75 n.m. each side of the fore-and-aft line which resulted in a (120, 30) array. In order to derive a measure of the ambient cross-channel density in the absence of a central ship an area 1·0 n.m. ahead and astern of the central vessel's athwartship line respectively was subtracted, leaving an area of only between 1·0 and 3.0 n.m. ahead and astern. It was assumed that vessels further than 1·0 n.m. ahead and astern would have no effect on the action of a central ship. The remaining rows within the 30 columns are summed and become the ambient distribution in the absence of a central ship. Let a_i be the number of ships in the ith column to starboard of the line of the central ship's direction, where $i = 1, 2, \ldots, 15$. Let x_i be the distance from the centre line of the furthermost edge of these columns, where $i = 1, 2, \ldots, 15$ and x_0 defines the centre line. Let m_i be the mean distance from x_0 where $m_i = \frac{1}{2}(x_i + x_{i-1})$, $i = 1, 2, \ldots, 15$. The situation to port of the central ship can be dealt with as a symmetrical case of the analysis to starboard; the description of the analysis to starboard is therefore also applicable to the analysis to port.

In the light of Goodwin's experiences, it was decided that the determination of the domain dimensions would depend upon a graphical approach. With this in mind it was thought better to smooth the data determining the ambient distribution substituting a_{si} for a_i, where a_{si} is the smoothed value. From inspection of the raw data it was thought it would be subject to some random variation, and after trying various smoothing methods a moving average with fixed weights, as follows, was thought most suitable: $a_{si} = \frac{1}{2}(a_{i-1} + a_{i+1})$.

To assess the actual cross-channel distribution in the presence of a central ship, rows are chosen only up to 0·2 n.m. immediately ahead and astern of the central ship's athwartship line, again restricted to 0·75 n.m. each side of the fore-and-aft line. The columns are summed and become the observed distribution of passing vessels in the central vessel's athwartship line. Let o_i be the number of ships in the ith column to starboard of the line of the central ship's direction. To starboard of the central ship are observed ship points, where $T_s = \sum o_i$ and ambient ship points, where $A_s = \sum a_{si}$, and from this the expected distribution e_i of passing vessels is calculated, where $e_i = (T_s/A_s) \times a_{si}$ for each column. In order to identify a domain boundary the number of ships observed in each column is compared with the number expected in the absence of a central ship by calculating the ratio $r_i = o_i/e_i$.

In the absence of a domain, the values of r_i would be expected to approximate to unity, subject only to random variation. In the presence of a domain there should be an observed displacement of ships away from the central ship, and values of r_i near the central vessel should be less than unity and corresponding values of r_i further away from the central

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vessel should be greater than unity. The position where r_i is locally maximized will indicate the domain boundary. In practice, a few modifications can be made to the method, to help in the determination where r_i is locally maximized.

This situation is indicated on Fig. 3 where distances x_p and x_s define the domain boundary to port and starboard respectively. Data from 64 hours of radar survey were used in the calculation as follows: (*a*) the central vessel was a grouping of merchant vessels under way irrespective of size; (*b*) all other vessels were under way.

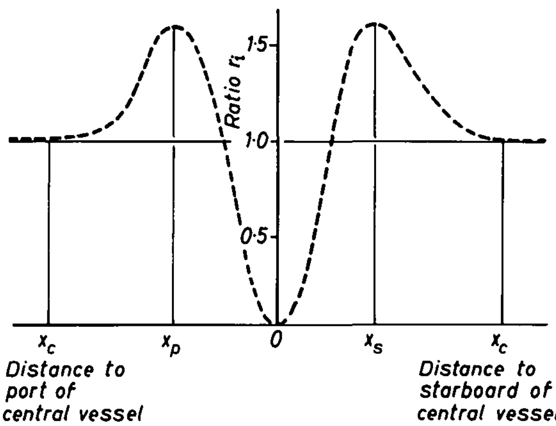

Fig. 3. Frequency of passing vessels around a central vessel. — Expected distribution assuming a domain does not exist. --- Expected distribution in the presence of a domain. x_p, Distance of domain boundary to starboard. x_c, Distance at which perturbation is over. x_p, Distance of domain boundary to port. x_s, Distance of domain boundary to starboard.

