Modeling of Observed Ship Domain in Coastal Sea Area Based on AIS Data

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ABSTRACT: It is well- known that an imaginary domain, which never let other ships enter, exists around a vessel. While the models of the domain in areas such as bays or harbors have been advocated and in practical use, there is little compiled data regarding the actual collision avoidance actions taken by operators under real encounter situations. The authors analyzed collision avoidance maneuvers which were extracted from AIS data recorded for a month, under one-to-one encounter situation, in order to examine collision avoidance behaviors in a coastal sea area. The results of analyses showed tendencies different from those described in the previous studies with regard to the actual offset distance between vessels. In this paper, we present some models of representative offset distances between a give-way vessel and a stand-on vessel in the coastal sea area.

1 INTRODUCTION

Determining a moment of initiating collision avoidance action and a passing distance for the action is critical in order to develop a collision avoidance algorithm. Regarding the passing distance, as is well-known, an imaginary domain which never let other ships enter, exists around a vessel. While the models of the domain in a bay or channel (Fujii 1980, 1983) and of the passing distance in a harbor (Inoue 1994) was advocated and empirical ship domain have been presented with AIS data when passing a bridge or a narrow channel (Martin 2013), there is still little compiled data regarding the actual collision avoidance actions taken by operators under real encounter situations.

The authors analyzed real behaviors under one-to-one encounter situations, which were extracted AIS data of Tokyo Bay, recorded for a month, in order to examine actual collision avoidance behaviors. In this area, a lot of encounters of various types and sizes of ships have been observed. According to the behaviors analyses based on AIS data, tendencies different from those described in the previous researches (Fujii 1980, 1983, Inoue 1994, Martin 2013, Yamasaki 2013) were seen regarding the actual offset distance between vessels in the coastal sea area.

The purpose of this paper is to specify the representative offset distances between ships in coastal sea area. Then we found that the offset distances were approximately proportional to the length of the stand-on vessels.

2 ANALYSES OF COLLISION AVOIDANCE BEHAVIORS

2.1 *Area and period of AIS data*

To examine an actual domain for collision avoidance around a vessel in a coastal sea area, we analyzed the real maneuvers which were extracted from the AIS data recorded for a month, under one-to-one encounter situation in southern Tokyo Bay. In this area, a lot of encounters of combination of ships of various types and sizes are constantly observed.

The AIS data recorded from 1st to 30th of June in 2013 were used for the analyses. Figure 1 shows the trajectories of AIS data only on 1st of June 2013.

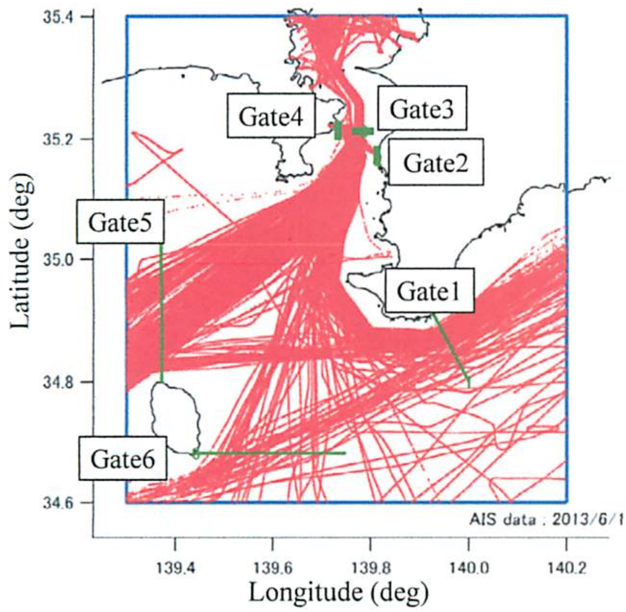

Figure 1. Trajectories of AIS data on 1st June 2013.

2.2 *Procedure for extracting collision avoidance behaviors*

In order to automatically extract the collision avoidance behaviors in the situation of the one-to-one encounter, six gates were set as shown in Figure 1. The vessels through these gates were extracted and their collision avoidance behaviors were analyzed. The vessels used in this analysis were satisfying all the following conditions: (1) the situation of encounter between a give-way vessel and its target ship, i.e. stand-on vessel, was head-on, overtake or crossing; (2) two vessels met on the five combinations of gates, i.e., 3-6 and 1-3, 3-6 and 1-5, 3-6 and 1-6, 3-6 and 2-4 or 3-6 and 3-5; and (3) two vessels met under the conditions that the distance of them was within 18520 m (10 miles), TCPA was within 30 minutes and DCPA was within 3704 m (2 miles). In this paper, the encounter situation was determined based on the relative position between the give-way vessel and the stand-on vessel at the moment of the aforementioned three encounter conditions.

