Journal of Navigation and Port Research International Edition
Vol.32, No.4 pp. 279~285, 2008 (ISSN-1598-5725)

A Study on Mariners' Standard Behavior for Collision Avoidance (3)

- Modeling of the execution process of an avoiding action based on human factors -

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Abstract : *We have proposed modeling methods of mariners' standard behavior for collision avoidance by analyzing mariners' recognition process in a previous study. As a subsequent study, the aim of this study is to build a model of mariners' execution process which is one of six processes in the condition of collision avoidance. In this study, thus, the structure of mariners' information processing on the process of taking avoiding actions is described and the relation between mariners' behavior and necessary factors in the process is analyzed. And then we have built a model of mariners' standard behavior for execution process based on the characteristics of mariners in ship-handling, which are obtained from the international collaborative research on human factors. It is tried to define the contents of execution process based on the standard behavior of mariners for collision avoidance and to formulate information processing of mariners.*

Key words : *Mariner's standard behavior, Execution process, Collision avoidance, Avoiding action, Modeling, Human factors*

1. Introduction

The characteristics of mariners' behavior in collision avoidance situation have been investigated utilizing a full-mission ship handling simulator and, as a result, it has been understood that the modeling of mariners' standard behavior in collision avoidance situation is necessary in order to achieve safe navigation (Park et al., 2003; Kobayashi, 2004; Kobayashi, 2005a). As a preliminary stage of modeling, the procedure of mariners' standard behavior for collision avoidance was analyzed and categorized into six processes: detection, identification, recognition, plan, execution, and return (Park et al., 2007a). And then the recognition model of mariners for collision avoidance was proposed by analyzing the result of international collaborative research on human factors in ship handling (Park et al., 2007b). As a subsequent study, the aim of this paper is to propose a modeling method for the execution process of mariners. In order to build a model for the execution process of mariners in collision avoidance, we applied the obtained results from international collaborative research on human factors and formulated the relation between mariners' behavior and the related factors in execution process (Kobayashi, 2005b).

2. Structure of Mariners' Standard Behavior for Execution Process

In a previous study, it was defined that mariner's avoiding behavior is a continuous sequence of information processing of a human in ship handling for collision avoidance, and their behavior for collision avoidance was categorized into six processes. In this study, the contents of execution process based on the standard behavior of mariners for collision avoidance were described and the structure of information processing of mariners was formulated. As shown in Fig. 1, the execution process can be expressed by the relation among a mission (M_E), mariner's information processing (F) and necessary information (I). In other words, the execution of the planned actions for collision avoidance (M_E) is resulted

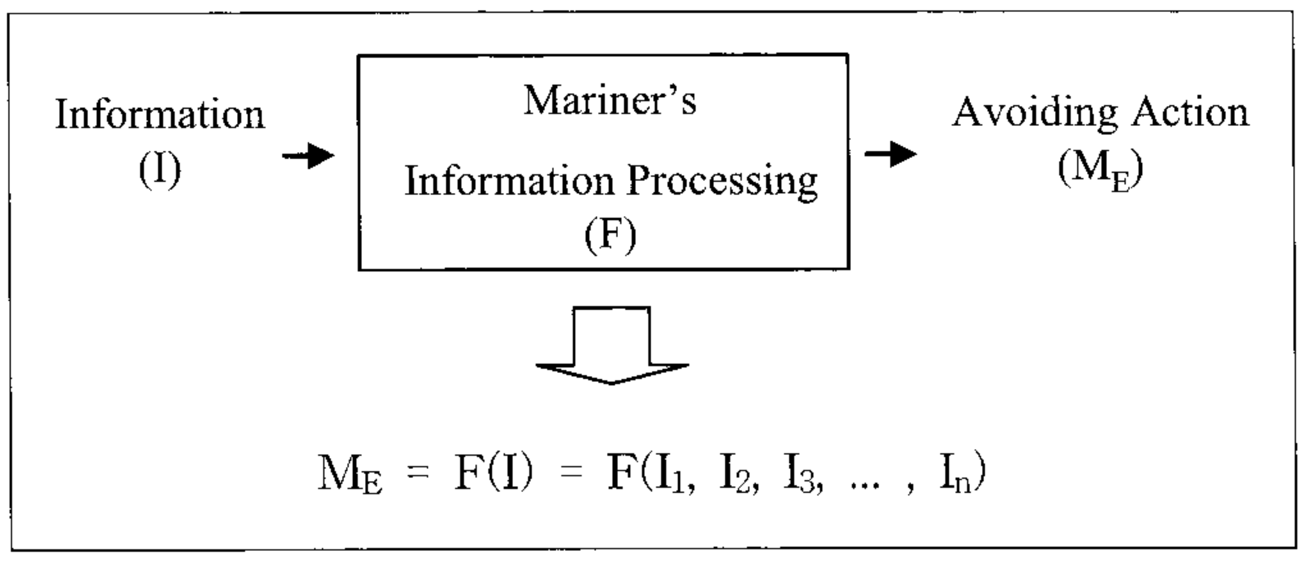

Fig. 1 Simple Model of Execution Process

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from mariner's information processing (F) based on necessary information (I: I_1, I_2, I_3, ..., I_n). The detailed contents of a mission, the mission-related information processing and necessary information in execution process are as follows (Park et al., 2007a).

<Mission>

M_E : To take an avoiding action to the target ship for collision avoidance,

<Task>

T_1 : To take the planned action for collision avoidance,

T_2 : To analyze the relations between the relating ships and surroundings to the own ship during the execution of avoiding actions,

T_3 : To analyze the surroundings,

T_4 : To make plans for the planned condition to return,

<Judgment>

J_1 : To decide whether the applied avoiding action is proper or not,

J_2 : To decide whether there is anything else to avoid in surroundings or not,

J_3 : To decide whether it is proper time to start the planned condition or not,

<Relating information>

I_1 : Planned action,

I_2 : Own ship's condition,

I_3 : Target ship's condition,

I_4 : Current interference condition,

I_5 : Estimated passing condition,

I_6 : Surroundings,

I_7 : Rules,

I_8 : Ship's maneuverability,

I_9 : Planned condition,

I_{10} : Destination.

