Study on redefinition of traffic flow parameters and basic diagram based on ship scale

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***Abstract*—The basis and premise for the study of Fundamental Traffic Flow Diagram are the traffic flow characteristics parameters. Most of the research on maritime traffic flow is simply a direct transfer and application of knowledge from road traffic flow. However, this assumes that there is minimal difference between maritime traffic flow and road traffic flow. Obviously, this assumption is difficult to make. The scale of different types of ships varies considerably, often differing by a factor of ten or twenty, in contrast to the relatively uniform scale of road traffic vehicles. This significant variation in scale renders the results obtained from the previously defined methods for solving road traffic flow characteristic parameters unrealistic. In order to discover a method for defining traffic flow characteristics parameters that aligns better with the characteristics of maritime traffic flow, this paper first analyzes the disparities between road and maritime traffic in terms of the dimensions of the means of delivery. Building upon these distinctions, it examines the impact on maritime traffic flow parameters. Subsequently, the paper proceeds to redefine the traffic flow characteristics parameters by utilizing separate definitions for ship length and ship area, respectively, to mitigate the influence caused by these dissimilarities. Firstly, the South Channel of the Yangtze River is selected as the target, and the traffic flow characteristics parameters are calculated under various definitions using the Automatic Identification System (AIS) data of the channel. The results are then used to create a fundamental traffic flow diagram in the channel. Finally, the fundamental traffic flow diagrams produced by these definitions are compared and analyzed. This study proposes a method for defining traffic flow characteristics parameters that take into account differences in vessel scales, which can more accurately reflect the traffic status of waterways and provide a more scientific basis for water traffic management and decision-making departments.**

Keywords*—traffic flow characteristics parameters, AIS, smart waterways, ship scale , fundamental traffic flow diagram

I. Introduction

Transport is a fundamental, pioneering and strategic industry and an important service industry in the national economy, and is an important support for sustainable development. In recent years, the Chinese government has released a series of national directives to promote sustainable development in the transportation industry. These include "Sustainable Development of China's Transport," "Action Plan for the Development of Smart Ships (2019-2021)," "Outline for the Construction of a Stronger Transport Country," and the "14th Five-Year Plan for National Water Transport." These documents demonstrate the government's commitment to developing and improving the transportation sector. In particular, water transportation has become an increasingly vital component of this effort due to its high capacity, low cost, and minimal environmental impact when compared to other modes of transport.

Traffic flow theory is used to analyze the patterns of individual and collective behavior of pedestrians and motor vehicles, especially cars, on roads. This analysis involves examining the relationship between traffic volume, speed, and density to reduce traffic delays, and accidents, and improve road facilities' efficiency [1]-[3]. Most scholars' research has primarily focused on road transportation, while the development of traffic flow theory for maritime transportation has been relatively slow. Currently, most scholars study maritime transportation by drawing upon existing research in road traffic. However, significant differences exist between road and sea transportation. In the field of waterway transit capacity studies based on vessel traffic volume, it usually refers to the maximum number of standard vessels that can pass through a specific control zone during the low-water period in a given year [4]. Wang Hong-da et al. proposed an estimation approach for navigational capacity based on multiple vessel states [6], while Zhu Jun et al. investigated navigational capacity using the car-following theory [5]. Meanwhile, scholars like Liu Sai-long and Shen Min combined vessel traffic flow theory with navigational service level indicators for their research on navigational capacity [7]-[8], and Xue Han and Pei Jian-ping conducted studies on traffic flow prediction [9]-[12]. Additionally, some researchers have depicted basic traffic flow diagrams to represent road and waterway transit conditions [13]-[16]. Despite their accurate depiction of roadway transit, implementation of these diagrams in marine transportation has been less ideal, and they cannot fully depict the situation [17]. This may be due to researchers not considering the differences and characteristics between road and sea traffic during their studies. Instead, they continued to base their research on vessel quantity characteristics when studying waterborne transportation, thus neglecting the significant differences in traffic characteristics between vessels and vehicles. For example, if there are five ships at different time junctions on the same leg, in one case there are five 20m long ships and in the other case, there are five ships of about 360m. When studying traffic conditions on waterways using a methodology based on vessel counts borrowed from road traffic flow, the calculated traffic flow densities are the same for both scenarios. However, it is important to note that the latter scenario has a significantly greater impact on the navigational safety of the channel compared to the former.

