Research on the level of service of water transportation based on the perspective of traffic differences

Yihua Liu*
College of Merchant Marine
Shanghai Maritime University
Shanghai, China
liuyh@shmtu.edu.cn

Siqing Zhuang
College of Merchant Marine
Shanghai Maritime University
Shanghai, China
202030110067@stu.shmtu.edu.cn

Rui Guo
College of Merchant Marine
Shanghai Maritime University
Shanghai, China
2323536938@qq.com

Li Xiyue
College of Merchant Marine
Shanghai Maritime University
Shanghai, China
lixinyue202103@163.com

Jinsong Li
College of Merchant Marine
Shanghai Maritime University
Shanghai, China
1315930846@qq.com

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***Abstract*—The surge in the volume of maritime import and export trade has put enormous pressure on water transportation. The National Comprehensive Three-Dimensional Transport Network Planning Outline sets out the transport construction objectives of improving the efficiency of the use of transport facilities and the level of service (LOS). It is obviously unscientific and uneconomical to directly expand and upgrade the waterway without considering the current state of the waterway traffic service level. Decision-making departments need to determine whether the waterway should be expanded and upgraded to improve the water transport service level, which needs the basis of decision-making. Therefore, it is very important to find an objective indicator to evaluate the water traffic condition and operation quality. In road transportation. LOS is an important indicator of the performance of transport facilities. It is a simple and effective method to determine the service level evaluation standard based on the fundamental diagram. Due to the difference of vehicles, there are doubts about the scientificity and rationality of the evaluation criteria and indicators of road traffic service level applied on waterway traffic. The selection of evaluation indicators and the establishment of standards for the service level of water t traffic need to be solved urgently. Firstly ,This paper analyzes and summarizes the differences of the means of transport; Secondly, the method of construction the fundamental diagram of water traffic flow with area occupancy instead of density is proposed; Thirdly, based on the optimal area occupancy and speed, four levels of service levels are divided. Finally, based on the water service level classification criteria established in this paper, the service level of the south channel of the Yangtze River is evaluated. This study can provide decision-making basis for the planning, design, operation and management of the waterway.**

Keywords—fundamental diagram, level of service, waterway traffic flow

I. Introduction

With the rapid rise of economy and the continuous growth of international trade, the throughput of cargo at terminals and the number of vessels arriving at ports have increased drastically, the congestion in waterways is remarkable, water traffic accidents are frequent, and the operation and management of water traffic are under unprecedented and tremendous pressure[1]-[2]. The increasingly prominent contradiction between traffic demand and supply makes it urgent for the waterway management to take effective measures to solve it. Therefore, scientifically describing and characterizing the performance of waterways enables waterway managers to have a deeper understanding of the characteristics and traffic conditions of waterway traffic, which helps managers make scientific decisions in waterway management, waterway renovation and expansion, and improving water transportation operations.

In the 1950 edition Highway Capacity Manual (HCM1950), the concept of level of service (LOS)was introduced to quantify an objective measure of how much a road can serve its users[3]. This allows even laymen who do not know much about traffic to clearly understand the performance of traffic facilities. There are two ways to classify LOS: 1. LOS is divided into 6 classes, namely ABCDEF, which is related to people's habit of classifying classes in real life; 2. Some scholars consider that traffic flow states can be divided into 4 states, and therefore propose that LOS should be divided into 4 classes[4]-[5]. In classifying the classes, scholars also consider different factors to determine the respective LOS. For example, in road traffic flow, traffic flow characteristics, waiting time, and the ratio of demand traffic volume to capacity (v/c) are used as factors to classify the level of the waterway[6]-[9]. The level of service classification of sidewalks considers factors such as occupied area per capita, longitudinal distance per capita, and walking speed. In the HCM and the Design Specification for Highway Alignment ,LOS standard classification is closely related to the fundamental diagram, according to which the capacity conditions (i.e., capacity and the corresponding optimal density and optimal speed) are determined. Between density range 0 and optimum density, LOS is subdivided into A ~ E or 1 to 6[7,10].

In waterway traffic engineering, the study of waterway service level is still in its initial stage, and relevant researchers usually borrow the concept and method of road service level for research. Z. Guo et al. (2009) [11] proposed a method to calculate the conversion coefficient of standard ships and other ships, and applied the number of standard ships to define the passage capacity of the waterway based on the service level of harbor. Xu ZH et al. (2016) [12] studied the service level of waterways in the harbor section of inland rivers, and used the flow saturation to classify the level of service based on the analysis of the conflict points of vessel flow in the harbor section of waterways . Zhu J et al. (2009) [13] constructed an index system for evaluating the service level,