In the contents of relating information, the planned action I_1 means the planned action to avoid the target ship in plan process before the execution for collision avoidance. The own ship's condition I_2 means the condition of factors such as course, speed and position of the own ship at the moment. And the target ship's condition I_3 can be expressed by factors such as course, speed and position of the target ship at the moment. The position of the target ship is viewed from the own ship, which can be estimated by relative bearing and distance between the ships.

The current interference condition I_4 means the relation between the own ship and the target ship at the moment, when mariners are taking the planned action for collision avoidance. This condition can be expressed by factors such as courses and speeds of the own ship and the target ship, relative bearings and distances between the ships, and crossing angle of them. The estimated passing condition I_5 can be explained by the distance of closest point of approach between the own ship and the target ship, the time to the closest point of approach between them, the passing distance of the target ship on the own ship's bow or stern line and the passing side of the target ship on the own ship's bow or stern side. The surroundings I_6 can be explained by mainly two navigational condition, one is the flow of the vessels surrounding the own ship and the other is the characteristics of navigational waters. This condition can be expressed by the combination of traffic condition such as volume, positions and movements of the vessels surrounding the own ship, and navigational water's condition such as fairway, shape of waters and navigational aids. The rules I_7 can be explained by local rules and international regulation to prevent collision.

The ship's maneuverability I_8 means the ship's moment in general; however, it is estimated from the length of the ship in this paper. The planned condition I_9 means the original condition of the own ship before the planned avoiding actions happen, which can be explained by factors such as course, speed and position of the own ship. And the destination I_{10} means the position for the own ship to arrive finally. The relating information $I_1 \sim I_{10}$, therefore, can be defined as following sets;

$$
\begin{aligned}
I_1 &= \{\text{Planned action}\} \\
I_2 &= \{Co_1, V_1, O_{POS}\} \\
I_3 &= \{Co_2, V_2, \alpha, D_R\} \\
I_4 &= \{Co_1, Co_2, V_1, V_2, \alpha, \theta, D_R, V_R\} \\
I_5 &= \{TCPA, DCPA, P_{DIS}, P_{DIR}\} \\
I_6 &= \{Co_{SUR}, V_{SUR}, \alpha_{SUR}, D_{SUR}, \theta_{SUR}, \text{Fairway}, \\
&\qquad \text{Shape of waters, Navigational aids}\} \\
I_7 &= \{\text{Colreg, Local rules}\} \\
I_8 &= \{L_1, L_2\} \\
I_9 &= \{\text{Planned } Co_1, \text{Planned } V_1, \text{Planned } O_{POS}\} \\
I_{10} &= \{O_{DES}\}
\end{aligned}
\qquad (1)
$$

where, Co_1 : own ship's course, V_1: own ship's speed,
Co_2 : target ship's course, V_2: target ship's speed,
α : relative bearing, D_R: relative distance,
θ : crossing angle, V_R: relative speed,
O_{POS} : own ship's position, P_{DIS}: passing distance,
P_{DIR} : passing direction, L_1: own ship's length,
L_2 : target ship's length, Co_{SUR}, V_{SUR}, α_{SUR}, D_{SUR}, θ_{SUR} : courses, speeds, relative bearings, relative

distances, crossing angles of the vessels surrounding the own ship respectively.

In general the task T_1, the avoiding action, is taken according to the planned method in a previous step and then the task T_2, the analysis of situation at the moment during the taken avoiding action, can be based on the information such as the condition of the own ship and the target ship, the condition of the real-time interference and the estimated passage between them, the surroundings of navigational environment, the applied rules and ship maneuverability of them. The task T_3, the analysis of surrounding situations, can be derived directly by the relative conditions of the surrounding vessels to the own ship to find out anything else to avoid. And the task T_4, making plans for return to the previous situation, can be determined by the information such as the condition of the own ship and the target ship, the condition of the real-time interference between them, the surroundings, the planned condition before the taken avoiding actions and destination. These relations between information and tasks can be expressed by following equations;

$$
\begin{aligned}
T_1 &= F(I_1) \\
T_2 &= F(I_2, I_3, I_4, I_5, I_6, I_7, I_8) \\
T_3 &= F(I_6) \\
T_4 &= F(I_2, I_3, I_4, I_6, I_9, I_{10})
\end{aligned} \qquad (2)
$$

Using the equations (2), the judgements $J_1 \sim J_3$ can be expressed as follows;

$$
\begin{aligned}
J_1 &= F(T_1, T_2) \\
J_2 &= F(J_1, T_3) \\
J_3 &= F(J_1, J_2, T_4)
\end{aligned} \qquad (3)
$$

Consequently, the mission (M_E) of the execution process is resulted from the function of following equation,

$$M_E = F(T_1, T_2, T_3, T_4, J_1, J_2, J_3) \qquad (4)$$

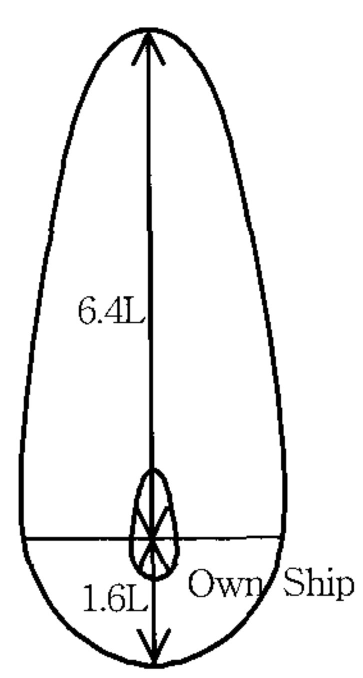
Therefore we can understand that mariner's behavior for execution process is decided by the function of the task and judgment based on information mentioned above.