We conducted separate statistical analyses on ship navigation data and vehicle travel data, respectively. We identified the differences in terms of the scale of transport vehicles between maritime traffic and road traffic, and pointed out that it is inappropriate to directly borrow quantity statistics from road traffic for statistical purposes.

1. We conducted separate statistical analysis on ship navigation data and vehicle travel data, respectively. We identified the differences in terms of the scale of transport vehicles between maritime traffic and road traffic, and pointed out that it is inappropriate to directly borrow quantity statistics from road traffic for statistical purposes.
2. We draw on the use of traffic flow characteristic parameters from road traffic to describe the traffic conditions, and incorporate ship-scale factors into these parameters to make them more applicable to maritime traffic.
3. We describe the waterway using a basic traffic flow diagram and draw traffic flow diagrams based on four statistical approaches: ship count, equivalent traffic volume, ship length, and ship area. This enables a more effective reflection of the waterway traffic conditions.

The rest of the paper is organized as follows. In section 2, we provide a detailed description of the definition and solution of traffic flow characteristic parameters obtained by considering different ship characteristics Section 3, we outline the experimental content of this paper. Finally, we conclude the study and outline possible future work in Section 4.

II. METHODOLOGY

A. Differences in scale between vehicles and vessels

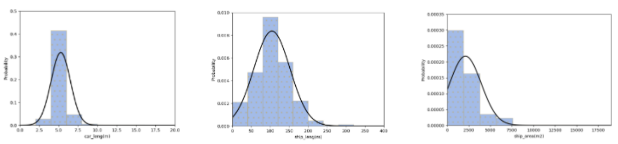
The focus of this study is on the impact of vessel scale on traffic flow parameters. To explore this, AIS data from the South Channel of the Yangtze River segment containing vessel information and vehicle information data from a certain stretch of highway were selected and analyzed statistically, as presented in Table 1. Probability density histograms were plotted to illustrate results, as shown in Figure 2.

TABLE I COMPARISON OF VEHICLE AND SHIP CHARACTERISTICS

Type	Max	Min	Mean	Std	Median	Var	Kurt	Skew	CV
Vehicle	18.2	1.363	5.281	1.25	5.282	1.563	34.347	4.121	0.2367
LOA	368	11	104.41	47.667	100	2272.299	1.148	0.551	0.4565
CSA	18768	36	2118.345	1829.667	1610.5	3347683.093	11.752	2.569	0.8637

[a] LOA: length overall,(ship length),m

[b] CSA: cross-sectional area(ship area),m²



a) Vehicle b) LOA c) CSA

Fig. 1. Probability Density Distribution Char

The average length of the vessel is 104 meters with a standard deviation of 47.6 meters; while the average length of the vehicle is 5.28 with a standard deviation of 1.25. The distribution of vessel lengths is more dispersed compared to the distribution of vehicle lengths. In addition, the variation in the area of vessels is even greater. Based on the statistical results, it can be concluded that the impact of vessel area on traffic flow parameters cannot be ignored.

To reduce the discrepancy between traffic flow studies and actual results, particularly regarding the representation of traffic conditions in waterways, we have incorporated a weighted ship size factor into the parameters of traffic flow characteristics. This approach enables a more precise analysis of maritime traffic flow and facilitates the creation of a fundamental traffic flow diagram that accurately depicts the traffic conditions in the waterway. This specific process is shown in Figure 2.