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which was based on the freedom of vessel traffic and channel saturation, and used actual traffic flow data to verify the analysis of the model. J. Tan et al. (2014) [14] based on the concept of road service level, based on factors such as vessel traffic flow density, speed, vessel one-way service traffic and traffic load (V/C), the service level of the waterway was into four levels and used this method to evaluate the channel operating capacity and service level of the Xijiang waterway in the Zhaoqing area . Yu J et al. (2006) [15] introduced the concepts of design service level and operation service level into the evaluation system of inland waterway service level, discussed their classification and determination respectively, and used this method to evaluate the operation of the waterway in Guiwu section of Xijiang River. Song Xiangqun et al. (2010) [16] proposed the concepts of coastal waterway service level and waterway utilization rate and analyzed the influencing factors of waterway service level.J. Zhao (2010) [17] applied the queuing theory to study the level of service and passing capacity of coastal port waterways. Based on Anylogic simulation modeling platform,X. Ma et al. (2023) [18] combined the automatic identification system (AIS) ship dynamic trajectory, simulated the port operation environment, and studied the influence of LNG ships on navigation and port service level. W.Wang et al. (2017,2013) [19,20] analyzed the ship's own attributes, ship navigation characteristics, berth and anchorage and other factors, while considering the port service level, operation days and The calculation model of port throughput was established by considering the relationship between the level of port service, operating days and channel throughput, and the port import single channel transit capacity was studied. Drawing on the definition of road traffic flow fundamental diagram, Y. Liu et al. (2022) [21] drew the fundamental diagram of ship traffic flow and established the channel LOS standard based on the fundamental diagram for the first time, dividing the channel LOS into four levels and delineating the traffic conditions corresponding to these levels based on the traffic flow density, respectively, as the service metric expressed by the standard ship per nautical mile per channel (pv/nmi/channel). The direct application of the definition of the fundamental diagram of road traffic flow to draw the fundamental diagram of ship traffic flow implicitly assumes that water traffic flow is same with road traffic flow. However, practical experience shows that there are differences between water traffic and road traffic and the above assumption may not be strictly valid. The scientific rationality of directly applying the definition of the fundamental diagram of road traffic flow to draw the basic map of ship traffic flow is questioned.

In summary, in terms of LOS, most of the studies on LOS are still focused on road transportation, and there are relatively few studies on water traffic. In the drawing of the fundamental diagram of ship traffic flow, the differences between water traffic and road traffic are ignored. In this study, we try for the first time to draw the fundamental diagram of ship traffic flow and propose the LOS criteria of ship traffic flow on the basis of considering the differences between water traffic and road traffic. The results of this study can be used as a basis for waterway planning and design and waterway traffic operation and management by waterway traffic management departments.

This paper is organized as follows. The next section describes the differences between ship traffic and road traffic, definition of basic parameters of road traffic flow and the method of drawing fundamental diagram. This is followed by a section that introduces the new definition of basic parameters of road traffic flow and proposes the criteria of waterway LOS. Then the method is applied to the south channel of the Yangtze River, including the generation of fundamental diagram from actual data and the evaluation of channel LOS. Finally, the study is summarized and the future research directions are discussed.

II. COMPARISON OF SIMILARITIES AND DIFFERENCES IN TRANSPORTATION

2.1 Dimensions of transportation tools

Vessel data are selected from the south channel of the Yangtze River with regional information as shown in the chart, and road vehicle data are selected from the publicly available road traffic flow study data (Next Generation Simulation _Data).

Fig. 1. Location diagram

From the results of the statistics, it is found that the length of vehicles in the statistical area is 0-24m, and the length of vessels in the statistical area is 0-300m, and the range of variation of the scale of vessels is much larger than that of vehicles. The distribution of statistics shows that the distribution of vehicle length is more concentrated, 0-6m accounts for the statistics of, and accounts for the whole area, and the distribution of vessels length is relatively scattered. According to the survey of bicycle pedestrians, the length of bicycle pedestrians is about 1.5-2.5m, and pedestrians is about 0.5-1m, with the smallest length variation range.