3. Modeling of Mariners' Standard Behavior for Execution Process

The characteristics of mariner's behavior in execution process for collision avoidance are discussed with the related factors by applying the obtained data from the collaborative research and the characteristics of maritime traffic. Especially, the influence of relating factors to mariner's decisions in the process of taking actions for collision avoidance is analyzed. The evaluating factors of mariner's behavior are as follows; own ship's length (L), own ship's speed (V_1), target ship's speed (V_2), crossing angle (Θ), passing distance (P_{DIS}), passing direction (P_{DIR}), time to closest point of approach (TCPA) and distance of closest point of approach (DCPA). And the important mariner's behavior for collision avoidance is as follows; the time to CPA at the first recognition point of the danger to the target ship (Tr), the time to CPA at the start point of avoiding action to the target ship (Ta), the relative distance to the target ship at the start point of avoiding action to the target ship (A_{DIS}), the maximum altered heading angle (ϕ), the distance to the target ship at the position when the target ship passes an own ship's bow or stern side (P_{DIS}) and the direction that the own ship passes the target ship's bow or stern side (P_{DIR}). Consequently, through the relation between the evaluating factors and the main behavior of mariners mentioned above, the standard model of mariner's behavior for execution process is shown in this section.

(1) The characteristics of maritime traffic

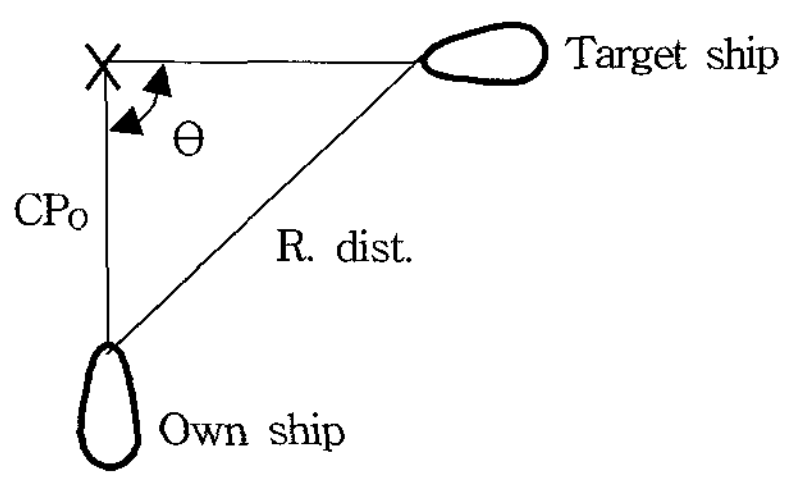
According to the research on the characteristics of maritime traffic, mariners tend to keep the specific distance to target ships from their ship, the own ship (Fujii et al., 1981). Fig. 2 shows the area of the specific distance to target ships which the mariners intend to keep, which is named "Exclusive area" (Yahei et al., 1981). The exclusive area is defined as the combination of a circle with the radius of 1.6 times of length of an own ship in the aft part and a ellipse with longer radius of 6.4 times of length of an own ship in the fore part. The size of the area is decided by the length of



L: Length of an own ship

Fig. 2 Shape of Exclusive Area

the own ship. In other words, mariners try to maneuver the ship to keep the exclusive area from traffic vessels for collision avoidance and the length of the own ship (LOA) will give a major influence on such behavior. Thus the characteristics of mariner's standard behavior in the condition of collision avoidance can be explained with the area. Fig. 3 shows the definition of crossing angle between two vessels.



Θ: Crossing angle
X: Estimated collision point
CPo: Distance from an own ship to estimated collision point
R. dist.: Relative distance from an own ship to a target ship

Fig. 3 Definition of Crossing Angle

(2) The relation between Tr, Ta and Θ (Park et al., 2007b)

Fig. 4 shows the relation between recognition points, action points and crossing angle using the information of TCPA. In Fig. 4, the correlation coefficient (R) between the recognition and action points is 0.6698. This indicates that the time of recognition points have correlations with the one of the action points. That is, the mariner's recognition time of ships considered as danger has an influence on the decision of start time for avoiding actions. And moreover, it is shown that the values of crossing angle make different start time for avoiding at the same time of recognition points. It is considered that mariners start to avoid the target ships approaching with big crossing angle in earlier time than those with small crossing angle. Thus we can understand that the crossing angle between ships is one of important factors to affect mariner's behavior for avoiding actions. The relation between the recognition time as dangerous ship and the start time of the avoiding action can be expressed by equation (5) as shown in Fig. 4.

$$Ta = 5.6832 \times Ln(Tr) - 5.1672 \quad (5)$$

(3) The relation between ADIS, V_R and Θ

Fig. 5 shows the relation between action points, crossing angle and relative speed. In Fig. 5, the correlation coefficient (R) between the action points and crossing angle is 0.6649. The relation shows that the action point to avoid collision has correlations with the crossing angle between the own and target ship. The bigger the crossing angle is, the earlier the avoiding action taken for each direction becomes. It is considered that the value of crossing angle can makes different start time of avoiding action.