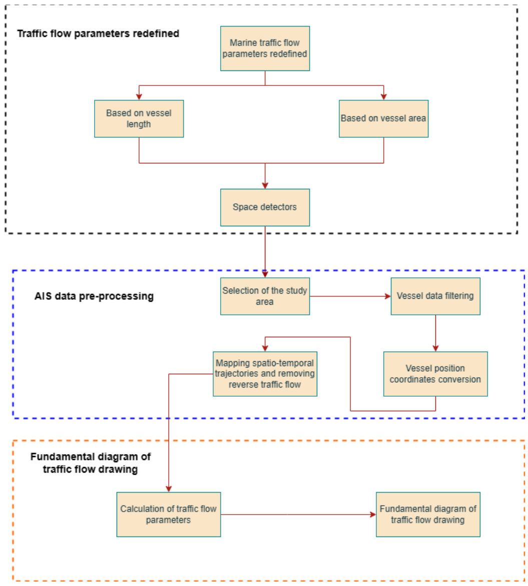


Fig. 2. technology roadmap

B. The redefinition of traffic Flow characteristics parameters

1.Redefinition of traffic flow characteristics parameters based on vessel length

The instantaneous velocity of the vessel, denoted by $\dot{x}$, represents the vessel's velocity at a certain cross-section of the waterway. The formula is:

$$\dot{x} = v_i = \frac{dx}{dt} = \lim_{(t_2-t_1)\to 0} \frac{x_2 - x_1}{t_2 - t_1} \tag{1}$$

where x_1 and x_2 are the ship's position at the moments t_1 and t_2 respectively, and the ship's speed information can be obtained from the AIS data.

Based on the vessel length, the average speed $\bar{\dot{x}}_t$ represents the arithmetic mean of the vessel's speed through a certain section during the observation period. The formula is:

$$\bar{\dot{x}}_t = \frac{\sum_{i=1}^{N} l_i \dot{x}_i}{\sum_{i=1}^{N} l_i} \tag{2}$$

where $\dot{x}$ denotes the speed of the i-th ship, N denotes the number of ships observed, and l_i denotes the length of the i-th ship.

The interval average speed $\bar{u}_l$, has two definitions:One is defined as the quotient of the average form time based on the ship length correction corresponding to a certain distance D

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travelled by the ship, which can become the empty average flow speed $\bar{u}_{s1}$, with the following equation:

$$\bar{u}_{l1} = \frac{D}{\frac{\sum_{i=1}^{N} l_i t_i}{\sum_{i=1}^{N} l_i}} \tag{3}$$

where t_i denotes the time taken by vessel i to travel distance D, and the formula is

$$t_i = \frac{D}{u_i} \tag{4}$$

The following deformation can be made, which allows the interval speed to be derived as a reconciled average of the ship's speed based on the ship's length correction for the observed leg, with the following equation:

$$\bar{u}_{l1} = \frac{D}{\frac{\sum_{i=1}^{N} l_i t_i}{\sum_{i=1}^{N} l_i}} = \frac{1}{\frac{\sum_{i=1}^{N} \frac{l_i}{\dot{x}_i}}{\sum_{i=1}^{N} l_i}} = \frac{\sum_{i=1}^{N} l_i}{\sum_{i=1}^{N} \frac{l_i}{\dot{x}_i}} \tag{5}$$

Another definition of the interval average speed is the average value of all vessel speeds, which are modified based on the vessel length, at a certain moment on a road section. It is also called the interval time-averaged flow velocity $\bar{u}_{s2}$. By receiving the AIS information of the location of a navigation segment two or more times within a very short period of time $\triangle t$, the instantaneous speed and interval average speed of all vessels can be obtained. The formula is as follows

$$\dot{x}_i = \frac{\triangle x_i}{\triangle t} \tag{6}$$

$$\bar{u}_{s2} = \frac{1}{\sum_{i=1}^{N} l_i} \sum_{i=1}^{N} \frac{l_i \triangle x_i}{\triangle t} = \frac{1}{\sum_{i=1}^{N} l_i} \sum_{i=1}^{N} l_i \dot{x}_i \tag{7}$$

where $\triangle t$ is the time interval between the two ship messages and is a constant value; s_i is the distance travelled by the ship in $\triangle t$ time.