Figure 4 shows the calculated values of r_i up to a distance of about 5 cables each side of the central vessel's fore-and-aft line. It was thought unnecessary to plot all values of r_i because of small values of e_i, especially to starboard. In any case values of r_i greater than about 5 cables would occur outside the main navigable channel and are not of interest for the calculation. The curve in Fig. 4 shows a systematic displacement of ships away from the central vessel, suggesting the presence of a ship domain. The distance from central vessel where the value of r_i is locally maximized is clearly distinguishable and this defines the value of the athwartship domain dimension.

In constructing Fig. 4 there was some doubt as to whether to continue the curve at a non-zero level across the central vessel's fore-and aft line. It was decided to discontinue the line across the central vessel because, although the point is of interest, it was largely academic and in no way affected the location of the domain boundary.

There was some concern as to whether the area chosen for calculation of the ambient distribution was appropriate, but by an iterative method

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of trials on various ambient distributions the results obtained were usually similar to those given in Fig. 4. It was found that the observed distribution of passing distances was so different from that ahead and astern that the area chosen for an ambience is not critical.

It was found that 80·5 per cent of vessels (about 4 out of every 5) pass port-to-port within a passing distance of 0·5 n.m.; 19·5 per cent of vessels (about 1 out of every 5) pass starboard-to-starboard within a passing distance of 0·5 n.m.

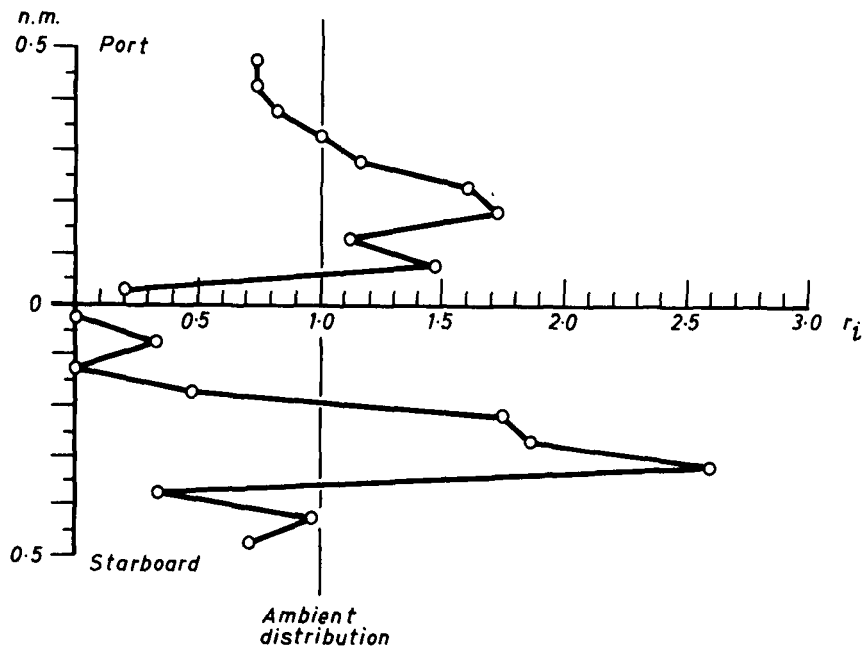

Fig. 4. Ratio between observed and expected distribution of passing distances. Athwartship domain dimension (meeting encounter, whole area, merchant vessels), to port 1·75 cables, to starboard 3·25 cables. For practical purposes the half-ellipse domain shape abaft of the vessels athwartship line is not used.

The athwartship domain dimensions are as given in Fig. 4, that is 1·75 cables and 3·25 cables to port and starboard respectively.

What is interesting in these results is the high proportion of vessels which pass starboard-to-starboard (about 20 per cent), contravening Rule 9 of the Collision Regulations. The dimension of the domain boundary to starboard is larger than that to port. This indicates that when vessels do pass starboard-to-starboard, in contravention of Rule 9, the central vessel is uneasy about the situation and prefers a wider separation than that which it would accept for a port-to-port situation.

Under the same definitions but a slightly different analysis the fore-and-aft dimensions of the domain boundary were found to be: ahead, 6·1 cables, astern, 9·2 cables. The next consideration was how to bound

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the domain for the meeting encounter. It proved impossible to determine precisely the shape of the domain due to lack of data, but from inspection of the raw data it would appear that an ellipse would be the most suitable shape, and for practical purposes only the ellipse shape forward of the central vessel's athwartship line. The situation under discussion is of course the meeting encounter, and for navigational purposes once two vessels have passed each other in a two-way traffic flow the situation is no longer of interest. Also, due to the geometry of the seaway, broad crossing situations do not arise, and only the area ahead of the central vessel is of interest. The area astern may thus not have any practical relevance but indicates the distance when passing vessels again return to the ambient flow. In this case the precise shape of the domain is largely academic because, in restricted waters, the shape does not necessarily enter the argument, as will be shown later.

