

# Qualitative and Quantitative Analysis of Congested Marine Traffic Environment – An Application Using Marine Traffic Simulation System

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**ABSTRACT:** Difficulty of sailing is quite subjective matter. It depends on various factors. Using Marine Traffic Simulation System (MTSS) developed by Osaka University this challenging subject is discussed. In this system realistic traffic flow including collision avoidance manoeuvres can be reproduced in a given area. Simulation is done for southward of Tokyo Bay, Strait of Singapore and off-Shanghai area changing traffic volume from 5 or 50 to 150 or 200% of the present volume. As a result, strong proportional relation between near-miss ratio and traffic density per hour per sailed area is found, independent on traffic volume, area size and configuration. The quantitative evaluation index of the difficulty of sailing, here called risk rate of the area is defined using thus defined traffic density and near-miss ratio.

## 1 INTRODUCTION

Recently, marine traffic is congested and complex according to the increasing of marine traffic volume, high speed ships, and larger ships. Accordingly, navigators and captains are stressed more. As the result, it is supposed to increase accidents such as collisions between ships and so on. Once an accident happens, not only ship, cargo, and human are lost, but also it is influenced on the local economy and environment because of load and oil spillage. Therefore, evaluating the difficulty of sailing is necessary in order to design routes and improve the safety in marine. On the difficulty index of sailing in marine, some methods are suggested. In this paper, a method using marine traffic simulation system is used.

For reproducing marine traffic flow, so-called macro simulation such as the network simulation is used, but nowadays so-called micro simulation where individual ships are directly controlled, is used. In

most cases, ships are sailing according to the predefined planed route, but there are some methods where ships can avoid collisions according to the situation. Marine Traffic Simulation System (abbreviating as **MTSS** hereafter) (Hasegawa (*et al.*) 1987, 1989, 1990, 1993, 1997, 2000, 2001, 2004a, 2004b, 2008, 2010, 2011, 2012a, 2012b), which is developed in Osaka University and used in this study, has this feature. It applies fuzzy reasoning to predict collision risk using *DCPA* and *TCPA*, and can treat multiple ship encounter situation. Applying for several marine areas, it is proved that MTSS can reproduce the marine traffic flow in the most realistic way compared to the other existing methods. However, the result is a case study, and the sailing difficulty or danger of the area cannot be compared quantitatively among various marine areas. Therefore in this study, the indices for evaluating the difficulty or danger of sailing under the different conditions are proposed and compared among various marine areas quantitatively.

## 2 COLLISION AVOIDANCE ALGORITHM

The feature of MTSS is having automatic collision avoidance function. In this chapter, automatic collision avoidance function is briefly explained (Hasegawa 2012a).

### 2.1 Collision risk

There are many collision risk indices proposed by several researchers. Ship domain concept is probably the first concept treating it. In this study CR is used. CR is the collision risk defined by  $DCPA$  and  $TCPA$  using fuzzy reasoning. Later the definition of CR is somewhat modified and now the following definition is used. For assessing collision risk in normal (WP mode in Figure 4) condition, CR defined by  $TCPA$  and  $DCPA'$  (eq. (3)) is used.

For determining avoiding action,  $ACR$  is used to check the collision risk of the assumed avoiding action. In this case, following modified  $TCPA$  is used for calculating  $ACR$  considering individual ship manoeuvrability, especially for large ships.

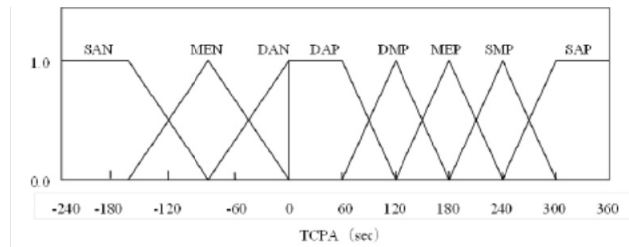


Figure 1. Membership function for  $TCPAc$  or  $TCPAv$

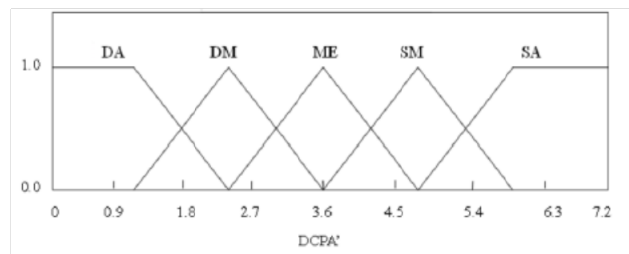


Figure 2. Membership function for  $DCPA'$

$$TCPAc = TCPA - C_c T \quad (1)$$

For determining the timing to take returning to the original path,  $VCR$  and  $OCR$  are used to check the collision risk of assumed returning action. In this case, following modified  $TCPA$  is used for calculating  $VCR$  and  $OCR$  considering rapid turn of small ships.