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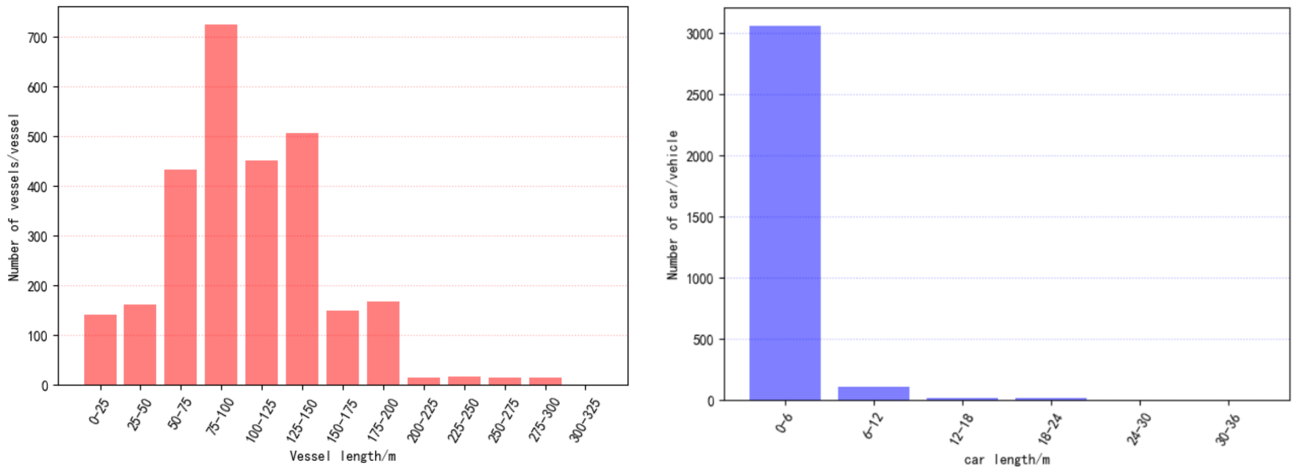

Fig. 2. Vessel length and vehicle length distribution diagram

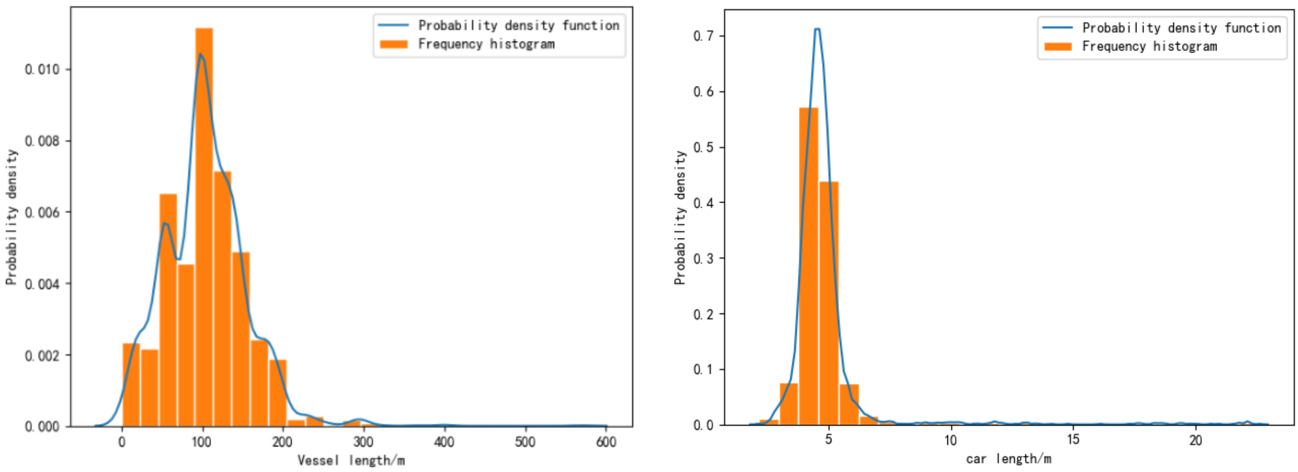

Fig. 3. Vessel length and vehicle length probability distribution diagram

2.2 Reaction time

Collision avoidance decision process of vehicles or pedestrians or bicycles is simple, the number of people involved is usually 1. This makes the driver reaction time of this type of traffic is usually in the seconds level, about 1-6s. At the same time, The response time of such transport tools itself is very small and can be almost ignored due to their fast reaction and good maneuverability of the machine. While the ship's collision avoidance decision is a process involving multiple people in multiple processes and the machine response time of vessels is longer than the machine response time of other transport tools and can not be ignored due to the large scale of the vessels and different maneuverability. Reaction time should be redefined for vessels. One part is the reaction time of the officers onboard, the other part is the response time of the vessel herself due to the maneuverability. Hence, for waterway traffic, the reaction time is not only in the minute scale but also the reaction time will show the distribution characteristics. This makes the heterogeneous rate of ship traffic flow is also much larger than other types of traffic.