The collision avoidance behaviors were automatically extracted by the procedure described hereafter. First, the status of each encountered vessel, such as heading, speed, DCPA and TCPA and so on, was calculated at every synchronized 10 second based on the AIS data. Next, in the case where the actions of the give-way vessel for evading the stand-on vessel, such as altering course or reducing the vessel's speed, have been observed simultaneously with the increase of DCPA or TCPA, we considered that the give-way vessel evaded the stand-on vessel. In addition, the time at which the give-way vessel started to evade the stand-on vessel, have been identified.

2.3 *Extracted collision avoidance behaviors*

Table 1 shows the number of extracted collision avoidance behaviors from AIS data.

Table 1. Number of extracted collision avoidance behaviors.

Gates	Avoided			Not Avoided		
	HO*	OT**	CS***	HO*	OT**	CS***
3-6 & 1-3	106	44	428	222	66	737
3-6 & 1-5	31	29	230	85	57	474
3-6 & 1-6	30	29	131	86	49	352
3-6 & 2-4	29	29	243	84	49	424
3-6 & 3-5	63	61	912	125	93	1650
Total	259	192	1944	602	314	3637

* Head-on; ** Overtake; *** Crossing

Figure 2 shows the relation between the lengths of the give-way vessel and the stand-on vessel. Figure 3 shows the types of the give-way vessel and the stand-on vessel. In these both figures, the give-way vessel passed by Gate 3&6, the stand-on vessel passed by Gate 1&5 and encountered with the give-way vessel. As shown in these figures, the extracted cases of collision avoidance behaviors include the various situations on encounters of combination of various types and sizes of ships.

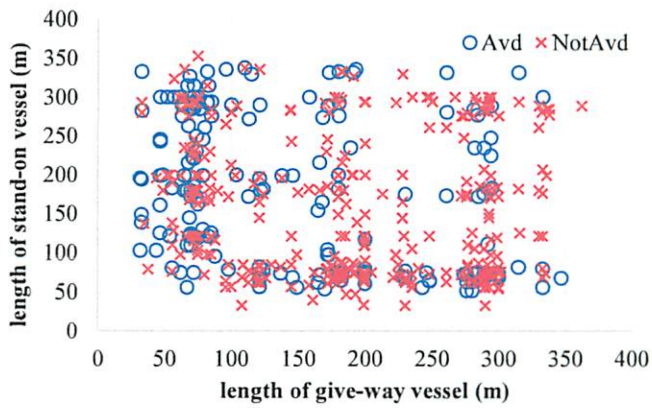

Figure 2. Length of give-way and stand-on vessels under one-to-one encounter situation.

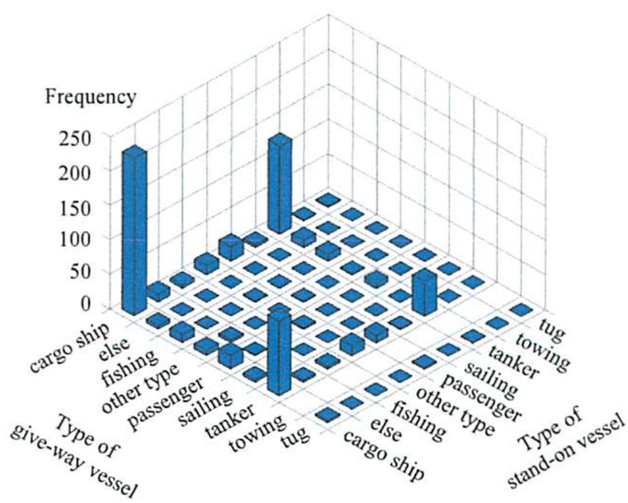

Figure 3. Type of give-way and stand-on vessels under one-to-one encounter situation.

3 OBSERVATION OF OFFSET DISTANCE FOR MODELING

3.1 *Examination of actual offset distance*

The individual distance on longitudinal or lateral line of a give-way vessel between the center of the give-way vessel and the stand-on vessel, is defined as an offset distance, which is minimum passing distance between two vessels in each direction. In this paper, we analyze four directions of the offset distance, i.e. "forward", "backward", "starboard" and "port" under three encounter situations, i.e. "head-on", "overtake" and "crossing".

Relative trajectory under a one-to-one encounter situation is shown in the small figure for explanation in Figure 4. A forward offset distance is defined as the length of line A on the ordinate in the figure, i.e. the distance between the origin, i.e. the center of the give-way vessel, and intersection of the ordinate and the relative trajectory. Similarly, the port offset distance is defined as the length of line B on the abscissa.