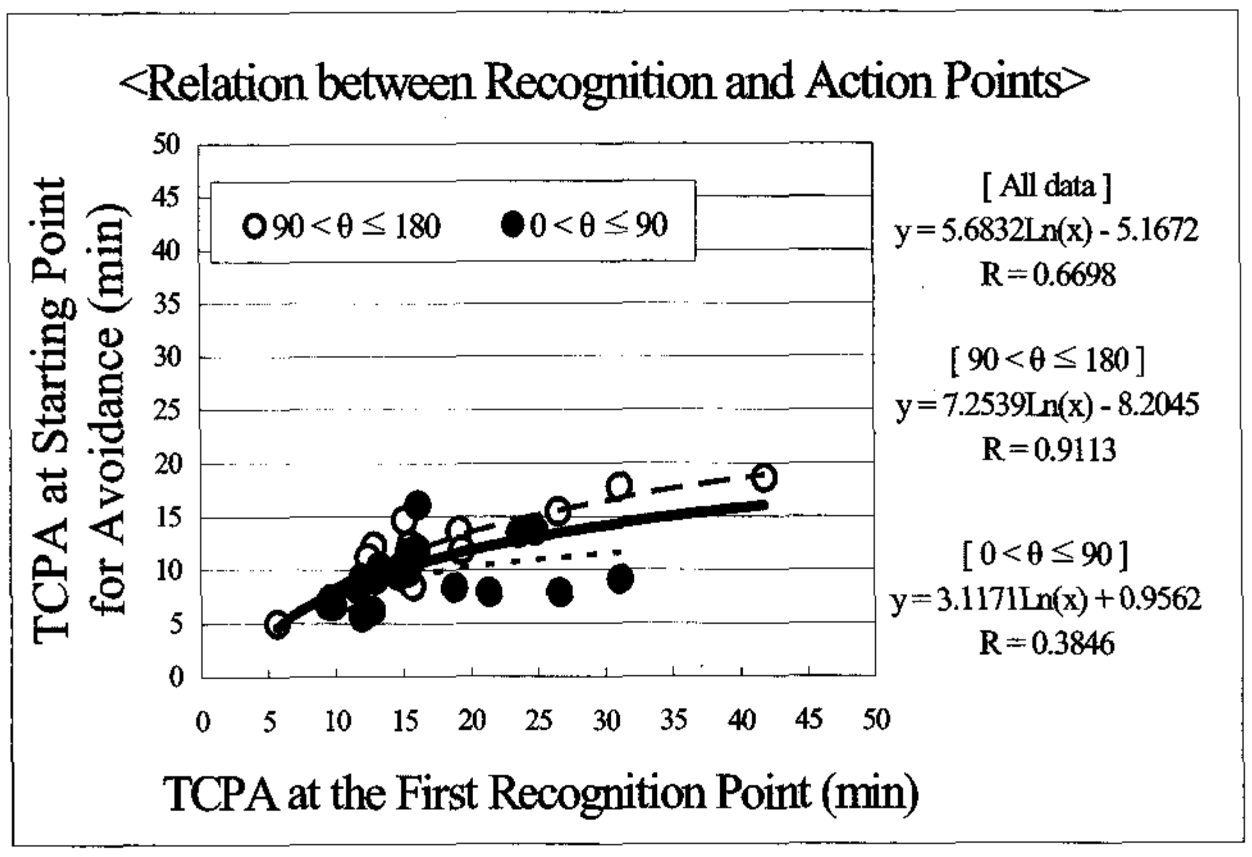


Fig. 4 Relation between Recognition Points, Starting Points for Avoidance and Crossing Angle (min-min)

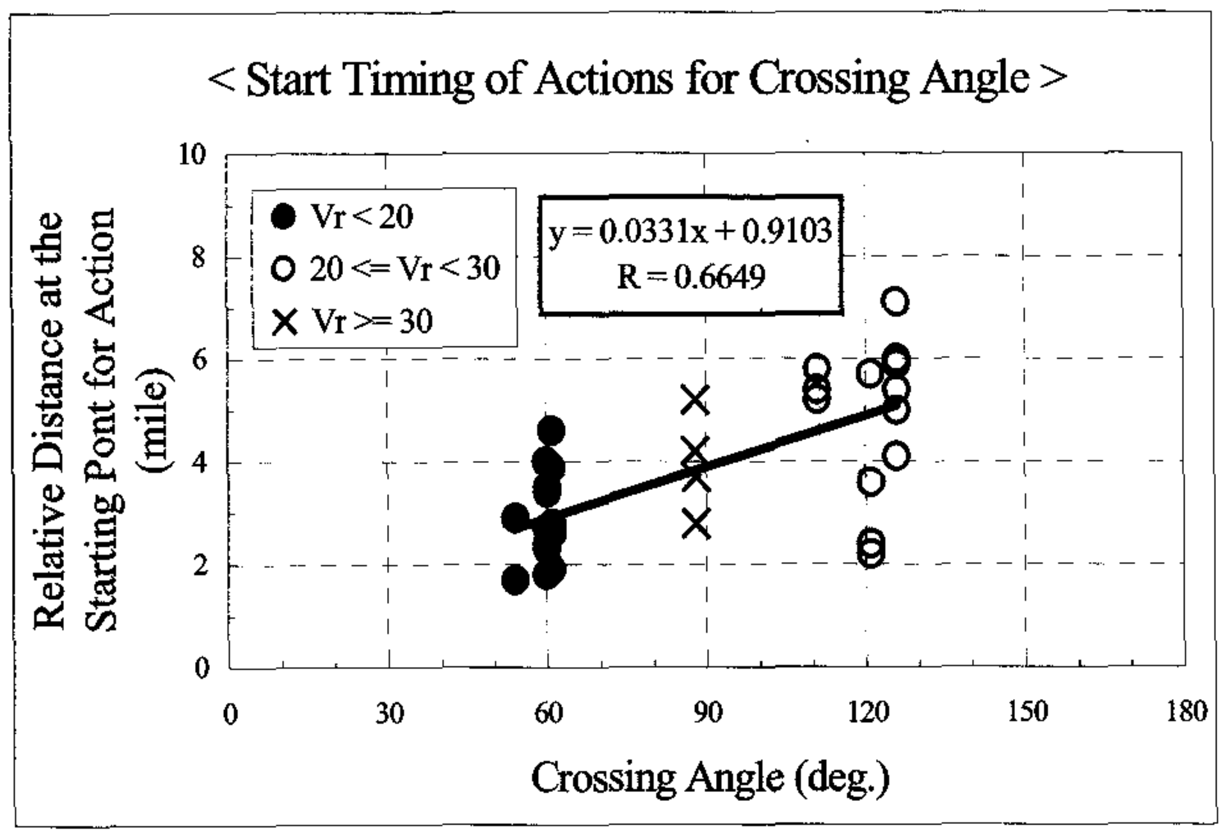


Fig. 5 Relation between Crossing Angle, Relative Speed and Starting Points for Avoidance (NM-deg.)