Based on the vessel speed data obtained from the AIS data, the interval average speed obtained belongs to the interval average speed belongs to the interval hourly average flow speed $\bar{u}_{s2}$. It is obtained that:

$$v = \bar{u}_{s2} = \frac{1}{\sum_{i=1}^{N} l_i} \sum_{i=1}^{N} l_i \dot{x}_i \tag{8}$$

where v is measured in m/s.

Re-define the traffic flow parameter density k. Traffic flow density k represents the spatial density of vessels, also known as space occupancy rate, referring to the proportion of the length of vessels present in a waterway at a certain moment. Its formula is as follows:

$$k = \frac{\sum_{i=1}^{N} l_i}{L} * 100\% \tag{9}$$

where L is measured in m.

Re-define the traffic flow parameter flow rate q, which represents the total length of vessels passing through a certain section of a waterway per unit time. The unit is m/s. The relationships between traffic flow parameters, speed v, density k, and flow rate q are as follows:

$$q = k * v = \frac{\sum_{i=1}^{N} l_i \dot{x}_i}{L} \tag{10}$$

2.Redefinition of traffic flow parameters based on vessel area

The formula for calculating the area of a ship is as follows:

$$S_i = l_i * b_i \tag{11}$$

where l_i and b_i are the length and width of the i-th ship respectively.

As described in defining ship length, the interval average velocity $\bar{u}_s$, based on the area of the ship, is of two kinds:

$$\bar{u}_{s1} = \frac{\sum_{i=1}^{N} S_i}{\sum_{i=1}^{N} \frac{S_i}{\dot{x}_i}} \tag{12}$$

$$\bar{u}_{s2} = \frac{1}{\sum_{i=1}^{N} S_i} \sum_{i=1}^{N} S_i \dot{x}_i \tag{13}$$

$$v_s = \bar{u}_{s2} \tag{14}$$

where $\bar{u}_{s1}$ and $\bar{u}_{s2}$ are the empty average flow rate and hourly average flow rate after area-based redefinition, respectively, and v_s is the redefined traffic flow parameter in kn (knots) based on the area of the vessel.

The area-based redefinition of the traffic flow parameter, k_s is expressed as the sum of the area of vessels in the channel area as a percentage of the channel area for a very short period of time.

$$k_s = \frac{\sum_{i=1}^{N} S_i}{S_H} \tag{15}$$

Flow q_s expressed as the area of vessels passing through the channel per unit time and channel width.

$$q_s = v_s * k_s = \frac{\sum_{i=1}^{N} S_i \dot{x}_i}{S_H} \tag{16}$$

C. *Calculation of traffic flow parameters*

Calculate various traffic flow parameters under different definitions by plotting the spatiotemporal trajectory of ships. The vertical axis represents the distance traveled by ships along the channel, with the maximum distance denoted as the channel length, L. The horizontal axis represents the time taken by ships to navigate through the channel, with the maximum navigation time represented as T. The principle of solving this problem is shown in Figure 3.

The methods for calculating the flow rate q, density k, and velocity v are shown in Formula 17-19.

$$k = \frac{t(A)}{|A|} \tag{17}$$

$$v = \frac{d(A)}{t(A)} \tag{18}$$

$$q = kv = \frac{d(A)}{|A|} \tag{19}$$

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$d(A)$ refers to the total distance traveled by a ship in the channel based on its characteristics during the time interval dt; $t(A)$ is the total time of ship navigation based on its characteristics, and $|A|$ is the area surrounded by the length of the channel and the time interval dt.