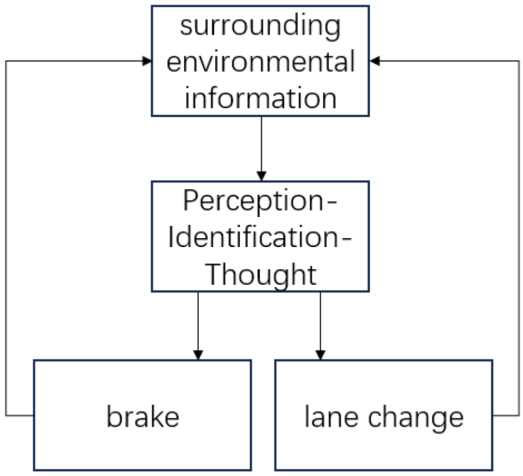

Fig. 4. Flow chart of car collision avoidance decision process and information flow transmission

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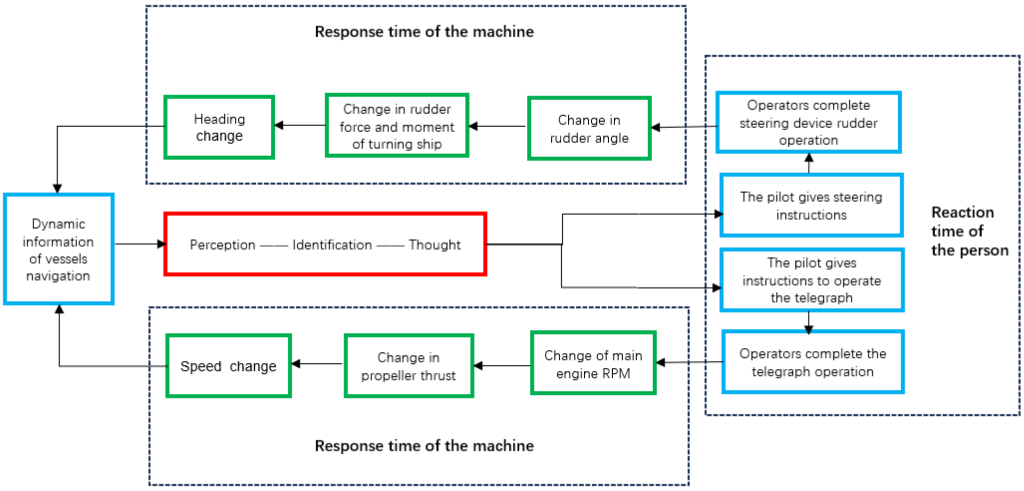

Fig. 5. Flow chart of vessel collision avoidance decision process and information flow transmission

2.3 Navigation Environment

In the environment, cars, bicycles, pedestrians and trains in the road are navigated by road and air, while vessels are navigated by water and air. The resistance of water flow, wave load and air resistance result in a complex force model of the ship, which is difficult to describe by an accurate model. In addition, for automobiles, the road is usually divided into clear physical dividing lines, and vehicles generally travel strictly within the lane lines, and trains are even more so because they must travel on the tracks and have strict lanes. In the case of waterway traffic, there are no such strict "physical dividing lines" on the water, and the same is true for bicycle traffic and pedestrian traffic, which leads to similarities and differences in the movement patterns between transportation tools.

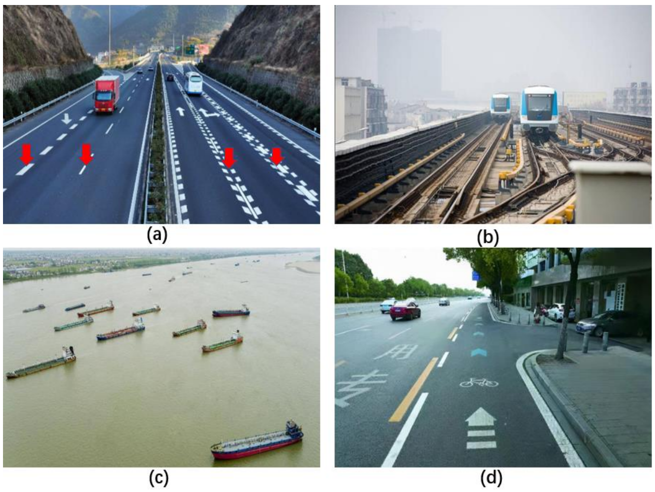

Fig. 6. Media and lane characteristics of various types of traffic diagram

TABLE I.
DIFFERENCES AND SIMILARITIES OF SEVERAL TYPICAL TRANSPORTATION MODES

Traffic classification	Scale (m)	Reaction time	Transmission medium	Physical Diversion Line	Maximum motion dimension
Vehicle	0-24	4-6s	Roads and air	Yes	1.5D
bicycle	1.5-2.5	2s	Roads and air	No	2D
pedestrian	0.5-1	1s	Roads and air	No	2D
Vessel	0-300	178s[22]	Air and water	No	2D
Train	440	Approximately 4s	Roads and air	Yes	1D

The above analysis summarizes that ships have similarities and differences with cars, bicycles, pedestrians, and train traffic in terms of dimensions of transportation tools, reaction time, transmission medium, physical lane lines, and motion dimensions. Especially compared to other types of transportation, there are significant differences in scale between the various vessels, which makes it unscientific to directly apply the definition of basic parameters in road traffic flow that only reflect the number of transport tools in the traffic flow state to waterway traffic. At the same time, the similarities between waterway traffic and other types of traffic, making it possible to refer to traffic types with similar points when solving waterway traffic related problems. Such as whether there are physical lane lines, waterway traffic are the same as bicycle and pedestrian traffic. Waterway traffic may draw inspiration from bicycle or pedestrian traffic to address issues related to lane discipline.

