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Research on Capacity of Mixed Vessels Traffic Flow Based on Vessel-Following Theory

C. Zhao[1], H. Yan[1], G. Zhou[2] & T. Liu[3]
1 Merchant Marine College, Shanghai Maritime University, Shanghai, China
2 Wusong Maritime Administration, Shanghai, China
3 Communication and Transportation College, Shanghai Maritime University, Shanghai, China

ABSTRACT: In order to study the characteristics of mixed vessel traffic flow, based on classical head distance model and probability analysis, by studying the combination time head way of different vessel-following sequences, the capacity model of mixed vessels traffic flow was established. Through analyzing two representative types of vessels, research results indicate that the capacity of mixed traffic increase with the traffic flow speed in a certain speed range, but the increasing trend slow down. The closer length and inertial stopping distance of different kind vessels are, the more capacity of mixed traffic increases. And the influence of reaction time on the capacity is related to proportion of different kind vessels.

1 INTRODUCTION

In the maritime traffic engineering, traffic capacity refers to the capacity of a channel to manage vessel, which is measured by the maximum number of vessels passing through in a certain time [1]. At present, the formulas for calculating the passage capacity mainly include the West German formula, the Polish formula, the Yangtze River formula and the Changjiang formula. Its common characteristic is that a series of parameters need to be analyzed and determined according to the actual situation and data of the channel. The value of parameters varies from person to person and is highly subjective, which leads to the non-standard calculation of channel passing capacity. Moreover, existing studies on channel passing capacity often take traffic flow velocity and vessel density as fixed values without considering their mutual influence, and lack of further study on their internal traffic characteristics and mechanism [2][3].

The study of traffic flow theory shows that flow rate, velocity and density are a kind of dynamic equilibrium relation vessel. In recent years, some scholars have been aware of the deficiencies in the previous studies on channel passage ability, and have begun to make a preliminary discussion on channel passage ability using the macroscopic traffic flow theory. Shao Changfeng made a preliminary dynamic exploration and analysis of vessel traffic flow by applying fluid model [4]. Using the research method of highway traffic for reference, He Liangde and Zhu Jun established the direct functional relation vessel between vessel density and vessel speed by using the following theory, and strengthened the analysis of vessel traffic mechanism [5][6]. However, the above researches are limited to the analysis of a single vessel type in the waterway. In practice, due to the different sizes and types of vessels in the channel, the sequence composition of vessel following in the mixed vessel flow is also random, resulting in different vessel spacing, which has a great impact on the channel passage capacity. Therefore, it is significant to study the passage capacity in the case of mixed traffic flow.

2 THEORETICAL MODEL OF VESSEL FOLLOWING

The car following theory is a dynamic study model of the following vehicle's corresponding behavior caused by the change of the leading vehicle's motion. The characteristics of single-lane traffic flow are understood by analyzing each vehicle following each other so as to connect the microscopic behavior of vehicles with the macroscopic phenomenon of traffic flow. This model has been widely applied in micro-traffic simulation, self-cruise control, capability analysis, traffic safety evaluation and other fields [7].

2.1 *Fundamental assumption*

The vessel following model in the channel is based on the following hypothesis: a group of vessels navigate one by one, the officer only responds to the action of the front vessel. The movement of the response is accelerating or decelerating, and there is no overtaking. Channel width and lateral interference are ignored.

In addition, from the perspective of safety, the following vessel should meet two requirements. Firstly, the speed of the behind vessel should fluctuate around the speed of the front vessel, and not greater than that of the front vessel for a long time. Secondly, a safe distance must be kept between the front and behind vessel to make sure that there is enough time for the behind vessel officer take action to responding [8].

There are two means for vessel to brake, stop engine and reverse engine. Generally speaking, the reverse engine will cause the vessel's bow to turn uncontrollably under the influence of the deep transverse force, the discharge transverse force, the wind and current force, the shallow water effect or the bank effect when the vessel navigating on the channel. In addition, emergency reverse engine will cause the main engine rotating parts stress too much. Therefor vessels usually braked by stop engine.

2.2 *Prow time - distance model based on stop engine*

The prow time - distance model that applied to analyze the following up of vessels as shown in figure [9][10]. *n* is the front vessel, *n+1* is the behind vessel $x_n(t)$ and $x_n+1(t)$ is the position of two vessels. t_m is the responding time, which include the officer responding and action time and the engine receiving command time. d_1 is the distance that vessel navigating with the original speed in a certain time t_m. d_2 is stop stroke of the behind vessel, d_3 is stop stroke of the front vessel, ε is the lee-way factor, m_0 is the safety margin after the two vessels stop [11].