By a similar analysis the dimensions of the domain boundary were found under the criteria outlined for the meeting encounter.

From inspection of the raw data it was thought that the full ellipse was the most suitable shape with which to bound the overtaking encounter. In fact there is a fine argument whether to choose a full or half ellipse for the final shape. It could be argued that it is the area ahead of the central vessel that is of importance because, in practice, a central vessel when being overtaken really has no control over how close the overtaking vessel comes, apart from ensuring an adequate passing distance. The Collision Regulations (Rule 13) lay down that 'any vessel overtaking any other shall keep out of the way of the vessel being overtaken', and this must bias the action of a central vessel. On the other hand, when considering the safety of the seaway, if a central vessel is being overtaken by another which has its domain astern encroached, although its master cannot do much about it in practical terms he may still become alarmed and feel uneasy about the situation. A full ellipse shape would allow for this situation. Although the precise shape of the ship domain is of interest, however, it is largely academic.

It is interesting to note that in the overtaking encounter there are two actions which are generally taken. First, the bunching forward and aft of the central vessel suggests a preference of some vessels to follow one another at a similar speed; and secondly, others overtake or are overtaken, keeping the other either to port or starboard in almost equal proportions.

Figures 5 and 6, which summarize the shape of the ship domain for the meeting and overtaking encounters respectively, were derived from the observations of 222 merchant vessels over a sea lane of 19 n.m.

It was decided for a more detailed analysis to separate the radar survey area into three zones, to determine whether any difference can be seen in vessel behaviour in areas which differ in their sea-room availability. The three chosen zones within radar coverage were as follows.

Zone A. A sea area of length about 5·5 n.m. of relatively open waters

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with marine traffic tending to converge and diverge to and from the Spurn light-vessel; there is, however, a definable buoyed channel from the Humber light-vessel to Spurn light-vessel for deeper draught vessels (Fig. 1).

Zone B. A sea area of length about 6·0 n.m. between the Spurn and Bull light-vessels. The area has definable sea room narrowing from about 1 n.m. to the south of No. 3 buoy to about 0·5 n.m. between Bull light-vessel and Spurn Head. There is an awkward bend in the channel of about 35° in the region of No. 3 buoy (Fig. 1).

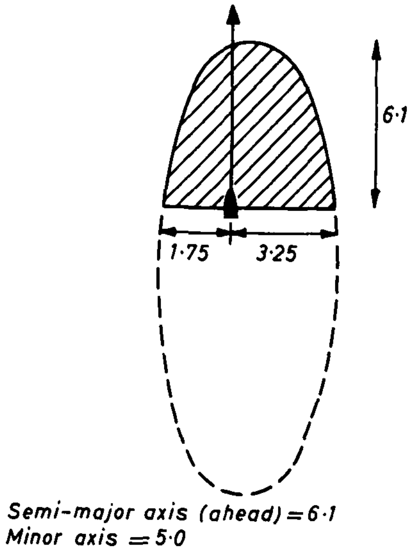

Fig. 5

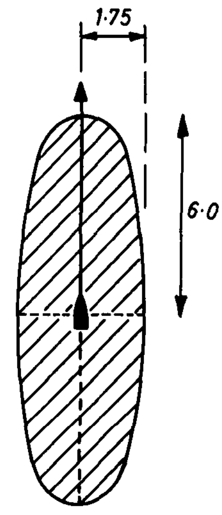

Fig. 6

Fig. 5. Domain for merchant vessels for the meeting encounter, whole area (distances in cables)

Fig. 6. Domain for merchant vessels for the overtaking encounter, whole area (distances in cables)

Zone C. A sea area of length about 7·5 n.m. from the Bull light-vessel to about No. 10 buoy. The area has definable sea room narrowing from about 0·5 n.m. between Bull light-vessel and Spurn Head to 0·4 n.m. north of No. 4 buoy (re-named 4A), then widens slightly in the region of No. 6 buoy where marine traffic diverge and converge from the main traffic flow when entering and leaving Grimsby (Fig. 1).

The analysis was repeated on the data obtained from the Spurn Head radar surveys for Zones A, B and C. Table 1 summarizes the results.

