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CAPACITY ANALYSIS FOR BIFURCATED ESTUARIES BASED ON SHIP DOMAIN THEORY AND ITS APPLICATIONS

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ABSTRACT

The bifurcated estuary is an important segment of increasingly important marine transportation systems. Due to branching channels, cyclical change of water levels, and sophisticated operating rules in many large bifurcated estuaries, it is often difficult to estimate the traffic capacity and simulate the ship motions, even though it is critically important for traffic management and efficiency. In recent years, the increasing number of ships that collect and contribute to the Automatic Identification System (AIS) have made it possible to monitor traffic flow along waterways, including bifurcated estuaries.

This study developed a typical capacity estimation model based on ship domain theory. Utilizing AIS data collected in the Yangtze River Estuary, a typical Bifurcated Estuary System, the authors have analyzed various physical characteristics, weather conditions, and vessel characteristics in order to derive related impacts of each on overall capacity of the bifurcated estuary. Validated with practical observations, the method can be applied to similar estuary fairway systems to improve waterway operations and management.

KEYWORDS

Capacity analysis, AIS, bifurcated estuary, ship domain theory

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4,055 + 4 tables + 8 figures = 7,055

1. INTRODUCTION

Estuarine waters, as an essential element of waterway network, play a significant role in the development of a maritime economy. More than two-thirds of the largest cities in the world are located at the estuaries of respective rivers (Ross, 1995). With continuous development of domestic and international economic activities, the number and size of ships have been growing continuously. As a result, the density of water traffic is much more condensed than before, especially in the estuarine waters, which causes higher demand for continuously increased utility of waterway capacity.

Given limited capacity in estuary waters and the large investment required to develop and maintain estuary channels, it is important to evaluate the existing capacity, plan future improvement, and manage or optimize waterway capacity, which are all built on the accurate estimate and forecast of the capacity of the estuary channels. However, as the transition zone between the river and the marine environment, estuaries are often subject to the influences of ocean such as tides, waves and influx of saline water, and of rivers such as flows of fresh water and sediment. Complicated by the geomorphological characters, weather conditions, and variations of bifurcated channels, the capacity analysis for bifurcated estuary waterways is very different from that of conventional inland waterways.

Since the implementation of the Automatic Ship Identification System (AIS), it has been possible to track the movements of a large number of ships in various locations by AIS data mining and advanced computation ability. Also, the real-time records of weather, wave, and tidal situations have provided a better platform to isolate and quantify the impact of each factor. These developments can facilitate studies of waterway capacity. However, there are few studies to evaluate the capacity of the bifurcated estuary waterways by AIS data mining.

To fill this gap and improve the capacity in estuarine waters, this study has developed a theoretical framework based on the ship domain theory and AIS data available to estimate the vessel capacity of bifurcated estuary waterways. The major contribution of this study is the application of a theoretical model proposed by Wu and Zhu to the Yangtze River Estuary, the largest estuary waterway network in China, taking full advantages of AIS data available. The estimation of the capacity of the Yangtze River Estuary is in agreement with the observations from 2013 and 2014. The content of this paper is as follows: Section 2 provides a description of the research background. Section 3 elaborates the formula of capacity analysis and method to compute the standard ship domain. Section 4 focuses on the Yangtze Estuary Waterways as a case study. The related parameters in the ship domain model are determined based on AIS data and sea-weather information from the Shanghai Maritime Safety Administration. Section 5 highlight the findings of this study and points out future research directions.

2. RESEARCH BACKGROUND

The capacity analysis is critically important as it is the foundation of the effective operation and management of waterway systems. Many scholars have developed theoretical frameworks and modeling approaches for conventional inland waterways, which are the prerequisite to the research on bifurcated estuary waterways. For example, Dian (2000) studied the traffic capacity of inland waterways in the low-water season based on the vessel traffic flow, and calculated the maximum capacity of a standard ship. Li (2006) studied the design traffic capacity of inland waterways and provided corresponding calculation methods and classification standards for various levels of services. Liu (2006) identified three main factors: the speed of the traffic flow, the ship domain, and the channel width, affecting the capacity of the congested inland waterways. Focused on the problem of the maximum capacity, Duan (2012) constructed a theoretical model regarding traffic capacity of network channels, which was based on the network topological structure of water-network channels and the basic characteristics of navigation as well as Space-time Consumption Theory. The idea capacity are modified by correction factors with which the characteristics of vessel traffic in waterways can be reflected. Generally, these models follow a similar form described in Equation (1):

$$C = n \cdot v \cdot \frac{1000}{L + D} \cdot \prod \alpha_i \qquad (1)$$

Where:

n: number of traffic lanes;

v : ship's operation speed;

L : ship length;

D : safe distance of vessels; and

α_i : correction factors.

Due to the influence of the kinetic dynamics of the river and the adjacency between estuary and ocean, the flow pattern of an estuary is typically a fork-shaped split. In mesh grids, the water channels in the estuary region often form unique flow patterns with various depths and widths, which may render traditional traffic flow models and/or capacity analyses futile, inaccurate or inadequate for application.