Each line in Figure 4 is a relative trajectory of a stand-on vessel to a give-way vessel. Each trajectory is plotted on a body-fixed coordinate system. The origin of coordinate is the center of give-way vessel. The relative trajectories shown in Figure 4 are those of stand-on vessels when give-way vessels evaded them under the situation of crossing on the combination of gates 3-6 and 1-5.

The respective offset distances were identified for all extracted collision avoidance behaviors, and a database of these offset distances was developed.

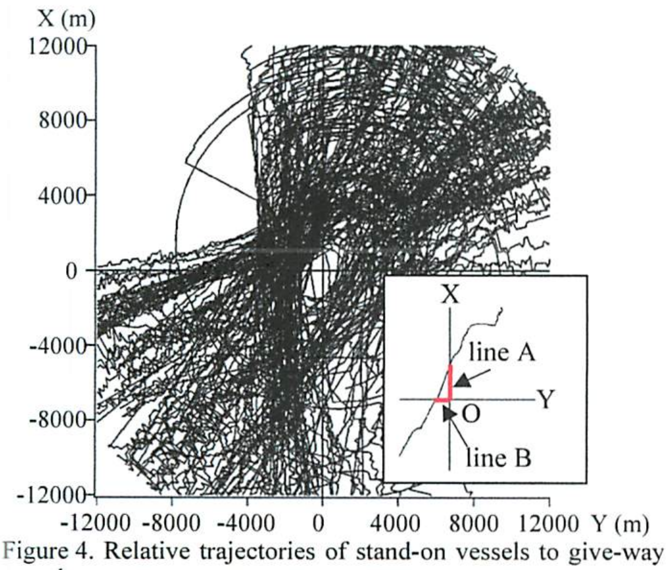

Figure 4. Relative trajectories of stand-on vessels to give-way vessels.

3.2 *Screening of offset distance on the database for modeling*

For the purpose of development of the model of the offset distances for one-to-one collision avoidance, we screened the offset distances on the database in order to eliminate irrelevant values owing to extract the behaviors as one-to-one encounter even if a give-way vessel avoided some vessels as its target.

In our previous study (Miyake 2014), a typical sequence for collision avoidance was observed. In the sequence, the give-way vessel altered its heading toward the space behind of the stand-on vessel for evading, and after the stand-on vessel crossed in front of the give-way vessel, it returned gradually to the original course following the stern of the stand-on ship.

The forward offset distances under crossing situations are analyzed as explained below.

Each arrow in Figure 5, i.e. the result of additional analysis to the data used in the previous study (Miyake 2014), is a relative velocity of a stand-on vessel to a give-way vessel when crossing the forward longitudinal line of the give-way vessel. Each relative velocity is plotted on a body-fixed coordinate system. The origin of coordinate is the center of give-way vessel. Unfortunately, some irrelevant values are included in the figure. As shown in this figure, regarding the relative velocities at the time when stand-on vessels are crossing the front longitudinal lines of give-way vessels, the lateral components are small negative and the longitudinal components are large negative when the distance between the stand-on vessel and the give-way vessel is not less than 9260 m (5 miles). The similar tendencies of components of the relative velocity are observed in another analysis as well, at the time when the give-way vessels are starting to return to the original courses.

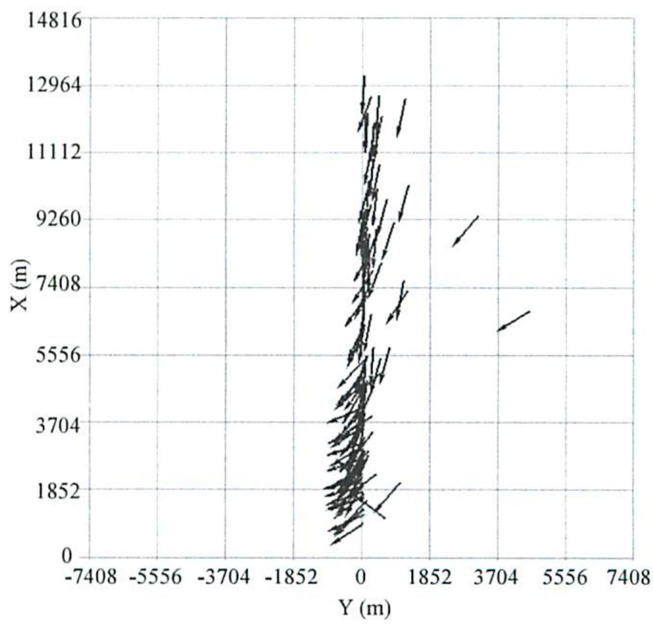

Figure 5. Relative velocities of stand-on vessels to give-way vessels when crossing the forward longitudinal line of the give-way vessels.