In general, the results were disappointing due to the lack of data within each zone, for example no results were possible in Zone A and only partly for Zone B.

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TABLE 1. SHIP DOMAIN IN DIMENSIONS (CABLES) FOR GIVEN AREAS, MERCHANT VESSELS ONLY

Area	Semi-major axis	Minor axis	To port	To starboard
		Meeting		
Whole	6·1	5·0	1·75	3·25
A	—	—	—	—
B	—	4·5	1·75	2·75
C	7·2	5·0	2·25	2·75
		Overtaking		
Whole	6·0	3·5	1·75	1·75
A	—	—	—	—
B	—	3·5	1·75	1·75
C	5·5	3·0	1·25	1·75

Sample 222 central vessels.

What is interesting in the results is the consistency of about 80 per cent of vessels passing to port and 20 per cent of vessels passing to starboard of the central vessel respectively for all zones; the high number of vessels (about 20 per cent) that pass starboard to starboard, thus contravening Rule 9 of the Collision Regulations, is also notable.

The analysis into differences in vessel behaviour in areas that differ in their sea-room availability proved inconclusive due to lack of data. From the few results possible, there would appear to be little if any significant difference in their dimensions. This could be explained by the fact that although the channel availability within the zones differed, the width of channel actually used did not differ significantly, except for the approaches in Zone A.

It could be argued that, since Zone A is relatively open waters, an analysis more suitable for open water would be more appropriate as the assumptions made for restricted waters would not necessarily apply. This may to a certain extent be true, but a previous paper[5] did show marine traffic with tendencies to channel, especially vessels having to use the buoyed channel between the Humber and Spurn light-vessels.

4. DIMENSIONS OF SHIP DOMAIN FOR FISHING VESSELS. Since a considerable amount of the marine traffic consists of fishing vessels within the Humber seaway it was decided to analyse their behaviour and find the dimensions of their domains to see how they differ from those of merchant vessels.

A similar analysis to that for the merchant vessels was undertaken for both meeting and overtaking encounters and the results are summarized in Table 2. The results are inconclusive because of the small sample size of central vessels, but the following points should be noted.

In the case of the meeting encounter 71 per cent of fishing vessels pass

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TABLE 2. SHIP DOMAIN DIMENSIONS (CABLES) FOR GIVEN AREAS, FISHING VESSELS ONLY

Area	Semi-major axis	Minor axis	to port	To starboard
		Meeting		
Whole	—	3·0	1·25	1·75
A	—	—	—	—
B	—	3·0	1·25	1·75
C	—	—	1·75	—
		Overtaking		
Whole	1·5	1·5	0·75	0·75
A	—	—	—	—
B	1·5	2·0	1·25	0·75
C	1·5	—	—	—

Sample 81 central vessels.

port-to-port and 29 per cent starboard-to-starboard. The percentage of starboard-to-starboard passings, in contravention of Rule 9, is slightly higher when a fishing vessel is the central vessel rather than a merchant vessel. When testing for statistical significance under a chi-squared goodness-of-fit test, the proportion of starboard-to-starboard passings when fishing vessels were central did not differ significantly from that directly proportional to merchant vessels chosen as central vessel.

In the case of the overtaking encounter, fishing vessels overtake or are overtaken, leaving the other vessel on their port or starboard side in almost equal proportions, as in the case with merchant vessels. The dimensions of the ship domain for the overtaking encounter are complete, and a point of interest is the size of the fishing vessel semi-major axis (1·5 cables) compared with that of the merchant vessels (6·0 cables). The analysis of the fishing vessel ship domain by zone was inconclusive.

5. DIMENSIONS OF THE SHIP DOMAIN BY LENGTH. Goodwin[3] has outlined the main independent variables affecting the size of the ship domain; there are, *inter alia*, size, type of vessel, and relative speed of vessel. It was decided to investigate the effect of central vessel size on the dimensions of the ship domain; the most convenient parameter is length, used in most Japanese studies on the effective domain. A similar analysis to that for merchant vessels was undertaken for both the meeting and overtaking encounters for the whole area, and the results are summarized in Table 3. It was possible to have only a limited breakdown by length as indicated in the table; there were in fact 55 vessels 100 m and over but the sample size was too small to obtain meaningful results. The following comments are made.