$$TCPAv = TCPA - C_v / T \quad (2)$$

where  $C_c$  and  $C_v$  are constants and  $T$  is the time constant of Nomoto's equation (Nomoto *et al.* 1957, Nomoto 1960) of the subject ship. In the simulation,  $C_c=2$  and  $C_v=1000$  are used based on some simulation results. These modifications are reflecting the difference of course changing ability roughly estimated from the time constant  $T$ .

$DCPA$  is non-dimensionalised using longer ship's length of two ships encountered.

$$DCPA' = DCPA / \max(L_o, L_T) \quad (3)$$

Both  $TCPAc$ ,  $TCPAv$  and  $DCPA'$  are defined by 8 and 5 linguistic variables using membership functions as shown in Figures 1 and 2 respectively, which are determined by authors' previous researches on experts knowledge and experience and both maximum values (360 and 7.2 for open sea respectively) can be modified based on the gaming area, or users can tune them as they like. Collision risk CR is defined by 8 linguistic variables and membership functions as shown in Figure 3. The reasoning fuzzy table to determine CR is provided using  $TCPAc$  and  $DCPA'$  as shown in Table 1. CR is thus defined between -1 and 1 and it is positive before passing CPA and negative after passing CPA. The absolute value is proportional to the collision risk.

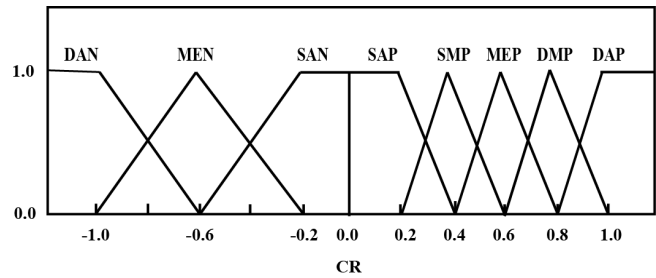
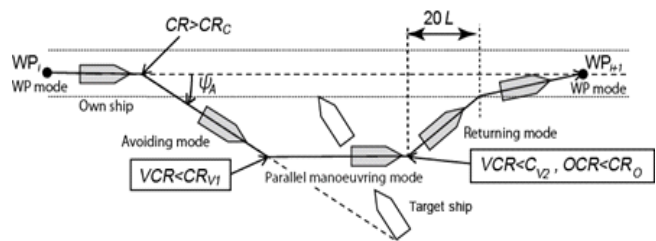


Figure 3. Membership functions for CR

Table 1. Fuzzy reasoning table for CR

	TCPA							
	SAN	MEN	DAN	DAP	DMP	MEP	SMP	SAP
DCPA'	DA	DM	ME	SM	SA			
	SAN	SAN	SAN	SAN	SAN	SAN	SAN	SAN
	SAN	SAN	SAN	SAN	SAN	SAN	SAN	SAN
	SAN	SAN	SAN	SAN	SAN	SAN	SAN	SAN
	SAN	SAN	SAN	SAN	SAN	SAN	SAN	SAN



Figures 4. Procedure of collision avoidance manoeuvre

Table 2. Simulation conditions

Simulation Area	Traffic Volume (%)
Southward of Tokyo Bay	50-200
Strait of Singapore	5-150
Off Shanghai Area	5-150