Therefore, from Figure 5 and the aforementioned of the observation, it can be said that the give-way vessel is not taking the evading action for the stand-on vessel which is far from the give-way vessel 9260 m or more. In other words, the stand-on vessels whose positions are 9260 m or more from the give-way vessels are deemed as out of the imaginary domain. Thus such give-way vessels can completely ensure their safety.

In this paper, the offset distances within 9260 m are extracted from the database to develop the model. The threshold of 9260 m applies only to the analysis for the forward offset distance under crossing situations.

Offset distances other than the forward offset distance under crossing situation are screened by the similar manner using different thresholds of distance, for the analysis of respective direction of offset distances under respective encounter situations.

3.3 *Dependence of offset distances on collision avoidance action*

We compare the offset distances on the both situations that give-way vessels evade the stand-on vessels and that the give-way vessels do not evade the stand-on vessels, in order to examine whether operators keep their offset distance regardless of evading stand-on vessels or not.

Figures 6 and 7 show the frequency and the cumulative values of the forward offset distances under crossing situations of give-way vessels, using the length of the give-way vessels as the parameter. Respective graphs in these figures show the similar tendency. Namely, the proportions of frequencies of give-way vessels of respective ranges by length are almost the same, in each offset distance range in both figures. Thus, it could be said that such proportion does not depend on whether give-way vessels take collision avoidance actions or not. This feature is observed in the cases other than forward offset distances under crossing encounter situations.

Therefore, we analyze the AIS data without distinction whether give-way vessels take collision avoidance actions or not.

3.4 *Dependence of offset distances on encounter situation*

We further compare the distributions of offset distances under respective encounter situations, in order to verify the dependence of offset distances under encounter situation.

Figures 8 and 9 show the frequencies and the cumulative values of the forward offset distances when give-way vessels take actions for avoiding collision with their stand-on vessels under the situations of head-on and overtake, respectively. As shown in Figures 6, 8 and 9, the distribution patterns of offset distances are quite different under respective encounter situations. Thus, we develop the model of the forward offset distance by each encounter situation.

On the other hand, significant differences of offset distances have not been observed under all three encounter situations in the respective three directions other than the forward offset distances, i.e. backward, starboard and port. Thus, we develop the models of the offset distance of three directions regardless of the encounter situations.

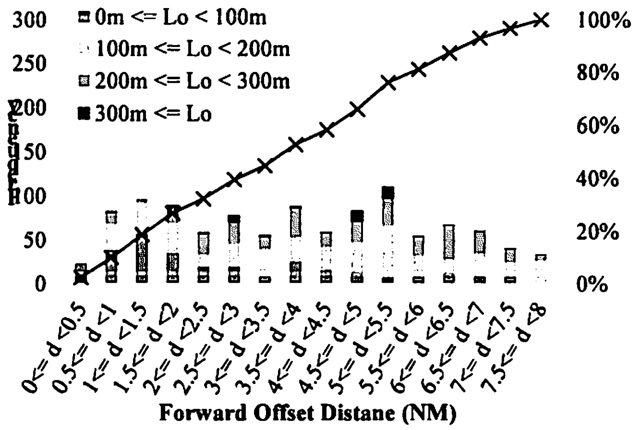

Figure 6. Frequency of forward offset distance by length of give-way vessel in crossing situation, where give-way vessels take collision avoidance actions.

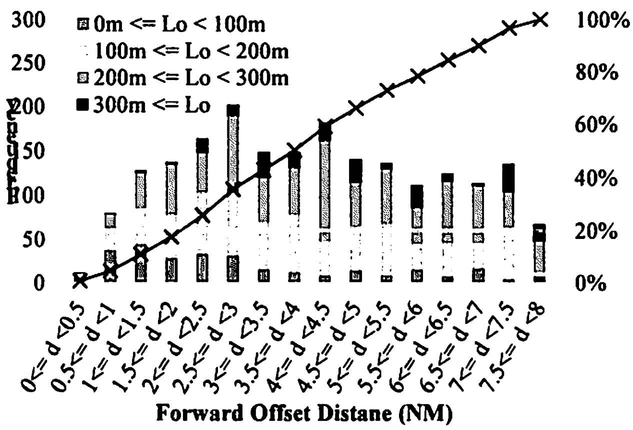

Figure 7. Frequency of forward offset distance by length of give-way vessels in crossing situation, where give-way vessels take no collision avoidance actions.