In meeting encounters between vessels less than 50 m length 32·4 per cent passed starboard-to-starboard as opposed to 18·6 per cent with

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TABLE 3. SHIP DOMAIN DIMENSIONS (CABLES) FOR ALL VESSELS BY LENGTH (m)

Length (m)	Semi-major axis	Minor axis	To port	To starboard	Vessels
		Meeting			
Less than 50	8·3	4·0	1·75	2·25	116
50–100	8·3	5·0	1·75	3·25	137
		Overtaking			
Less than 50	1·5	1·5	0·75	0·75	116
50–100	7·5	3·5	1·75	1·75	137

vessels 50–100 m length. When testing for statistical significance under a chi-squared goodness-of-fit, the proportion of starboard-to-starboard passings when central vessels were less than 50 m differed significantly from that directly proportional to central vessels 50–100 m. It was concluded that smaller vessels are more likely to contravene Rule 9; it must be remembered, however, that smaller vessels are more likely to be able to navigate outside the main navigable channel, and Rule 9 need not always apply.

In the case of the overtaking encounter both length classes shown in Table 3 overtake or are overtaken leaving the other vessel on their port or starboard side in almost equal proportions, as with merchant and fishing vessels. Throughout the analysis, central vessels have shown no tendency or preference to pass or be passed to port or starboard for the overtaking encounter.

The dimensions of the ship domain appear to increase with length for both the meeting and overtaking encounters. No equation was formulated as a function of length for the dimensions of the ship domain because of the limited class lengths shown in Table 3. What is interesting is the radical difference in the semi-major axis for the overtaking encounter; that is, 7·5 cables for central vessels of 50–100 m length. A similar difference was found between merchant and fishing vessels. From this it is obvious that smaller vessels are not so sensitive in keeping an area ahead free with respect to other vessels.

6. PRACTICAL APPLICATIONS OF THE SHIP DOMAIN IN RESTRICTED WATERS. A previous paper[5] on traffic flows within the Humber seaway suggested that marine traffic did not use the available sea room to its greatest advantage. With this in mind, a more precise study was undertaken to estimate the cross-track profile of marine traffic across the main navigable channel. A demonstration area was chosen between No. 3 buoy, Bull light-float, No. 5 and No. 4 buoys. This represents a reasonably straight navigable channel with a staggered buoyage configuration of about 6 n.m. in length, where the channel width varies from about 4 to 6 cables.

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When estimating the cross-track profile the distribution across No. 3 buoy, Bull light-float, No. 5 and No. 4 were superimposed, relative to the navigation mark. For example, across the navigable channel at No. 3 buoy the distribution of inward-bound marine traffic is farthest from the navigation mark whereas across the Bull light-float the distribution of inward-bound traffic is furthest from the navigation mark. The cross-track distributions were therefore separated into two: one for the traffic distribution nearest to the navigation mark, the other for the traffic distribution farthest from the navigation mark.

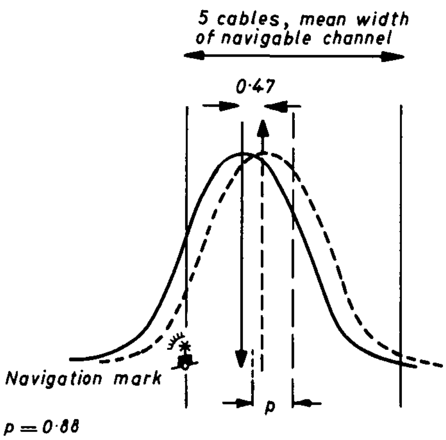

Fig. 7

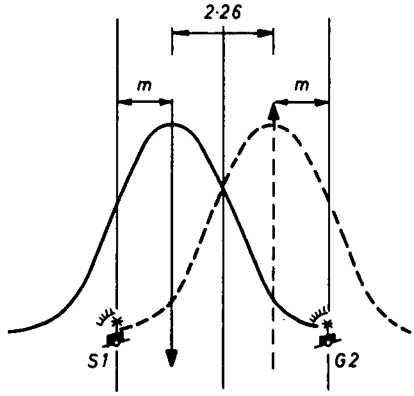

Fig. 8

Fig. 7. Cross-track profile of marine traffic between buoys 3 and 4 (distances in cables). – – –, Cross-track distribution of marine traffic furthest from the navigation mark. ——, Cross-track distribution of marine traffic nearest to the navigation mark.

Traffic flow relative to navigation mark	Highest movements from navigation mark (cables)	95% confidence limits of movements (cables)
Nearest	1·37	± 2·09
Furthest	1·85	± 2·11

Note. It would seem reasonable to assume from the 95% confidence limits that the distribution of marine traffic furthest from and nearest to the navigation mark has the same spread across the navigable channel.