## 2.2 AVOIDING ACTION STRATEGY

The own ship will start avoiding when CR is equal or greater than  $CR_c$ .  $CR_c$  is  $CR_s(0.7$  in the system) for the

give-way situation and  $CR_s$  (0.9 in the system) for the stand-on situation. After detecting the collision risk reaches to the criteria, each ship will take a collision avoidance action. Once avoiding mode started, the ship will take avoiding action normally by turning right. The angle of course change will be determined by  $ACR$ .  $ACR$  is  $CR$  assuming the present heading angle as this angle plus the course changing angle  $\Psi_A$ .  $\Psi_A$  is chosen 30 deg. first, but if  $ACR$  is bigger than  $CR_c$ , it will be increased every  $\Delta\Psi_A$  ( $= 5$  deg. in the system) and repeated until  $ACR$  becomes lower than  $CR_c$  but it stops at 45 deg. in the maximum. After  $\Psi_A$  is fixed, the own ship will change course to  $\Psi_A$ . Once getting in the avoiding mode, the system is checking  $VCR$  continuously until it falls below  $CR_{v1}$  (0.7 in the system). If  $\Psi_A$  reaches 45 deg. and  $ACR$  is still larger than  $CR_c$ , void course changing and reduce speed to half of the present speed.

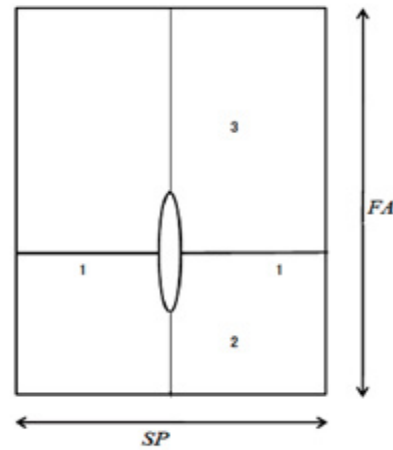


Figure 5. The definition of ship domain in harbour area (Inoue 1994)

### 3 SIMULATION CONDITIONS

In order to quantitatively assess and compare the difficulty of sailing, simulations are done for southward of Tokyo Bay, Strait of Singapore, and off Shanghai. Simulation time is 24 hours and the number of individual simulations is five times. Traffic volume is chosen in various percentage of the real traffic volume as shown in Table 2.

### 4 ASSESSMENT USING NEAR-MISS

In this chapter, quantitatively assessing the difficulty of sailing in individual areas is explained.

#### 4.1 Near-miss

On evaluating the difficulty of sailing by MTSS, the number of near-misses is proposed as an index. A near-miss is defined that it occurs WHEN  $CR \geq 0.7$  AND other ship exists within a rectangular area of  $FA$  height and  $SP$  width around the own ship, where  $FA$  and  $SP$  are defined for harbour area by Inoue (1994) as

$$FA = (0.0015 \times L_T + 2.076) \times L_O \quad (4)$$

$$SP = (0.008 \times L_T + 0.667) \times L_O \quad (5)$$

Figure 5 shows this area and the numbers in the figure is the ratio of the position of the own ship dividing this rectangular.

#### 4.2 Assessment examples using near-miss as an index

The number of near-misses  $NM$  for the simulation done for three areas for 100% traffic volume is shown in Figure 6. For each area five-time trial results are individually shown. The number of near-misses in Strait of Singapore is about 20 times and that of off-Shanghai area is about 70 times compared with that of southward of Tokyo Bay respectively. Does it mean the difficulty of the area is also proportional to this number?

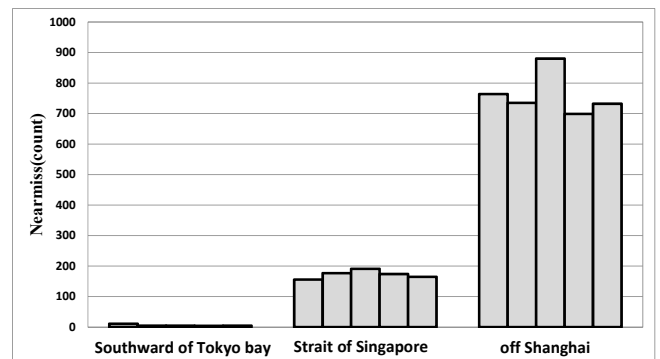


Figure 6. The number of near-misses by simulation

### 5 ASSESSMENT USING TRAFFIC DENSITY AND NEARMISS RATE AS INDICES

In previous chapter, the difficulty of sailing is discussed quantitatively using the number of near-misses. However, it is difficult to compare, because the number of ships and the area size, configuration and so on are different.