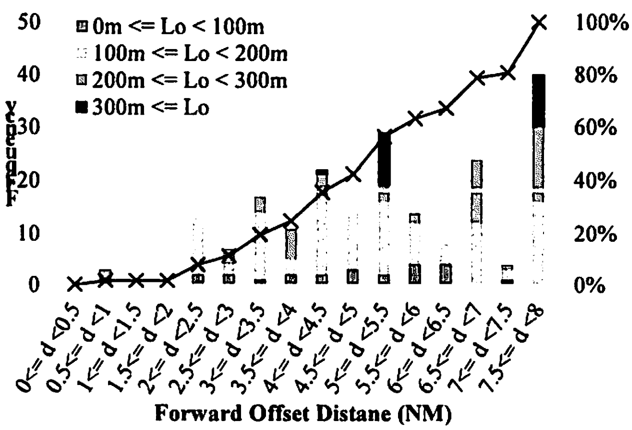

Figure 8. Frequency of forward offset distance by length of give-way vessels on head-on encounter, where give-way vessels take collision avoidance actions.

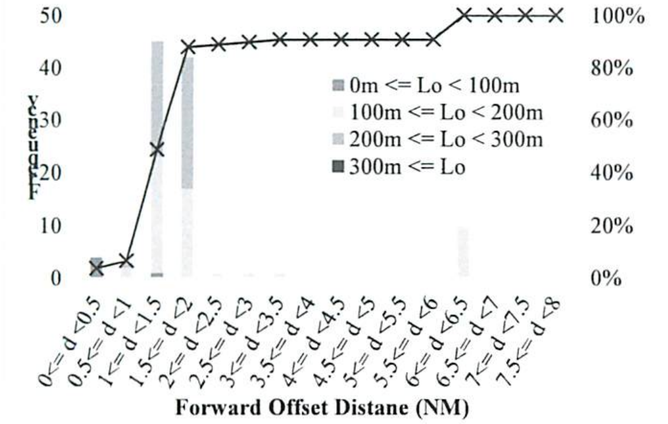

Figure 9. Frequency of forward offset distance by length of give-way vessels on overtake encounter, where give-way vessels take collision avoidance actions.

4 MODEL OF ACCEPTABL AND CRITICAL DOMAINS

4.1 *Observation of tendency of offset distance*

We developed models of actual representative offset distances mathematically in coastal sea area, applying to the previous research which mathematically presented models of offset distances in harbor by analysis of questionnaires (Inoue 1994).

In Sections 4.1 to 4.4, analyses of the forward offset distance under crossing situation are shown as concrete examples.

We sought to examine features of the relationship of three factors, i.e. representative offset distances, lengths of give-way vessels and stand-on vessels.

However, the direct correlation has not been examined between offset distances and give-way vessels' length. Then, the correlation between the ratio of give-way vessels' length to offset distance and give-way vessels' length was examined.

Figures 10 to 13 show the relations between the ratios and the length of give-way vessel under the respective ranges of length of stand-on vessels. A cross denotes the individual encounter. The abscissa indicates the length of give-way vessels. The ordinate indicates the ratio of length of give-way vessels to forward offset distances.

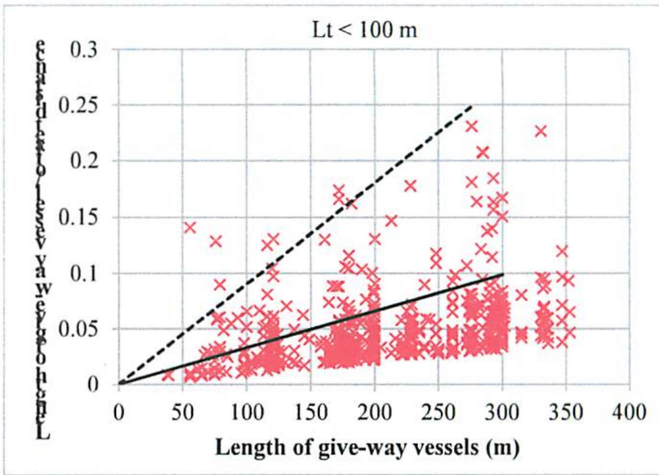

Figure 10. Forward offset distance and length of give-way vessels, where length of stand-on vessels is smaller than 100m.

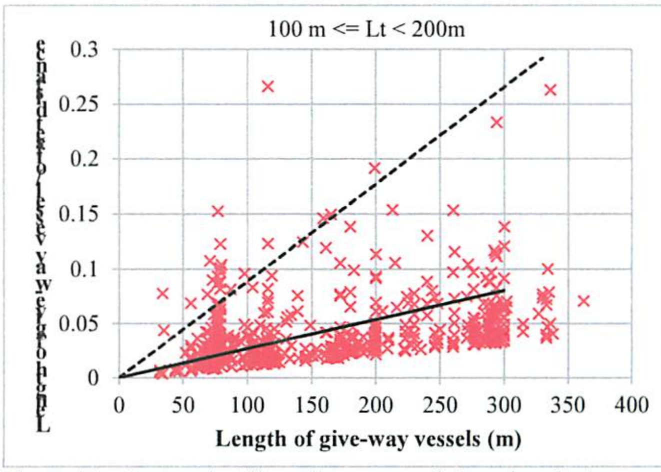

Figure 11. Forward offset distance and length of give-way vessels, where length of stand-on vessels is equal to 100m or more but smaller than 200m.