Thus it can be understood that mariner's behavior on the relation between the action points and crossing angle in execution process relates with the exclusive area mentioned above. The relation between the crossing angle and the relative distance at the starting point for action can be expressed by equation (6) as shown in Fig. 5.

$$A_{DIS} = 0.0331 \times Ln(\Theta) - 0.9103 \quad (6)$$

(4) The relation between Θ, ADIS and ϕ

Fig. 6 shows the relation between crossing angle, maximum altered heading angle and action points. The correlation coefficient (R) between the crossing angle and the maximum heading angle altered from the original course for collision avoidance is 0.541941. It is shown that the bigger the crossing angle is, the smaller maximum heading angle altered from the original course becomes. And the value of the maximum heading angle is, at least, 30 when the crossing angle is bigger than the degree of 90 and, at least, 10 when the crossing angle is smaller than the degree of 90. That is, there is a tendency that mariners take an avoiding action in a smaller angle to the target ships approaching with big crossing angle and in a bigger angle to the ones approaching with small crossing angle. In other words, it can be understood that the necessary altering angle for each direction to avoid collision is different and mariners have to alter their ships with the necessary angle to maintain the exclusive area when they are give-way ships. The relation between the crossing angle and the maximum altered heading angle can be expressed by equation (7) as shown in Fig. 6.

$$\phi = -0.4445\times\Theta+86.258 \tag{7}$$

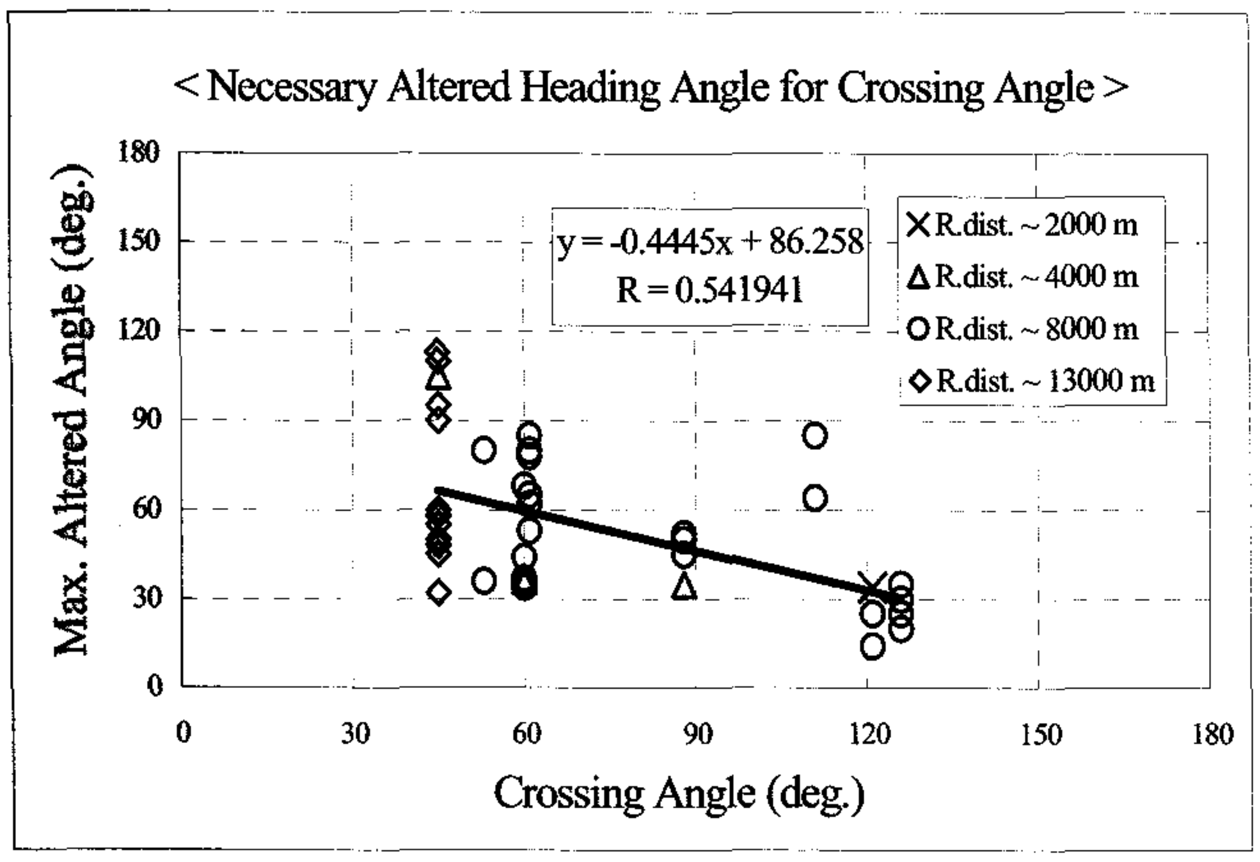


Fig. 6 Relation between Crossing Angle, Maximum Altered Heading Angle and Starting Points for Avoidance (deg.-deg.)

Moreover, according to the research of numerical simulation on necessary altering heading for crossing angle in case same "CP_O", the necessary altering angle becomes more when the crossing angle becomes smaller (Iwanaga et al., 2005). And the necessary altering angle for smaller crossing angle becomes bigger drastically when the CP_O and the R. dist. become smaller. An example of necessary altering heading for each crossing angle is shown in Table 1, which is obtained from the numerical simulation when the CP_O is the same as 3000 m (Iwanaga et al., 2005).

Table 1 Necessary Altering Heading for Crossing Angle

Crossing angle	45	90	135	180
Altering heading	66.5	30.72	14.34	6.25

(5) The relation between Ta, DCPA, Θ and L (Park et al., 2007b)

Fig. 7 shows the relation between DCPA, starting points of avoiding action and crossing angle. The correlation coefficient (R) between the start time of avoiding action and DCPA/L is 0.4243. The DCPA/L is the ratio of DCPA to the own ship's length (L), which means the distance of the closest point to the target ship in related to the own ship's length. The relation shows that earlier avoiding action and larger size of the own ship can make the DCPA bigger. And also, there is a tendency that mariners keep the distance of CPA to the target ship that is, at least, more than 5 times of the own ship's length. Furthermore, the values of crossing angle make different DCPA/L at the same start time of action points. In encountering situation that the crossing angle between the ships is big, DCPA/L is distributed in smaller value than the ones that the crossing angle is small. That is, mariners tend to accept closer distances to the target ships encountering with big crossing angle than the ones with small crossing angle. In other words, we can understand that mariners tend to make the passage situation keep the shape of exclusive area.