#### 5.1 Traffic density and Near-miss rate

In order to assess the difficulty of sailing on the same conditions in any marine area, number of ships, and near-miss count per the unit time and size of area, which are defined as traffic density  $TD$  and near-miss rate  $NR$ . In this study, the unit time is 1 hour and the unit size of area is 1 mile<sup>2</sup>. Next discussion is how to

evaluate the definition of the size of the area  $A$ . It is defined as the number of the unit rectangular areas where at least once by a ship or ships pass. In the case of Figure 7, the number of rectangular areas is 13, so number of ships  $NS$  is 2,  $A$  is 13 mile<sup>2</sup> and time of simulation  $T_s$  is number of hours taking both ships to pass this area in hours.

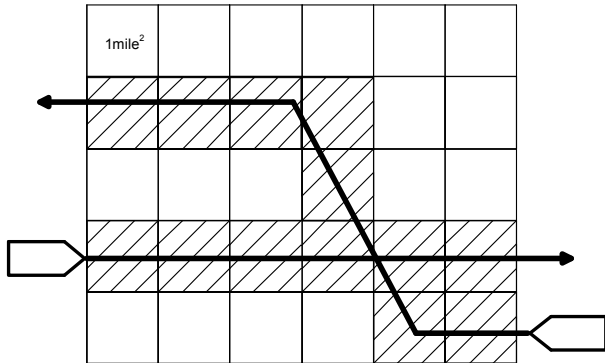


Figure 7. The example how to measure the size of the area

Using this method, the formula of Traffic density  $TD$  and Near-miss rate  $NR$  are defined as follows.

$$TD = \frac{NS}{A} \quad (6)$$

$$NR = \frac{NM}{T_s \times A} \quad (7)$$

### 5.2 Assessment examples using Traffic density and Near-miss rate

Under the conditions shown in Table 2, the results of near-miss rate  $NR$  is plotted versus traffic density  $TD$  in logarithm scale (Figure 8). The straight line in the figure is an approximate line fitting the simulation results. Although the areas are quite different in their size, configuration and traffic volume, the near-miss rate  $NR$  including the artificial variation of traffic volume is surprisingly proportional to the traffic density  $TD$ .

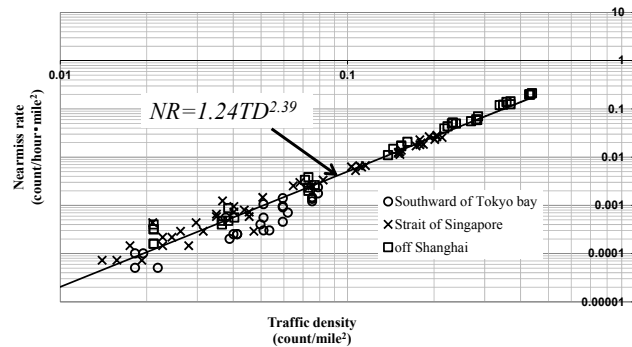


Figure 8. The relation between traffic density and Near-miss rate by simulation

## 6 ASSESSMENT USING RISK RATE OF THE AREA

In previous chapter, the strong relation between near-miss rate and traffic density is shown. However, it is still difficult to evaluate how much dangerous the area is. Are there any threshold values for the traffic density and the near-miss rate?

### 6.1 The definition of Risk rate of the area

To answer this question, an assumption is considered. Suppose all ships in the area feel dangerous (= near-miss), every time they meet other ships. This means the near-miss rate is  $O(NS^2)$ , where  $O()$  is the order and  $NS$  is the number of ship in the area.

This is the maximum near-miss rate to be expected. The ratio of the near-miss rate to this maximum near-miss rate defined as  $MNR$  will be a measure to evaluate the risk of the area. Therefore the risk ratio of the area  $RRA$  can be defined as

$$RRA = \frac{NR}{MNR} = \frac{1.24TD^{2.39}}{TD^2} = 1.24TD^{0.39} \quad (8)$$

### 6.2 Assessment example by using Risk rate of the area

Maximum near-miss rate  $MNR$  is added in Figure 9 and compared with Figure 8. Table 3 shows the risk rate of the area  $RRA$  thus estimated for each area at 100% traffic volume using equation (8), although the actual simulation results are somewhat more and less around these values. The difficulty of sailing in Strait of Singapore is about 1.7 times, and that of off-Shanghai are 2.1 times compared with that of southward of Tokyo Bay respectively. As  $MNR$  is extreme condition, from the safety point-of-view,  $RRA$  had better to be kept as low as possible and the value of off-Shanghai area seems quite close to the dangerous zone.