From the figure 1, To ensure the safety of the two vessels after stop engine, it should meet the requirement:

$$d_1 + d_2 - d_3 \geq \varepsilon m_0 \tag{1}$$

In critical condition：

$$x_n(t) - x_{n+1}(t) = d_1 + d_2 + \varepsilon m_0 - d_3 \tag{2}$$

$$d_1 = t_0 v \quad \text{(v is the speed before decelerate)} \tag{3}$$

So:

$$x_n(t) - x_{n+1}(t) = t_m v + \varepsilon m_0 + d_2 - d_3 \tag{4}$$

Corresponding distance of the bow is:

$$h_t = \left[x_n(t) - x_{n+1}(t) \right] / v \tag{5}$$

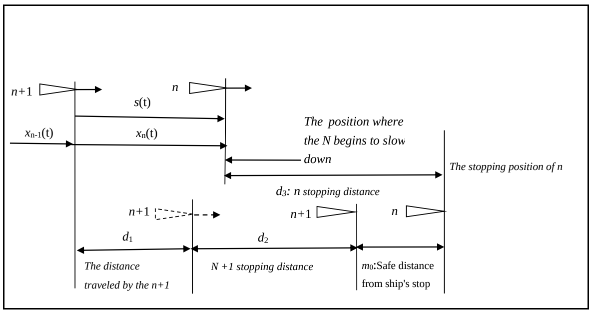

Figure 1. The follow theoretical analysis diagram

3 MIXED TRAFFIC FLOW CAPACITY MODEL

3.1 *Mixed traffic flow capacity calculation model*

Let $h_{i,j}$ is the bow distance of the combined two vessels. *i* is the front vessel, *j* is the behind vessel, *i,j=1,2……r*. Because the vessel type of two adjacent vessels in the traffic flow is random, the probability of the front vessel and the behind vessel *j* is $p_i p_j$, and:

$$\sum_{i=1}^{r} \sum_{j}^{r} p_i p_j = \left(p_1 + p_2 + \cdots p_r \right)^2 = 1 \tag{6}$$

Take the combination bow time interval h_t to represents the average minimum bow time interval under different tracking sequences of the mixed traffic flow consisting of *r* vessel types, According to the theory of probability:

$$h_t = \sum_{i=1}^{r} \sum_{j=1}^{r} p_i p_j h_{i,j} \tag{7}$$

So, it can be seen that in the calculation of mixed traffic passing capacity, it is very important to solve the interval between different vessel types.

3.2 *Bow time interval analysis of mixed traffic following*

Assume that the vessel traffic flow is composed of a mixture of large and small vessel types, the length of little vessel is *l*, the proportion is *p*, braking reaction time is *t*. The length of large vessel is *L*, the proportion is *1-p*, braking reaction time is *T*. Same speed before emergency braking. The braking distance of little vessel is *d(v)*, and that of large vessel is *D(v)*, the difference of them is *S(v)*. If there is a large vessel of the combination, the safety margin is M, otherwise, the safety margin is m. The safe distance between two vessels at rest is often expressed as a multiple of the length. Referring to the anchor distance, $M=3L$, $m=3l$ [12]. The corresponding situation as follows:

1. Both of them are large vessel.

$$x_n(t)-x_{n+1}(t)=Tv+\varepsilon M+\left[D(v)-D(v)\right] \tag{8}$$

$$h_{2,2}=\left(x_n(t)-x_{n+1}(t)\right)/v=T+\varepsilon M/v \tag{9}$$

2. Both of them are little vessel.

$$x_n(t)-x_{n+1}(t)=tv+\varepsilon m+\left[d(v)-d(v)\right] \tag{10}$$

$$h_{1,1}=\left(x_n(t)-x_{n+1}(t)\right)/v=T+\varepsilon m/v \tag{11}$$

3. A small vessel in front and a large vessel behind.

$$x_n(t)-x_{n+1}(t)=Tv+\varepsilon M+\left[D(v)-d(v)\right] \tag{12}$$

$$h_{1,2}=(x_n(t)-x_{n+1}(t))/v=T+\varepsilon M/v+s(v)/v \tag{13}$$

4. A small vessel in front and a little vessel behind. Since the large vessel has a larger inertia, it is assumed that when the large vessel is braking, the little vessel will be reducing with a same accelerated speed that belong to the large vessel.