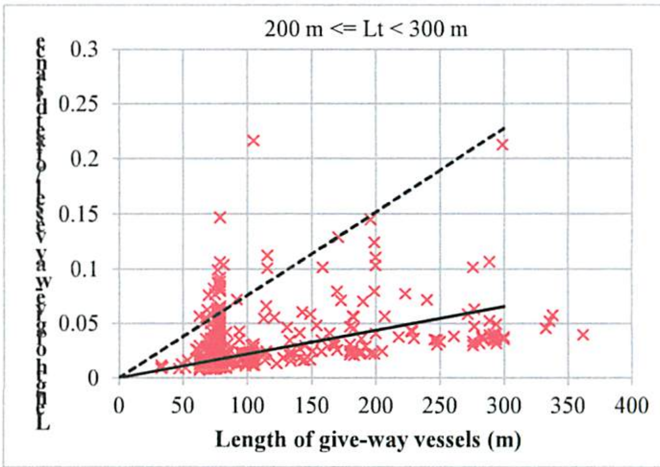

Figure 12. Forward offset distance and length of give-way vessels, where length of stand-on vessels is equal to 200m or more but smaller than 300m.

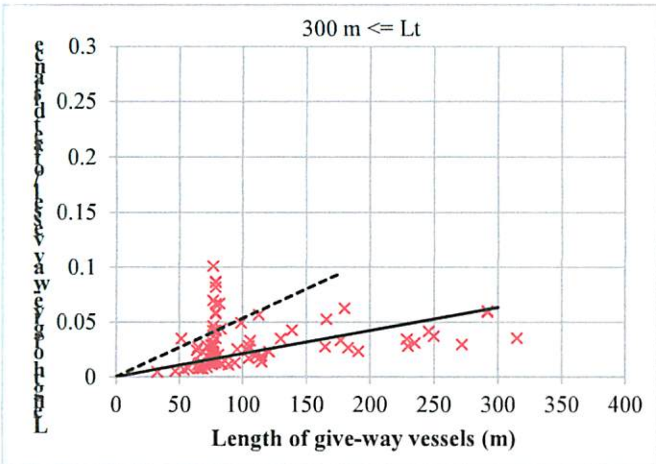

Figure 13. Forward offset distance and length of give-way vessels, where length of stand-on vessels is equal to 300m or more.

The difference of density of crosses could be observed in these figures, and the difference could be divided into three types. High, low and medium density is observed in the lower, upper and middle parts of these figures, respectively. The lines in the respective figures are drawn by one of the author in order to distinguish these parts.

4.2 *Definition of two domains*

Inoue et al. (Inoue 1994) described that two domains existed around vessels in the models at harbor. One is core domain which never let other ships enter, and the other is the area having to additional room to the core domain to maintain safer situations.

Applying the definition, two domains in coastal sea area are defined based on the analysis described in Figure 10 to 13. The left of Figure 14 shows the two domains, i.e. *acceptable domain* and *critical domain*. The *acceptable domain* is defined as the area where it is acceptable to let the vessels enter, but operators are concerning about the approaching vessels. The distances which configure the *acceptable domain* are called *acceptable offset distances*. The *critical domain* is defined as the area where it is unacceptable for operators to let the vessels enter. The distances which configure the *critical domain* are called *critical offset distances*.

The *acceptable and critical offset distances* have four directions as illustrated in the right of Figure 14, and are called as mentioned in the figure with adding the words "acceptable" or "critical", e.g. "*forward critical offset distance*", respectively. In this paper, an abbreviated notation regarding the individual offset distance shown in Figure 15 is used. The superscript denotes the type of domain, i.e. "acceptable (A)" or "critical (C)". The subscript denotes directions of the offset distance, i.e. "forward (f)", "backward (b)", "starboard (s)" and "port (p)", and the encounter situations, i.e. "head-on (h)", "overtake (o)" and "crossing (c).

According to the definitions, solid and dot lines in Figures 10 to 13 correspond to the *forward acceptable offset distance* and the *forward critical offset distance*, respectively.