The relations between the DCPA, the start time of the avoiding action and the own ship's length can be expressed by equations (8)~(10) as shown in Fig. 7, respectively. When crossing angle is bigger than 0 and less than 90, the equation on the relation between the DCPA, the start time of the avoiding action and the own ship's length is as follows.

$$DCPA = (1.4735\times Ta+1.3705)\times L,\quad 0 < \Theta \le 90 \tag{8}$$

When crossing angle is bigger than 90 and less than 180, the equation on the relation between the DCPA, the start time of the avoiding action and the own ship's length is as follows.

$$DCPA = (0.4193\times Ta+4.3244)\times L,\quad 90 < \Theta \le 180 \tag{9}$$

And the relation between the DCPA and the own ship's length can be expressed by equation (10).

$$DCPA > 5\times L \tag{10}$$

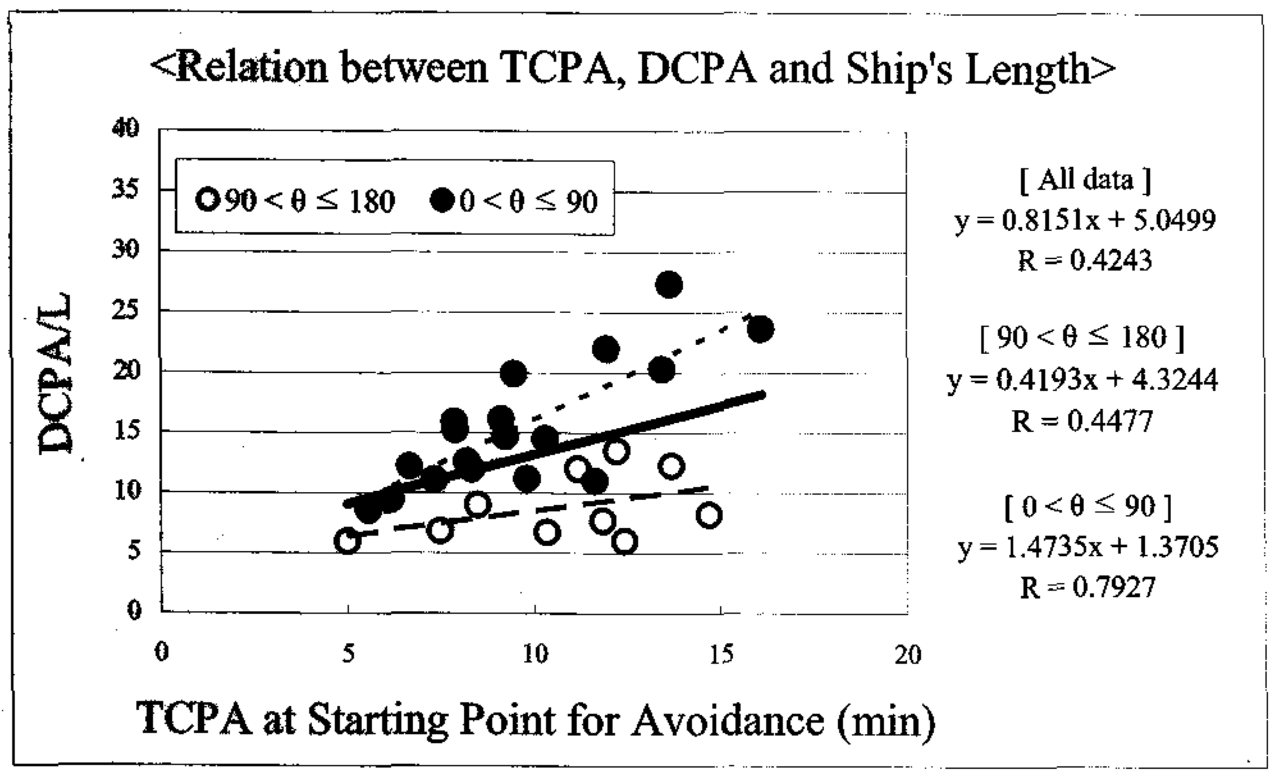


Fig. 7 Relation between DCPA, Starting Points for Avoidance and Crossing Angle (NM/L-min)

(6) The relation between Ta, PDIS, Θ and L (Park et al., 2007b)

Fig. 8 shows the relation between passing distance, start points of avoiding action and crossing angle. The correlation coefficient (R) between the start time of avoiding action and P_{DIS}/L is 0.5175. The P_{DIS}/L is the ratio of passing distance to the own ship's length (L), which means the distance of target ship to the own ship at the position where the target ship passes the own ship's bow line. The relation shows that earlier avoiding action and larger size of an own ship can make the passing distance bigger. Furthermore the value of crossing angle can makes different P_{DIS}/L at the same start time of action points. In encountering situation when the crossing angle between the ships is big, the P_{DIS}/L is distributed in bigger value than the ones that the crossing angle is small. And also, there is a tendency that mariners keep the passing distance to the target ship that is, at least, more than 10 times of the own ship's length. The relations between the passing distance, the start time of the avoiding action and the own ship's length can be expressed by equations (11)~(13) as shown in Fig. 8, respectively. When crossing angle is bigger than 0 and less than 90, the equation on the relation between the passing distance, the start time of the avoiding action and the own ship's length is as follows.

$$P_{DIS} = (1.4601 \times Ta + 9.1361) \times L, \quad 0 < \Theta \leq 90 \qquad (11)$$