$$d(A) = \sum_{i=1}^{N} t_i \times \varepsilon \times v_i \tag{20}$$

$$t(A) = N \times \varepsilon \times dt \tag{21}$$

where $t_i$is the time of the i-th vessel in the channel; ε is a correction parameter based on vessel characteristics,

$$\varepsilon = \begin{cases} 1 & ,Ship\ Num, \\ N_i & ,Ship\ Pue \\ l_i & ,Ship\ Length \\ S_i & ,Ship\ Area \end{cases} \tag{22}$$

N_i is based on equivalent traffic [17];

$$N_i = \begin{cases} 1 & ,l_i < l \\ \left[\left[\frac{l_i}{l}\right]\right] & ,l_i \geq l \end{cases} \tag{23}$$

l is the standard ship length, taken as the median ship length in the study area.

$$|A| = L \times dt \tag{24}$$

L is the length of the channel in which it is located;

$v_i (i = 1,2, \ldots, N)$ is the average speed of each vessel in the channel during the time interval dt. The average speed v_i in the channel during the time interval dt is calculated by the following equations:

$$v_i = \frac{x_{i1} - x_{i0}}{dt} \tag{25}$$

where x_{i0} and x_{i1} are the position at the channel where the ith ship is located at the beginning and end of the dt time interval respectively.

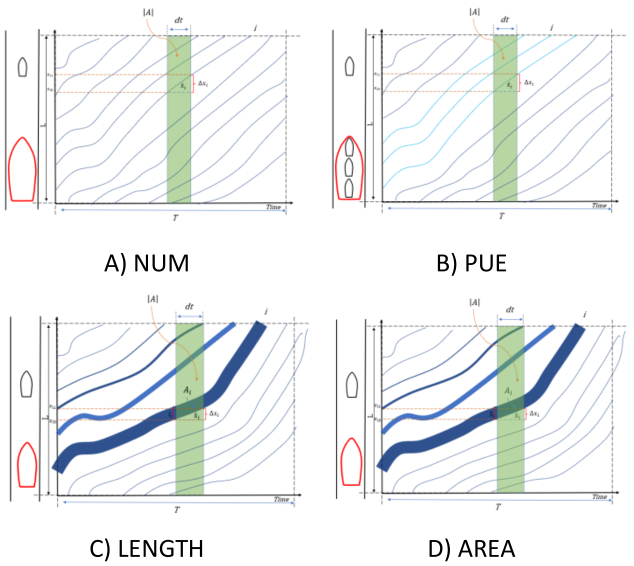

Fig. 3. Probability Density Distribution Char

III. EXPERIMENTS

Most data in maritime traffic are based on AIS data. Each AIS record includes precise vessel position information to the second, as well as information about its speed over ground (SOG), course over ground (COG), vessel type, speed, draught, and other details. The research of maritime traffic flow using these data has tremendous significance.

A. Study area selection

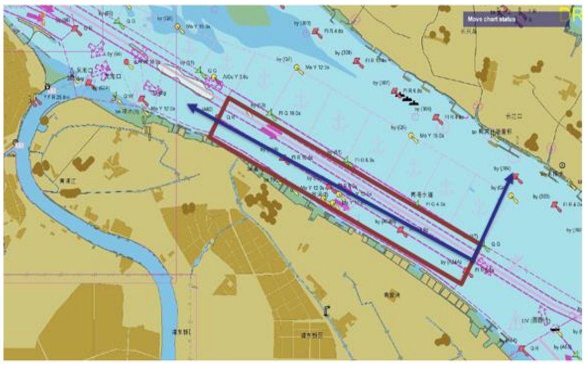

Fig. 4. Selected channel and coordinates

The selected research area for this study is the Yangtze River South Channel, and AIS data from this channel in 2021, totaling approximately 30 GB, ware used. traffic flow characteristics parameters were calculated based on this data. This study area was selected as shown in figure 4: with reference coordinates of (31.2395164,121.7919730), (31.2362131,121.7869119), (31.2737211,121.7493111), and (31.2764481,121.7534300). The course heading of the channel is 139°, and its baseline coordinates are (121.7869119,31.2362131), with a segment length of 3 nautical miles and a width of 600 meters. The traffic flow in this channel is high, and there is a complex mix of various types of vessels with significant differences in size. The x-axis represents the vertical axis of the channel, while the y-axis represents the navigational direction. AIS data for the month of May was selected for the study in the region, extracted from one year's historical data. A total of 332,797 AIS data points were collected, with each vessel's AIS data interval ranging from a few seconds to tens of seconds.