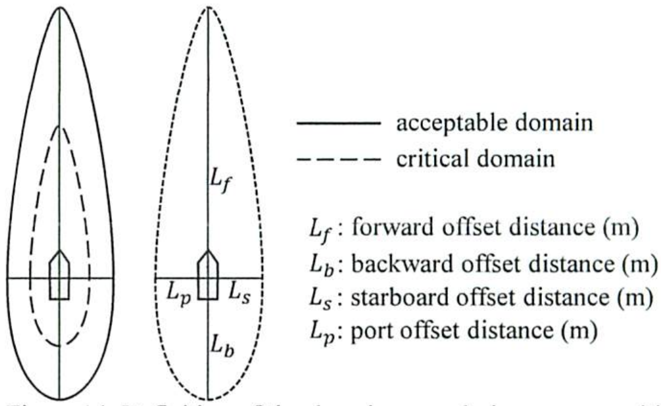

Figure 14. Definition of the domain around give-way vessel in coastal sea area and the respective offset distances configuring the domains.

(unit: m)

$$L^{\text{(Domain type)}}_{\text{(direction)(encounter situation)}}$$

Figure 15. Definition of abbreviated notation.

4.3 *Relationship between offset distance and length of vessel*

The respective offset distances corresponding to the lines in Figure 10 to 13 are evaluated. They are expressed as the reciprocal value of the gradient of the individual lines.

Table 2 shows the offset distances of the respective range of length of stand-on vessels. It is observed that the *acceptable and critical offset distances* increase as the lengths of their target vessels increase. It could be also said that operators of the give-way vessels try to keep the offset distance irrespective of the length of give-way vessels.

Table 2. Offset distance in the respective range of length of stand-on vessels.

Ranges of length of stand-on vessels (Lt)	offset distance (m) acceptable	critical
Lt < 100m	3030	1110
100m <= Lt < 200m	3700	1140
200m <= L t< 300m	4550	1320
300m <= Lt	4760	1890

4.4 *Model of offset distances*

Figure 16 shows the relations between the stand-on vessels' length and the *acceptable and the critical offset distances*. The abscissa and the ordinate indicate the length of stand-on vessels and the offset distance, respectively. Closed circles and triangles denote the *acceptable and critical offset distances* given in Table 2, respectively. In the figure, the range of the length of the stand-on vessels are representative by the median values.

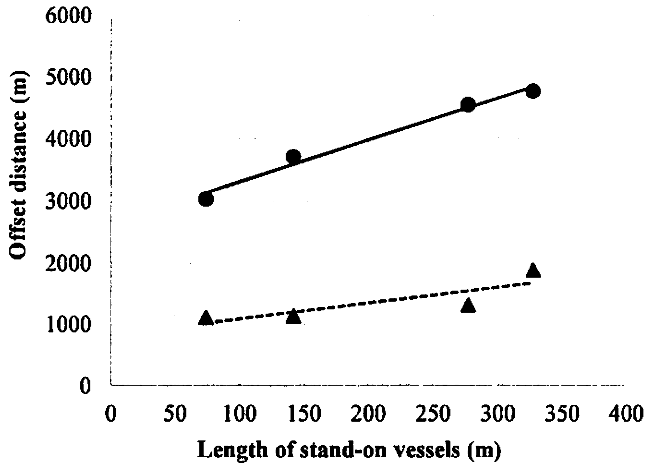

Figure 16. Forward offset distance in crossing and length of stand-on vessels.

Figure 16 shows that both circles and triangles increase linearly as the length of the stand-on vessels increases. Then it is assumed that the *acceptable and critical offset distances* are proportional to the length of stand-on vessels and the respective lines in this figure are determined by the regression analysis as shown in Equations (1) and (2). Namely, the *forward acceptable offset distance* and the *forward critical offset distance* under crossing encounter situation are:

$$L_{fc}^{A} = 6.75 \cdot Lt + 2627 \tag{1}$$

$$L_{fc}^{C} = 2.62 \cdot Lt + 826 \tag{2}$$

where Lt is the length of the stand-on vessel (unit: m).

4.5 *Offset distances other than forward offset distances under crossing situation*

By using the similar procedure, the *forward offset distances* for situations other than crossing can be obtained as shown in Equations (3) to (5).

Regarding the *forward offset distance* under overtake encounter situation, the two domains, i.e. *acceptable and critical domains*, cannot be distinguished, because the individual offset distances are uniformly distributed on the figures similar to Figures 10 to 13. On the other hand, the tendencies similar to those of *forward offset distance* in crossing situation are observed. Namely, the larger lengths of stand-on vessels are, the larger offset distances are. Then we draw single linier line in each figure on "forward offset distance and the length of give-way vessels" and determine the offset distance of a range of the length of the stand-on vessels in accordance with the gradient of the linier line. Thus, we determined the *forward acceptable offset distances* based on the results of the regression analyses, for the reason that the range of the distances are similar to the *forward acceptable offset distances* in the other encounter situations. Namely, the *forward critical offset distances* under overtake situation cannot be determined.