When crossing angle is bigger than 90 and less than 180, the equation on the relation between the passing distance, the start time of the avoiding action and the own ship's length is as follows.

$$P_{DIS} = (1.9324 \times Ta + 9.5294) \times L, \quad 90 < \Theta \leq 180 \qquad (12)$$

And the relation between the passing distance and the own ship's length can be expressed by equation (13).

$$P_{DIS} > 10 \times L \qquad (13)$$

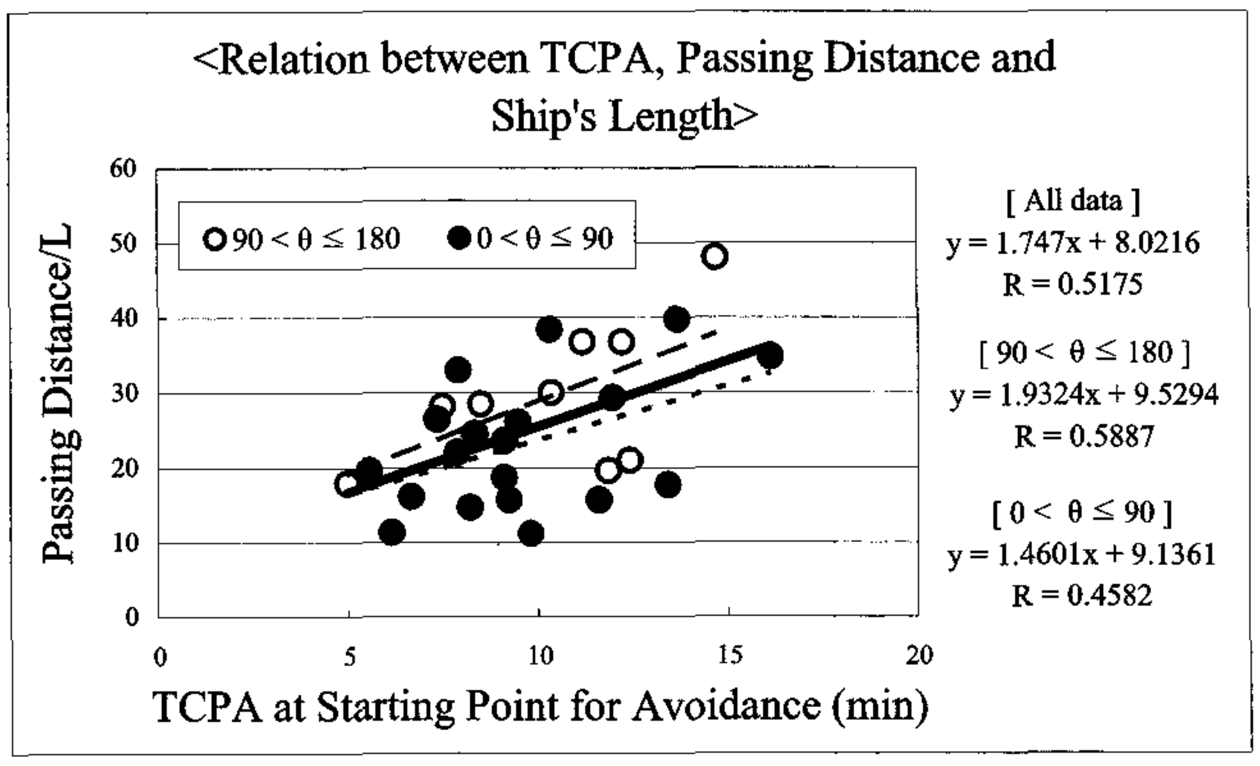


Fig. 8 Relation between Passing Distance, Starting Points for Avoidance and Crossing Angle (NM/L-min)

(7) The relation between the own ship and target ships at the passage situation

Fig. 9 shows "The relation between the own ship and target ships at the closest point of approach", which is the distribution of the positions where the CPA are occurred. The center is the position of the own ship and each point is the position of the target ships at the closest point of approach. It is distributed that most target ships are in bow side of the own ship when the CPA is occurred.