B. Data pre-processing

Due to potential quality issues with historical AIS data and potential differences from the experimental data, appropriate preprocessing is necessary to achieve the desired results. The data preprocessing flowchart is shown in Figure 5 and the specific steps are as follows:

- Select AIS data from within the area shown in Figure 4 of the original AIS data using a dot-shooting method [18].
- As shown in Figure 6, a rectangular coordinate system is established with the origin at point O, one of the polygon vertices. The x-axis represents the direction of navigation, and point P denotes the ship's position with coordinates (λ, φ) in latitude and longitude. Using Mercator navigation [19], we calculate the

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distance S from the position point P to point O and convert the coordinates of point P into rectangular coordinates (x, y) based on trigonometric equations.

- Revise the data of aberrant vessel information selected within this area, such as substituting the abnormal vessel length and width data with the median values based on statistics within the area. For any abnormal speed values that appear in the data, we will perform further analysis and modification accordingly.
- The ship trajectory spatiotemporal map [20] shown in Figure 7 displays the spatiotemporal trajectory of the distance between a ship and the starting point of the waterway over time. The x-axis represents the starting line of the waterway, while the slope of the trajectory indicates the ship's sailing speed. Different color trajectories represent different ships. However, there are instances of reverse traffic flow where ships' travel distance x decreases with time, which affects the calculation of traffic flow parameters. To address this, the ship trajectory data in this part was removed based on the ship's MMSI.
- Some of the raw AIS data have significant differences in time intervals between distributions, some of which even reach up to 2 minutes. This has an impact on the calculation of channel traffic flow parameters, thus requiring spline interpolation [21] of the raw AIS data with a time interval of 30 seconds.