The *forward acceptable offset distance* and *forward critical offset distance* under head-on and overtake encounter situations are:

$$L_{fh}^{A} = 17.69 \cdot Lt + 6192 \tag{3}$$

$$L_{fo}^{A} = 3.66 \cdot Lt + 2309 \tag{4}$$

$$L_{fh}^{C} = 11.40 \cdot Lt + 3347 \tag{5}$$

Furthermore, the backward, starboard and port offset distances are determined by the similar procedure for the *forward offset distances* under crossing situation. These offset distances are expressed by the individual regression equations without distinction of encounter situation as shown in Equations (6) to (11) because the significant differences were not observed in the three directions.

The *backward acceptable offset distance* and *backward critical offset distance* are:

$$L_{b}^{A} = 9.42 \cdot Lt + 1975 \tag{6}$$

$$L_{b}^{C} = 6.03 \cdot Lt + 752 \tag{7}$$

The *starboard acceptable offset distance* and *starboard critical offset distance* are:

$$L_{s}^{A} = 0.64 \cdot Lt + 875 \tag{8}$$

$$L_{c}^{A} = 0.31 \cdot Lt + 394 \tag{9}$$

The *port acceptable offset distance* and *port critical offset distance* are:

$$L_{p}^{A} = 2.05 \cdot Lt + 664 \tag{10}$$

$$L_{p}^{C} = 1.16 \cdot Lt + 308 \tag{11}$$

Based on the above mentioned analyses, we confirm the features of the domain in coastal sea as follows. There are two domains of give-way vessels in the coastal sea area. The individual offset distance depends on length of stand-on vessels, and does not depend on length of give-way vessels.

4.6 *Illustration of domains*

Figure 17 illustrates the models of the domains around give-way vessels under the three encounter situations. The digits denote the approximate ratios of individual offset distance in accordance with the modeled equations. Here it should be noted that the *acceptable offset distances* in the three directions, i.e. backward, starboard and port, are the same irrespective of encounter situations. Furthermore, it should be noted that the *critical offset distances* in the three directions, i.e. backward, starboard and port, are the same under the two encounter situations.

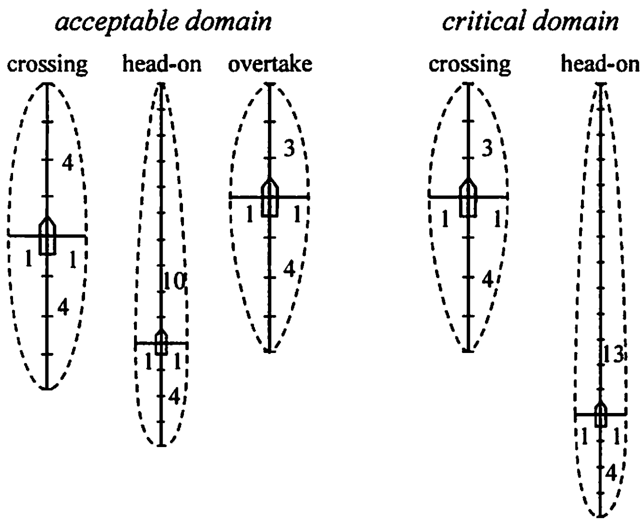

Figure 17. Illustration of domains.

5 CONCLUSIONS

We analyzed the real one-to-one collision avoidance maneuvers which were extracted from the AIS data recorded for a month, in order to examine the actual collision avoidance behaviors. Through the analyses, we find that

- The two domains around the give-way vessels can be distinguished when an operator of the vessel sails in the coastal sea area. One is the area where it is acceptable to let the vessels enter, but operators are concerning about the approaching vessels, and the other is the area where it is unacceptable for operators to let the vessels enter.

This is the same feature as the previous study on harbors by Inoue et al. (Inoue 1994). However, the individual offset distance which configures the domains is quite different from the previous study as follows:

- the individual offset distance can be determined irrespective of the length of give-way vessels;
- the forward offset distances heavily depends on the encounter situation;
- the backward, starboard and port offset distances do not depend on the encounter situations; and
- the forms of the *acceptable and critical domains* are quite different in respective encounter situations.

Meanwhile, the similar feature as the previous study regarding the offset distances is observed, i.e. the individual offset distances is approximately linear to the length of stand-on vessel.

In conclusion, we specified the representative offset distances between ships in the coastal sea area through the analyses with AIS data.

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