$$x_n(t)-x_{n+1}(t)=tv+\varepsilon M+\left[D(v)-D(v)\right] \tag{14}$$

$$h_{2,1}=\left(x_n(t)-x_{n+1}(t)\right)=t+\varepsilon M/v \tag{15}$$

The average bow time interval of the traffic flow is:

$$h=p^2\times h_{1,1}+(1-p)^2\times h_{2,2}+p(1-p)\times h_{1,2}+(1-p)p\times h_{2,1} \tag{16}$$

$$C=24\times 3600v/\left[T(1-p)+tp\right]v+3\left(1-p^2\right)L+p^2l+p(1-p)s(v)] \tag{17}$$

4 MODEL PARAMETER ANALYSIS

The parameters in the above equation can be divided into two categories according to their respective ownership relationship. The one is macro traffic flow characteristics, v and p. The other one is vessel characteristics, $t_m(t,T)$, $l_m(l,L)$, $S(v)$. From the point of view of water traffic control management, the first type of parameters is more important, which will be discussed in detail below.

4.1 *The relationship of C-p*

To confirm the influence of the first type parameters, we should first confirm the value of the second type parameters. According to China's "Design Code of General Layout for Sea Ports" and the actual situation of small and medium-sized coastal ports in China, GT3000 with a total length of 96 meters and GT10,000 with a total length of 135 meters are taken as the representative ship type of bulk carrier [13]. The response time of little vessel is 10 seconds, and that of large vessel is 20 seconds [14]. ε=1. For ships, the speed of 5kn is generally the minimum speed to maintain rudder effect, and the ship braking distance is mainly determined based on this. According to the latest research results of the China transportation planning and design institute on braking distance (see table 1), when the speed before parking is 4,6,8,10kn, the ship's stopping braking distance is 2 l_m(length),5 l_m,9 lm,16 l_m [15].

When the value of p is 0.3-0.9, we can obtain the relationship of *C-p-v*. From Fig.2, we can see that as p goes up, C goes up faster and faster. That is to say, under the same vessel traffic flow speed, the larger the proportion of small vessels, the greater the channel traffic capacity.

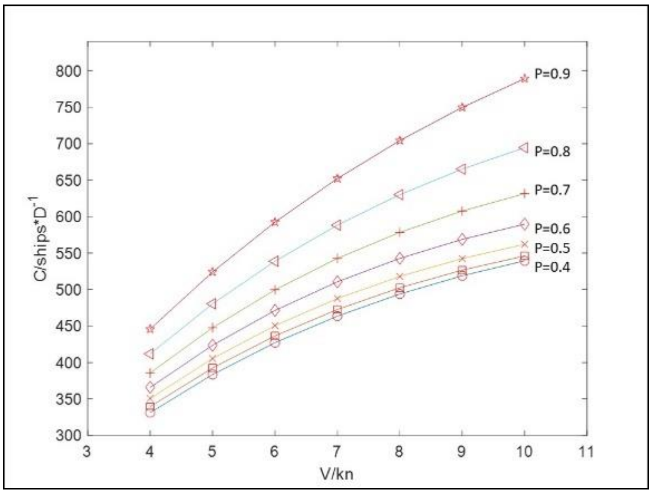

Figure 2. The relationship of *C-p-v*

Table 1. Stop engine stroke

Speed before stop engine	4~6kn	6~8kn	8~10kn
Straight-line distance (Majority concentration)	2~5lm	4~7lm	5~15lm
Mean straight-line distance	5.3lm	9lm	14.1lm
Actual distance (Majority concentration)	2~6lm	4~10lm	7~17lm
Mean straight-line distance	5.9lm	10lm	15.8lm

4.2 *The relationship of C-v*

From the Fig. 2, we can see that when p is constant, if v is smaller, C is also smaller. With the increase of v, C first grows rapidly and then slows down, and the smaller the probability is, the larger the growth rate decreases.

If the ship's stop engine brake is regarded as uniform deceleration motion, acc according to,

$$s(v)=D(v)-d(v)=v^2/2A-v^2/2a=v^2(a-A)/2aA \tag{18}$$

a is the acceleration of smaller vessel, A is the acceleration of larger vessel.