III. THE DEFINITION OF TRAFFIC FLOW PARAMETERS AND THE DRAWING OF FUNDAMENTAL DIAGRAM

3.1 Definition of basic parameters of traffic flow and the drawing method of fundamental diagram

Fundamental diagrams are effective tools for interpreting traffic phenomena and are widely used in various traffic analyses, including highways [23], pedestrian flow [24], bicycle flow, rail traffic[25], waterway traffic [26], and airport traffic [27].

The Study of fundamental diagram of ship traffic flows draws very much from the study of road traffic flows. The fundamental diagram of traffic flow is usually drawn according to the following process, firstly, the study lane and lanes are selected. For vehicles with strict lane discipline, the lane selection is simple, and single lane or multiple lanes can be studied together. However, for pedestrian, bicycle, and vessel flows without lane discipline, there is a degree of difficulty in lane selection. Next, the displacement-time variation trajectory graph X-T diagram is plotted based on the

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selected lane data. Then, the length of the study lane is selected and the time interval of ships in the statistical lane, the ships are counted and the standard ship conversion coefficients of standard ships and ships are determined, and finally, the ships calculate the traffic flow density K, flow rate Q and velocity V according to the definition of the basic parameters of traffic flow, and the fundamental diagram of the two-two relationship is drawn.

Scholars of waterborne traffic flow define the parameters of waterway traffic flow [28], and the definition is borrowed from the definition of road traffic flow parameters [29]. In the spatio-temporal trajectory diagram, density is defined as, the number of vessels contained in a unit distance, and velocity is defined as the average of vessel velocities at fixed moments in the observation area, i.e., the space mean flow velocity.

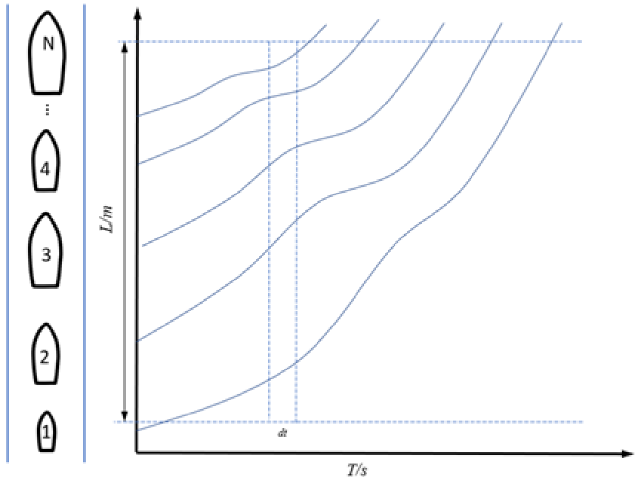

Fig. 7. Trajectory of ships displacement-time diagram

$$k = \frac{N}{L} \tag{1}$$

$$v_s = \frac{\sum_{i=1}^{N} v_i}{N} \tag{2}$$

$$q = k * v \tag{3}$$

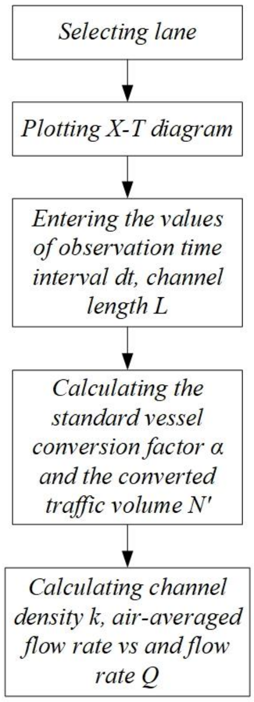

Fig. 8. Fundamental diagram drawing flowchart

For vehicles with strict lane discipline, lane selection is simple in selecting the research route and lane, and can be studied in single lane or multiple lanes together. However, for pedestrians, bicycles, and ship flows without lane discipline, the motion dimension is higher than that of vehicles. From the figure11, the actual motion trajectories of the ship are messy, how to scientifically divide the channel width will become a more difficult problem to solve.