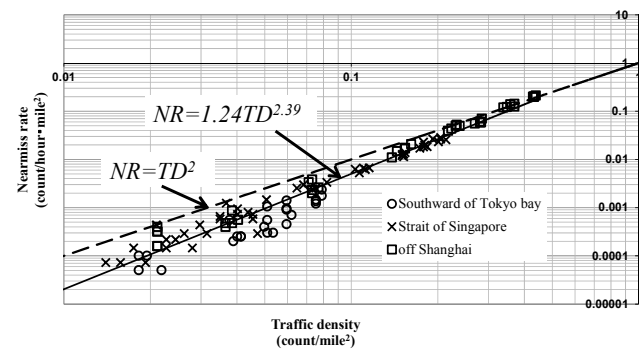


Figure 9. The traffic volume allowance degree

Table 3. Risk rate of the area by simulation results

Simulation Area (traffic volume)	Risk Rate of the Area
Southward of Tokyo Bay (100%)	0.35
Strait of Singapore (100%)	0.59
Off-Shanghai area (100%)	0.75

## 7 CONCLUSIONS

The difficulty of sailing is discussed in this paper. The proposed index of the difficulty of sailing is independent and quantitative for the area. Conclusions are summarized as follows.

- 1 *Near-miss rate* is strongly proportional to *traffic density*.
- 2 *Risk rate of the area* is defined and expressed the difficulty of sailing independently from the area size, configuration and traffic volume and quantitatively.
- 3 To determine the maximum allowance of *risk rate of the area*, further discussion should be done continuously.

## 8 NOMENCLATURE

[Symbol] [Definition] [(Unit)]

$ACR$	Collision risk assuming taking considered avoidance manoeuvre (-)
$A$	Areas where ships sail in the simulation at least once in a unit (1 mile <sup>2</sup> ) area (mile <sup>2</sup> ) ( <i>cf.</i> Figure 7)
$C_c$	Constant to evaluate $TCPA_c$ taking account of time constant $T$ (-)
$CPA$	Closest point of approach
$CR$	Collision risk calculated from $TCPA$ and $DCPA$ using fuzzy reasoning (-)
$CR_c$	$CR$ threshold for changing manoeuvring mode to avoiding mode from waypoint mode (-)
$CR_g$	$CR_c$ for give-way ship (-)
$CR_o$	$CR$ threshold for changing manoeuvring mode to returning mode from parallel manoeuvring mode (-)
$CR_s$	$CR_c$ for stand-on ship (-)
$CR_{v1}$	$CR$ threshold for changing manoeuvring mode to parallel manoeuvring mode from avoiding mode (-)
$CR_{v2}$	$CR$ threshold for changing manoeuvring mode to returning mode from parallel manoeuvring mode (-)
$C_v$	Constant to evaluate $TCPA_v$ taking account of time constant $T$ (-)
$DCPA$	Distance to closest point of approach (m)
$DCPA'$	Non-dimensionalised $DCPA$ (-)
$L, L_o, L_T$	Ship length in general, that of own ship and that of target ship (m)
$MNR$	Maximum near-miss rate (1/mile <sup>2</sup> hour)
$MTSS$	Marine Traffic Simulation System developed by Osaka University as a kind of marine traffic simulation system taking account of collision avoidance manoeuvres
$NM$	The number of near-misses in the simulation area and time (-)
$NR$	Near-miss rate (1/ mile <sup>2</sup> hour)
$NS$	The average number of ships existing in the simulation area (-)
$OCR$	Collision risk assuming taking returning manoeuvre (-)
$RRA$	Risk ratio of a area (-)
$T$	Time constant of a ship for manoeuvring (sec)
$TCPA$	Time to closest point of approach (sec)

$TCPA_c$	$TCPA$ for $CR$ evaluation (sec)
$TCPA_v$	$TCPA$ for $VCR$ evaluation (sec)
$TD$	Traffic density defined (1/mile <sup>2</sup> )
$T_s$	Simulation time (hour)
$VCR$	Collision risk assuming taking parallel shift manoeuvre (-)
$\psi_A$	Course changing angle in avoiding mode (deg)
$\psi_{TA}$	Relative angle to target ship measured from own ship stern (deg)
$\psi_{TE}$	Encounter angle of target ship measured from own ship bow (deg)

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