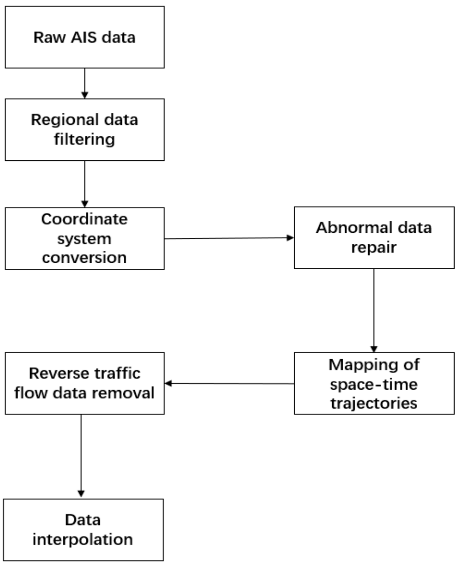

Fig. 5. Data processing flow chart

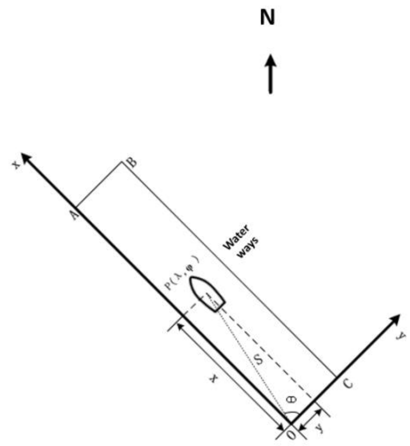

Fig. 6. Coordinate conversion diagram

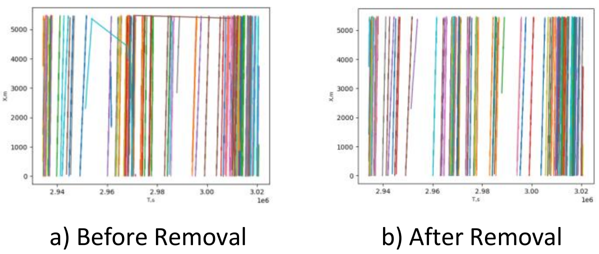

Fig. 7. Space-time trajectory chart

C. *Solving for traffic flow characteristics parameters and fundamental traffic flow diagram*

Based on the calculation method of traffic flow parameters mentioned earlier, the traffic flow parameters of the processed AIS data were separately calculated using the ship count, equivalent traffic conversion, ship length, and ship area methods.

As shown in Table 2, the distribution of traffic flow characteristic parameters for the studied navigation segment can be obtained. In terms of statistical analysis of the traffic flow characteristic parameter "speed," all four methods yielded identical results when the maximum speed reached 23.6 knots and the minimum speed was 1.5 knots. It was found through statistical analysis that during such instances, there was only one vessel present in the navigation segment. Therefore, different calculation methods for the characteristic parameters did not have an impact on determining the traffic flow speed.

TABLE II DISTRIBUTION OF TRAFFIC FLOW PARAMETERS

Category	parameters	mean	std	min	mid	max
Method 1	V(kn)	8.76	2.57	1.5	8.88	23.6
	K(vessel/nm)	1.18	0.87	0.33	1	6.67
	q(vessel/h)	11.16	9.79	0.5	7.87	60.09
Method 2	v(kn)	8.78	2.59	1.5	8.9	23.6
	k(vessel/nm)	1.2	0.9	0.33	1	6.67
	q(vessel/h)	11.42	10.22	0.5	7.93	66.33
Method 3	v(m/s)	4.55	1.36	0.77	4.61	12.14
	K	6.26%	5.24%	0.20%	4.76%	32.8%
	q(m/s)	0.319	0.318	0.0046	0.1972	2.006
Method 4	v(m/s)	4.576	1.392	0.772	4.627	12.14
	K	0.198%	0.1987%	0.0012%	0.1287%	1.896%
	q(m/s)	0.0104	0.01202	0.000027	0.005464	0.0879

[c] Method 1 and Method 2 are based on the number of vessels and equivalent traffic respectively

[d] Method 3 and Method 3 are based on ship length and ship area respectively

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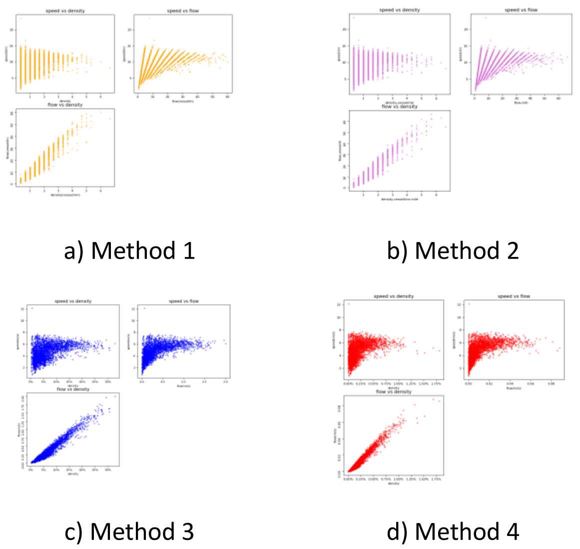

Fig. 8. Traffic flow fundamental diagram.