When drawing a fundamental diagram of road traffic flow, researchers use the method of converting non-standard vehicles to standard vehicles, and reflect the scale differences of vehicles in the fundamental diagram. In HCM, the standard car size has been determined as a 6m car, and there are also quite comprehensive conversion standards provided. Scholars studying the fundamental diagram of maritime traffic flow refer to the above methods and also attempt to reflect the differences in ship scale in the fundamental diagram of traffic flow. However, the size of standard ships at sea has not been determined yet, and there is a lack of reference standards for the coefficient of converting non-standard ships to standard ships. Therefore, there are doubts about the scientificity and rationality of studying maritime traffic flow using the definition method that draws on the basic parameters of road traffic flow.

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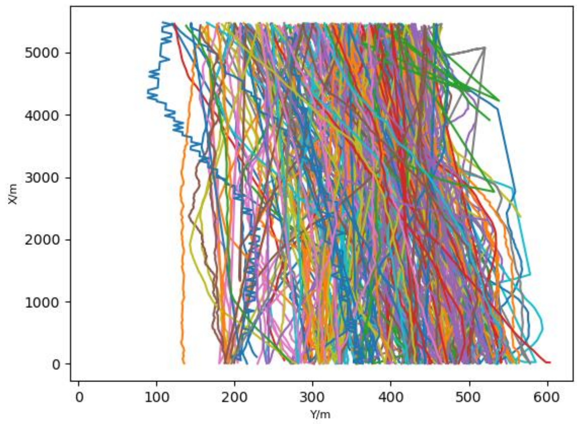

Fig. 9. Trajectory of ships displacement-time diagram

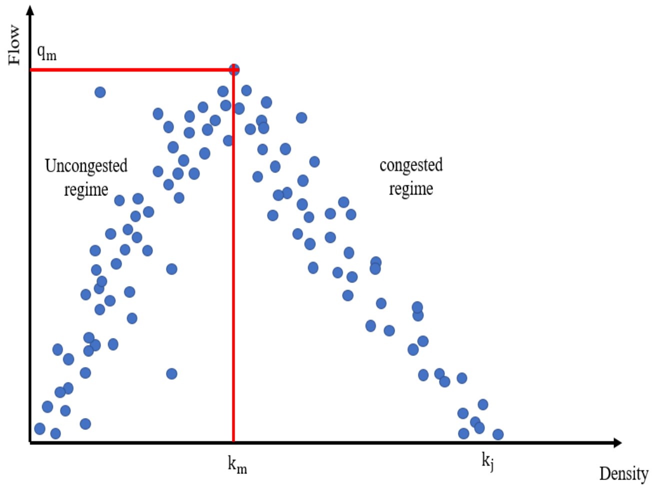

Fig. 10. Media and lane characteristics of various types of traffic diagram

IV. THE PROPOSED LOS CRITERIA FOR WATERWAY BASED ON FUNDAMENTAL DIAGRAM

4.1 The redefinition of traffic flow parameters

In order to solve the difficulty of waterway division, density 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.

$$k = \frac{\sum_{i=1}^{N} S_i}{S_{\text{channel}}} \tag{4}$$

Speed v_s expressed as average value of the vessels' speed

$$v_s = \frac{\sum_{i=1}^{N} v_i}{N} \tag{5}$$

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

$$q = v_s * k = \frac{\sum_{i=1}^{N} S_i \dot{x}_i}{S_{\text{channel}}} \tag{6}$$

4.2 The proposed LOS criteria for waterway based on fundamental diagram

Refer to the fundamental diagram of road traffic flow, the LOS standard for waterway traffic can be determined based on the maximum capacity conditions of the waterway, and the maximum capacity of the waterway can be determined based on the fundamental diagram. Drawing on the classification method of LOS standards used by others, the service level of the waterway is divided into four levels. For example, when the density is between 0-1/3 k_m, the service level of the waterway is level 1; When the density is between 1/3 k_m and 2/3k_m, the service level of the waterway is level 2; When the density is between 2/3 k_m - k_m, the service level of the waterway is level 3; When the density is greater than k_m, the service level of the waterway is level 4. k_m is the maximum density, corresponding to the maximum flow rate Q_m.

V. EVALUATING LOS BASED ON THE WATERWAY AIS DATA

5.1 AIS data processing

The ship Automatic identification system(AIS) is a kind of information exchange equipment that can realize near real time between ships and shore based, ships and ships. AIS data includes information such as time, ship name, captain, ship width, ship longitude and latitude, ship to ground speed, and ship to ground heading. Since the mandatory installation and use of AIS equipment, the spatiotemporal data of ships has grown rapidly, which contains a large amount of ship traffic information, providing data support for the study of fundamental diagram of waterway traffic flow.