Fig. 8. Suggested cross-track profile of marine traffic between Buoys 3 and 4 with a gate-buoyage configuration.

Figure 7 summarizes the cross-track profile with an assumed mean navigable channel width of 5 cables. Both the nearest and furthest cross-track distributions were found to follow a normal distribution using a chi-squared test with 8° of freedom at the 5 per cent significance level. The figure shows the distance at which the number of marine traffic movements for both the nearest and furthest traffic flows relative to

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the navigation mark reaches a maximum, and is within the same half of the navigation channel as the navigation mark, with peaks about 0·5 cables apart. This shows the cross-track distribution of marine traffic furthest from and nearest to the navigation mark with considerable overlap. This would mean that for a staggered buoyage configuration, as within this demonstration area, marine traffic would be continually crossing the centreline of the main navigable channel between navigation marks. This is probably due to the additional mental processing by mariners that must be done to interpret a navigation channel within an asymmetrical buoyage display. The navigation marks are obviously the primary navigational reference point and a mariner will mentally decide upon a passing distance irrespective of sea-room availability. The cross-track profile indicated in Fig. 7 shows poor usage of the navigation channel and indicates the preferred track of typical vessels for both the traffic flow nearest and furthest from the navigation mark in the absence of encounter situations.

Earlier it was seen that the action of a typical vessel in a meeting encounter was to pass port-to-port with dimensions given for a preferred passing distance, that is, the ship domain dimension port of central vessel. The ship domain dimension port of central vessel varies from 1·25 cables for fishing vessels to 2·25 cables in the extreme cases of merchant vessels in area C. This would mean that if a meeting encounter occurred within a staggered configuration a typical central vessel would always deviate from its preferred route in the absence of an encounter to achieve a preferred passing distance. There now arises a situation where vessels are momentarily uneasy when having to undertake some sort of avoiding action. If vessels deviate from their preferred route in the channel to achieve their preferred passing distance with another vessel they may, in the agony of the moment, deviate too far and stray outside the geometry of the channel – a grounding perhaps or collision with a floating mark. If a central vessel accepts an encroachment on its preferred passing distance with another vessel this could lead to possibilities of a collision.

Figure 8 suggests how the cross-track profile of marine traffic within a gate buoyage configuration would increase sea-room usage. This profile assumes that the original cross-track distribution furthest from S 1 (Fig. 7) reacts in the same way to the navigation mark G 2 (within a gate buoyage configuration) as did the original cross-track distribution nearest to S 1. In effect, distance *m* in Fig. 8 is the same. In practical terms, accepting that the navigation mark is the primary reference point when within a restricted channel with a gate buoyage configuration, the mariner's mental process in interpreting the navigation channel is to refer to the navigation mark on the starboard side. As Fig. 8 shows, the peaks between the two-way marine traffic flow change from 0·5 to 2·26 cables.

If a gate buoyage configuration were adopted, this would mean that

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when a meeting encounter occurred, a typical central vessel would no longer need to deviate from its preferred route to achieve a preferred passing distance; this would now occur naturally.

If we consider the cross-track profile of marine traffic as shown on Fig. 7 for a staggered buoyage configuration, then, in the absence of any avoiding manoeuvres, the probability of an encounter between two meeting vessels is 0·89. But when considering the cross-track profile of marine traffic as shown on Fig. 8 for a gate-buoyage configuration, in the absence of any avoiding manoeuvres the probability of an encounter between two meeting vessels is now only 0·31, which is a considerable reduction. The probability of a meeting encounter would now be reduced.

7. CONCLUSIONS. What has been suggested here is a method for testing an area to determine whether the channel geometry needs altering, or perhaps traffic separation introduced. The object of traffic separation is to reduce the frequency of meeting encounters. When considering the separation of marine traffic for the meeting situation in a channel the precise shape of the domain is not used, but only the extreme athwartship dimension. The main use of the ship domain for the overtaking encounter is to derive the traffic capacity for a particular seaway, that is the capability of a waterway to deal with traffic when it is so crowded that overtaking becomes impossible and vessels will follow each other at equal speeds; it is then that traffic volume has reached the capacity of the waterway. Factors influencing traffic capacity are well documented,[2] and the traffic capacity for the Humber seaway has been derived and is given elsewhere.[4] Again, the precise shape of the domain is not used but only the extreme fore-and aft dimension to estimate traffic capacity.

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