Deriving from A, When dc/dv=0,

$$v_{max}^2 = 2aA\left[\left(1-p^2\right)\varepsilon M + p^2\varepsilon m\right] / \, p\left(1-p\right)\left(a-A\right) \qquad (19)$$

From this, we can see that C is not increased by the increase of v, when, v=v_{max}, C is maximum. And from (19), v_{max} has nothing to do with the two vessels' reaction time T and t.

Under normal circumstances, the average speed of small and medium-sized vessels in channel is 8kn, the stop stroke: $m_0(v\text{=8kn})$ =9l_m.

The average acceleration of ship stop brake, a=9.3×10^{-3}m/s^2, A=6.6×10^{-3}m/s^2,

As it is difficult for the traffic flow in the channel to reach this speed, in general, with the increase of the ship traffic flow speed, it gradually increases, but the increase trend gradually slows down.

4.3 *The relationship of C-l_m, s(v) and t^m*

As for the influence of the second type of parameters, it can be seen from the 2.2 conclusion formula that with the increase of reaction time, ship length and stopping stroke, the passage capacity of mixed traffic decreases gradually. Then, the influence of the similarity degree of different types of ships on the passage capacity is analyzed.

Assuming the vessel traffic flow speed is 8kn, the original value in 3.1 is taken as the intermediate value to gradually expand and reduce the vessel type parameter interval. The results are shown as follows.

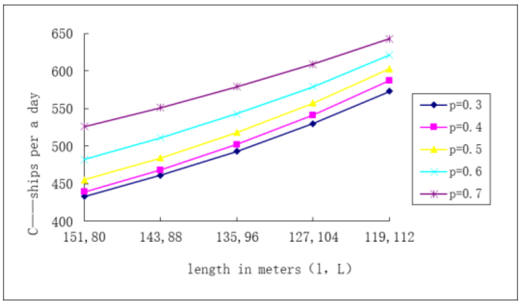

Figure 3. The relationship of C-l_m

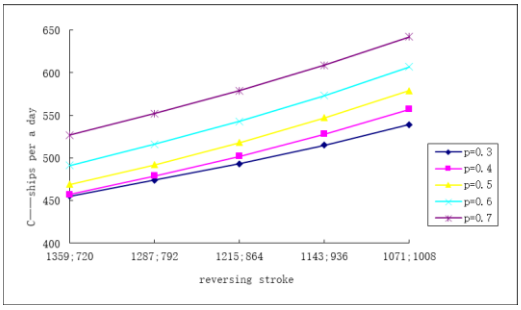

Figure 4. The relationship of *C-S(v)*

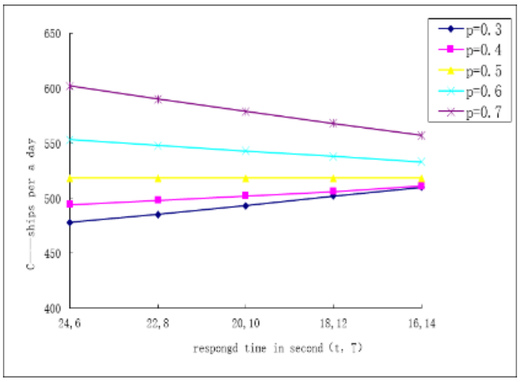

Figure 5. The relationship of *C-tm*

It can be seen from Fig. 4 and 5 that, with the narrowing of the value interval of the two ship types' length and stop stroke, the channel traffic passing capacity gradually increased. In other words, the more similar the length and stop stroke of different ship types in the channel, the greater the passing capacity.

It can be seen from Fig. 5 that, the effect of response time of different types of ships on passing capacity is related to probability (p). If p<0.5，with the decrease of the reaction time interval between the two types, the passing capacity shows a trend of gradual increase. It is reversed when p>0.5.

5 CONCLUSION

The above studies show that the mixed traffic flow passing capacity in channel is not only related to the vessel traffic flow speed and vessel type combination, but also related to the reaction time, vessel length and vessel stopping performance. Within a certain range, C is increasing with the increase of v, but the trend of increase gradually slows down. The closer the ship length and stopping stroke of different ship types are, the greater the capacity of mixed traffic to passing. At the same time, the influence of response time of different types of ships on the passing capacity *(C)* is related to probability *(p)*, and the variation trend of the passing capacity *(C)* of mixed traffic is different with different probability *(p)*.

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