Considering that the Yangtze River waterway is one of the busiest waterways for water transportation in China, the research area is set at the south channel of the Yangtze River. The area is shown in Figure 11, with reference coordinates of (31.23624° N,121.7869° E), (31.23957° N,121.7919° E), (31.27631° N,121.7535° E) and (31.27373° N,121.7493° E). Due to potential quality issues with historical AIS data and potential differences from the experimental data, appropriate preprocessing is necessary to draw a fundamental diagram. The data preprocessing flow chart is shown in Figure 12. Among them, the coordinate conversion is to convert the longitude and latitude coordinates of the ship into two-dimensional plane coordinates. The principle of coordinate conversion is shown in the Figure 13.

The methods for coordinate conversion are shown in Formula 7-13.

$$S = D_{\varphi} \sec C \tag{7}$$

$$D_{\varphi} = \varphi_i - \varphi_o \tag{8}$$

$$D_{\lambda} = \lambda_i - \lambda_o \tag{9}$$

$$\mathrm{DMP} = \mathrm{MP}_2 - \mathrm{MP}_1 \tag{10}$$

$$C = tan^{-1}(\frac{|D_{\lambda}|}{|DMP|}) \tag{11}$$

$$X_i = S * \cos\theta \tag{12}$$

$$Y_i = S * \sin\theta \tag{13}$$

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Among them, S is the voyage; D_φ is the latitude difference; D_λ is the difference in longitude; MP_2 is the latitude gradient at which AIS data points are located; MP_1 is the latitude gradient at which the reference point is located; DMP is the difference in latitude elongation rate; C is the heading; θ is the angle between the straight line connecting the reference point and AIS data point and the direction of the waterway; X_i is the X value corresponding to AIS data points in the channel coordinate system, and Y_i is the Y value corresponding to AIS data points in the channel coordinate system.

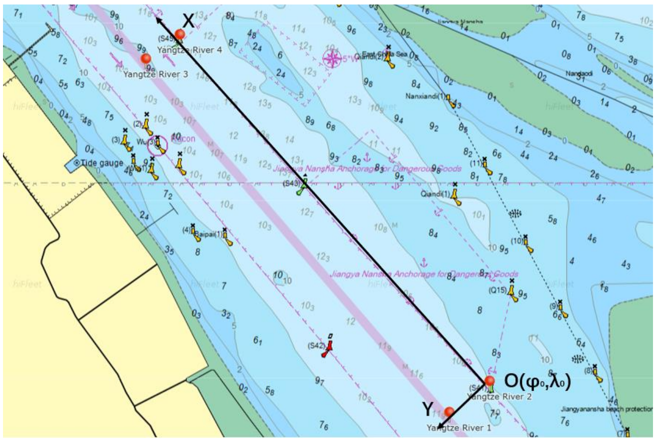

Fig. 11. Schematic diagram of the research area

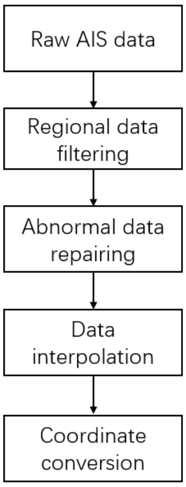

Fig. 12. data processing flow chart

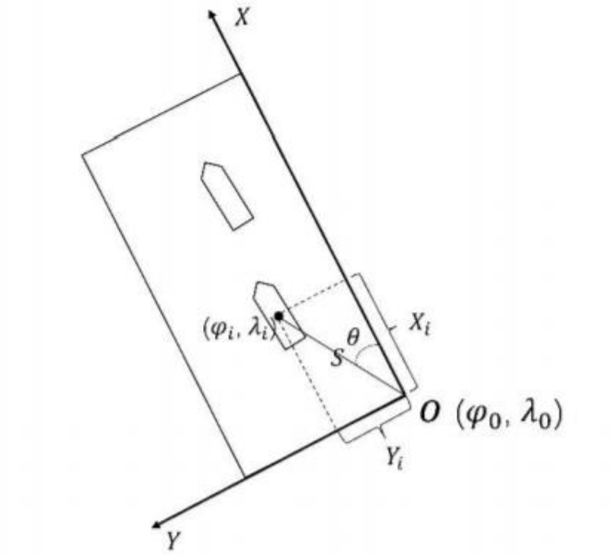

Fig. 13. Schematic diagram of longitude and latitude coordinate conversion

5.2 Draw the fundamental diagram of traffic flows

With the result of the data processing, Figure 14、15 and 16 show the fundamental diagrams of waterway traffic flow with data collected in May 2021 as an example.

The fundamental diagram of waterway traffic flow in Figure 14 shows that space mean speed is mainly within 30nmi/h and flow rate roughly under 0.3 m/s. The data points are clustered around a linear flow– density relationship in uncongested regime with few data points revealing congested regime, which is the area when demand flow exceeds capacity or density exceeds optimal density.