According to Figure 8, in the first subgraph of the fundamental traffic flow diagram, which is the speed-density diagram, the diagrams obtained by various methods all indicate that at low traffic flow densities, ship speeds are mostly between 1.5 knots and 15 knots. This is unlike road traffic flow, where vehicle speeds tend to be concentrated in higher ranges at low traffic densities. Furthermore, there is a trend of decreasing ship speeds as traffic flow density increases. The second subplot, the speed-flow plot, exhibits a similar shape to that of the velocity-density plot. In the third subgraph of the fundamental traffic flow diagram, namely the flow-density diagram, it can be observed that traffic flow increases with an increase in traffic density. However, none of the methods show a decrease in traffic flow with increasing traffic density, as observed in the latter part of the basic flow diagram in road traffic. Nevertheless, method 4, which takes into account ship-related factors, reveals that after reaching a density of 1%, the rate of traffic flow increase slows down as density increases. At this point, a trend towards the second half of the fundamental traffic flow diagram emerges, indicating the presence of maximum capacity and a decrease in traffic flow in the channel.

In conclusion, the fundamental traffic flow diagrams based on several different definitions provide a better reflection of the maritime traffic situation. The basic diagrams generated by Method 1 and Method 2 exhibit a noticeable stratification phenomenon. This phenomenon is caused by the following factors. Firstly, the ships are of larger size while the number of ships present in the channel is relatively small, resulting in lower density values of maritime traffic flow. During the study period, there were typically only around 20 ships at the moment of maximum traffic flow density in the channel. As a result, when counting the number of ships and calculating traffic flow characteristic parameters, the range of density values for the traffic parameters is limited, leading to the observed stratification phenomenon. Furthermore, the reason why the latter part of the traffic flow fundamental diagram did not appear in the third subgraph using various methods is as follows: The selected research area is the navigation section of the Yangtze River South Channel. During the chosen research period, no significant instances of traffic congestion were observed. Additionally, this water area serves as a critical navigational segment, and maritime authorities impose certain restrictions on vessel navigation to ensure the safety of ship operations. Therefore, it is difficult for traffic congestion to occur in this maritime traffic. In this study, ship-scale factors have been taken into consideration when determining traffic flow characteristics parameters and creating the traffic flow fundamental diagram. This approach allows for a better representation of the navigational traffic conditions compared to previous studies that focused solely on road traffic. By incorporating ship-scale factors, such as vessel size, the analysis can provide insights specific to maritime traffic patterns and accurately depict the dynamics of traffic flow in waterways.

IV. CONCLUSION

This study conducts separate statistical analyses of ship voyage data and vehicle movement data to identify differences in the scales of road and sea carriers. It points out that borrowing the traffic flow parameters defined based on quantity from road traffic is inappropriate for describing maritime traffic. Therefore, this paper proposes two new definition methods based on ship length and ship area to provide a more detailed description of the maritime traffic flow conditions. The study selected historical AIS data from South Channel of the Yangtze River as the research object to calculate the traffic flow characteristics parameters and develop algorithms to draw fundamental traffic flow diagram using the four different definition methods. The study found that with the refinement of the definition methods that consider of ship scale, the effectiveness of the traffic flow fundamental diagram improved. This can offer more scientific decision-making support to Maritime Traffic Management and decision-making departments.

However, the drawn traffic flow fundamental diagrams still failed to show a significant congestion part in the latter half, as found in road traffic. This may be due to strict control of the navigation area, such as the strict regulation of the safe distance between ships during their voyage, which makes it difficult to form congested parts. This results in ships excessively focusing on safety during their navigation in the waterway, thereby neglecting the navigational efficiency of the waterway. On the other hand, this study aims to depict the traffic flow fundamental diagram by considering ship scale factors, providing a more accurate depiction of the traffic flow conditions in the waterway. This approach helps identify the maximum capacity of the waterway for navigation. Regarding future research, this study will select data from areas that are more prone to traffic congestion as the research target to draw the traffic flow fundamental diagrams. Additionally, scatterplots will be utilized to conduct clustering analysis, allowing for an assessment of the passage capacity and navigational efficiency of different waterways. This analysis can offer valuable theoretical support for the development of intelligent waterways and ship technology.

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