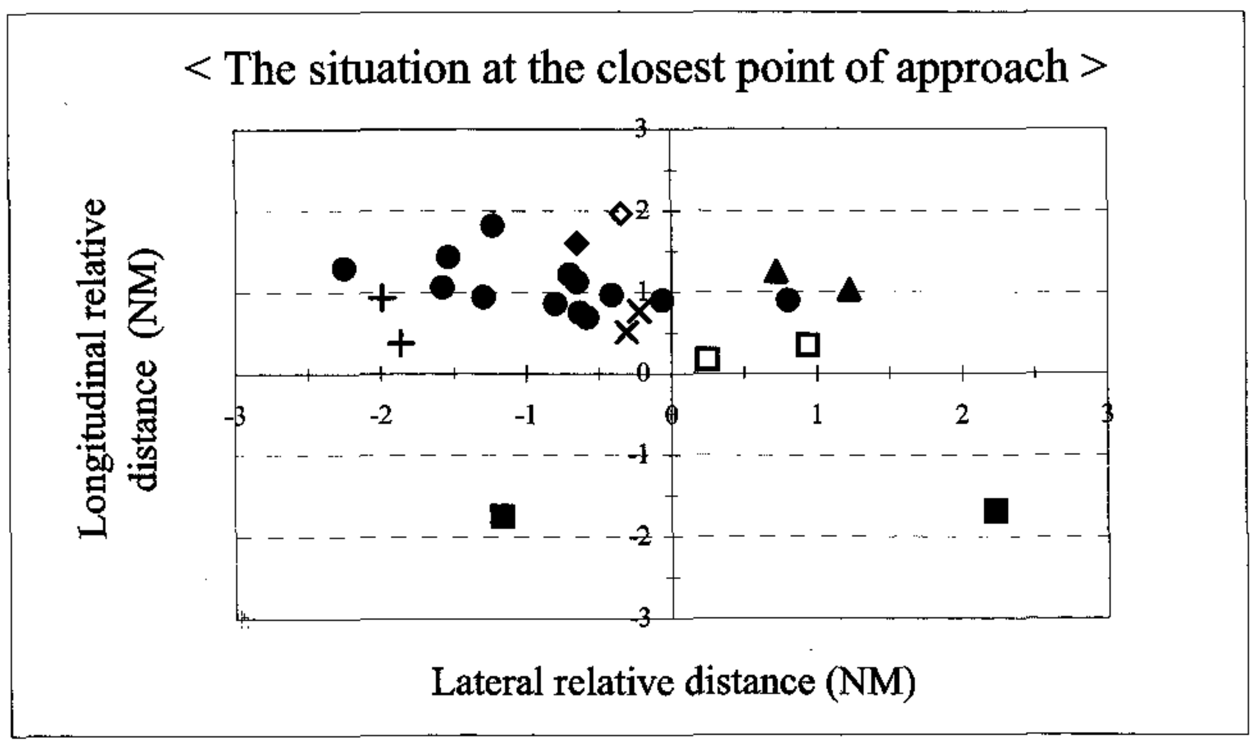


Fig. 9 Polar Diagram for the situation at the closest point of approach

Fig. 10 shows the direction that the own ship passes the target ship (bow side or stern side) at the passing situation. It is shown that the number of passage that the own ship passes the target ship's stern side is 50 and that the own ship passes the target ship's bow side is 2. That is, 96 percentage of mariners control the own ship to pass the target ship's stern side. In other words, there is a tendency that the majority of mariners take an avoiding action for their operating ships to pass the target ship's stern side when they are give-way vessels.

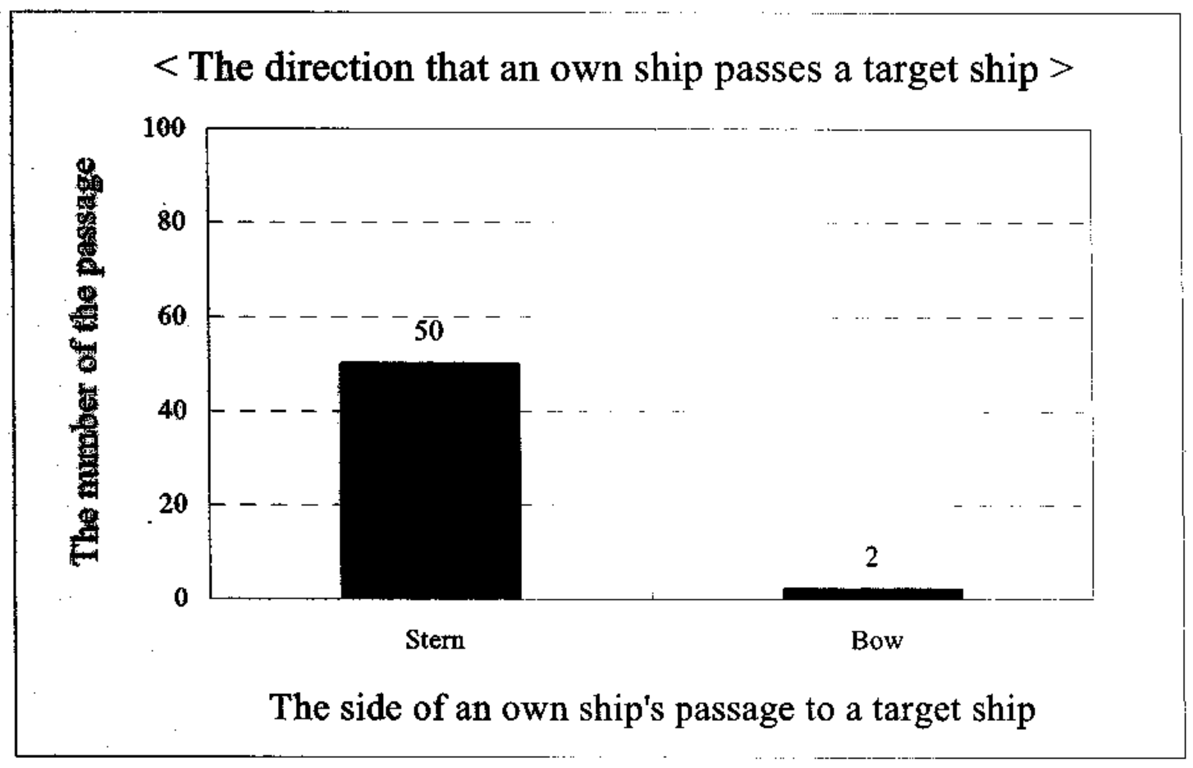


Fig. 10 Direction that an own ship passes a target ship in the passage situation

As shown in Fig. 9 and Fig. 10, therefore, it can be considered that most mariners control their operating ships to pass the target ship's stern side, but occasionally they pass the target ship's bow side when considering it has enough distance to pass from the position the target ship approaches.

4. Conclusion

We have built a model for mariner's behavior in execution process by applying the results of the collaborative research on human factors in ship handling. The followings are obtained as a result.

① The start time of an avoiding action can be affected by the recognition time of a target ship in collision situation. And when mariners recognize the target ship in an early stage, they take the proper time to avoid; however, in case of their recognition is late, they start to avoid as soon as possible.

② When an own ship is a give-way vessel and the altering course for collision avoidance is required, mariners take an avoiding action to make port to port passing according to the COLREGs and they control the ship to secure the exclusive area from the target ship. In order to secure the area, they alter her course to the necessary heading angle, which can be decided by the distance to collision point, the relative distance and crossing angle between the own and target ship;

- The necessary altering angle becomes more when the crossing angle becomes smaller.
- The necessary altering angle for smaller crossing angle becomes more drastically when the distance from the own ship to estimated collision point and the relative distance between the ships become smaller.

③ Mariners keep such an avoiding action until they confirm the safety. They tend to pass on the stern side of the target ship in general. When there is enough distance from the target ship, however, they may maneuver an own ship to pass the bow side of target ship.

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Received 2 May 2008
Revised 28 May 2008
Accepted 20 June 2008