In Figure 14 , it appears that capacity of approximately 0.28m/s occurs at an optimal density of approximately 5.24%, as flow increases before the optimal density and decreases after the optimal density. It can be seen from Figure 15 that most of the traffic conditions in the selected area are in LOS I and LOS II with few data points in LOS III and almost no data point in LOS IV. The figure shows that that traffic conditions in this water area are generally good, and traffic flows relatively smoothly most of the time.

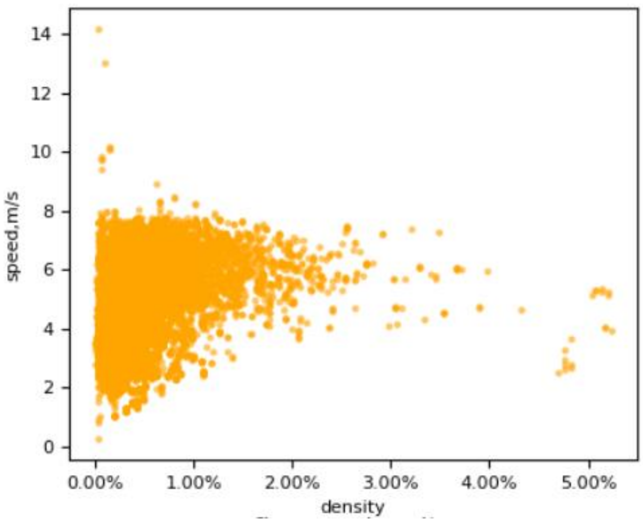

Fig. 14. Speed-density fundamental diagram

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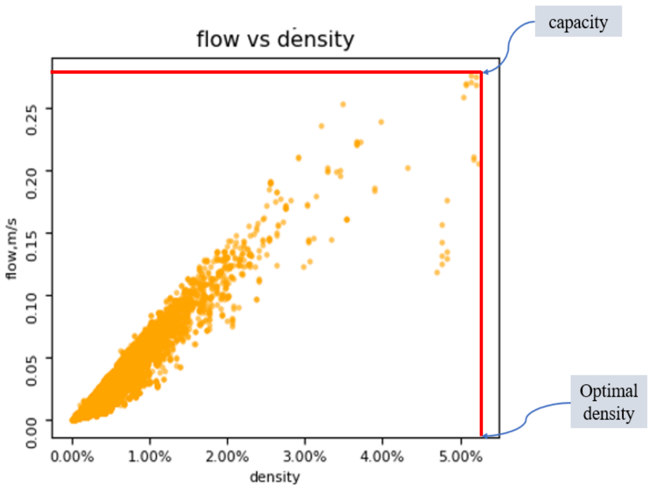

Fig. 15. Flow-density fundamental diagram

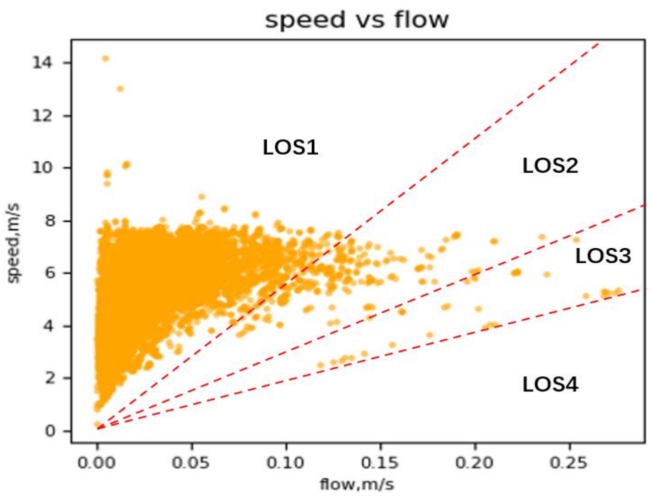

Fig. 16. Speed-flow fundamental diagram

VI. Conclusion

LOS is an important indicator to evaluate the performance of waterways in serving ship traffic. This paper proposed a new method for drawing fundamental diagram , which considers the differences between water traffic flow and other types of traffic flow , and proposed a method of evaluating waterway LOS based on the fundamental diagram of waterway traffic flow. Waterway traffic density was chosen as the service measure to determine waterway LOS. Historical AIS data obtained in the Yangtze water area were used to illustrate the application of the proposed waterway LOS criteria. This research can be useful for waterway authorities to make wise plans and designs to organize traffic operations. Meanwhile, the result of LOS evaluation is helpful to correctly plan navigable standards and formulate navigable rules.

The limitation of this method is that the selection of different channel widths will have a certain impact on the basic shape. Analyzing the impact of different channel widths on the shape of the basic diagram is an interesting topic worth further exploration.

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