To improve the conventional traffic flow vessel capacity analysis for inland waterways, we investigated the origins of the Ship Domain Theory (SDT). First defined by Japanese scholars (Fujii and Tanaka 1963), SDT dictates an effective area around a ship that a navigator would like to keep clear with respect to other ships or stationary objects in order to ensure the safe operations of the vessels. SDT is one of the most effective theories to describe and estimate vessel traffic and ship behavior (Wu and Zhu 2004).

Since the original establishment of an ecliptic model of ship domain by SDT, quite a few researchers have established many models of ship domains with different shapes and sizes including the oval, round and polygon (Wang 2010, Liu and Wu 2011, Qi and Li 2011, and Xu et al 2004). Prior to the implementation and application of the AIS System, research on ship domains developed slowly and was restricted by vessel information. With the recently aggressive promotion of the AIS system, it is now possible to acquire massive, accurate, and real-time vessel data and movement information (Mou, Tak, and Ligteringen 2010). Erwin (2012) developed ship domain boundaries by plotting distances and relative direction between the target and reference ships. By eliminating certain ratios of the reference ship versus the subject ship, Erwin has developed the most representative ship domain dimensions. Ren (2013) established a model of dynamic ship domain by using recently collected AIS data. However, limited by the AIS data available, the boundaries of the model are still rough. Hansen (2013) found that the establishment of an empirical minimum ship domain related to a comfortable navigational distance via analyzing AIS data. Tu (2016) surveyed AIS data sources and relevant aspects of navigation in which such data could be exploited for collision prediction based on Ship Domain Theory

Based on the concept of ship domain theory and the lack of development in capacity analysis for bifurcated estuary waterways, this manuscript documents a dynamic model that is suitable to estimate the capacity of bifurcated estuary waterways. The framework of the model is illustrated in Figure 1. Detailed concept and mathematical equations are introduced in Section 3.

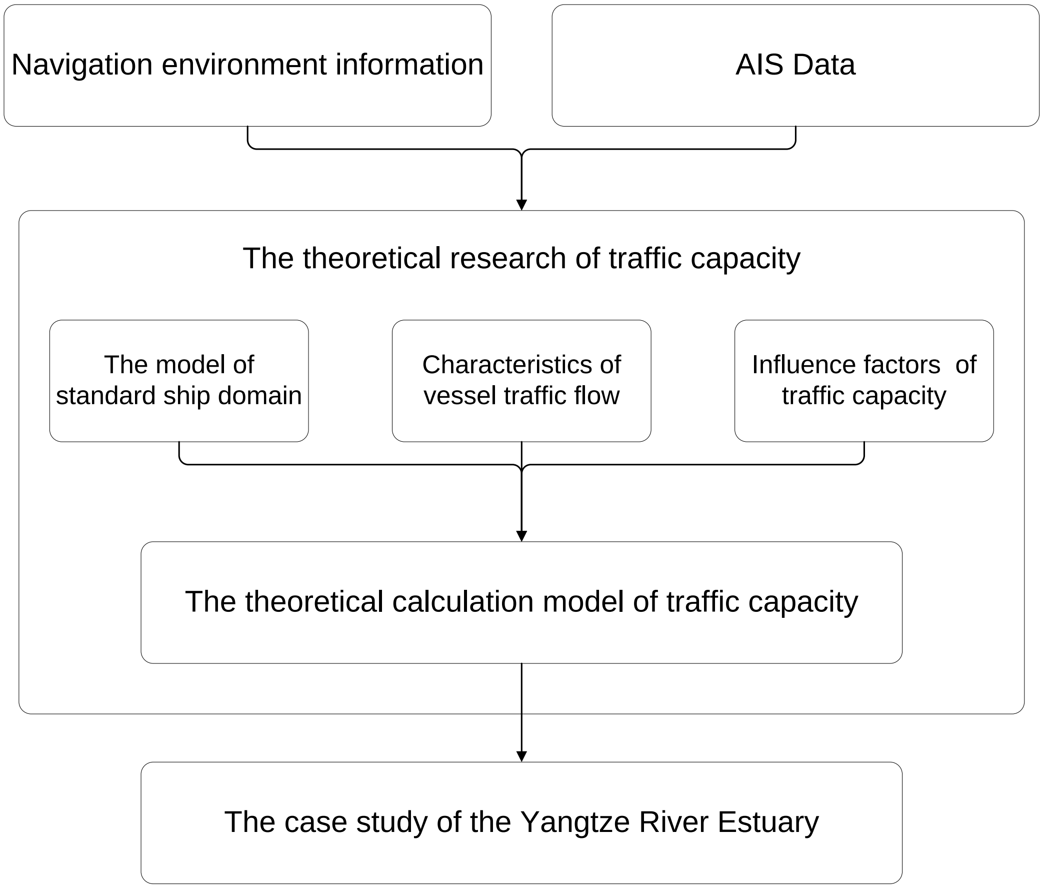

Figure 1. The framework of the model

3. CAPACITY ANALYSIS

Similar to the capacity analysis for surface transportation modes, the basic principle in the capacity analysis for marine transportation is largely based on the density of the vessels and their speeds. What is different from the conventional surface transportation is that the waterway channel delineation is much more fluid than the lane marking direction division. Such fluidity is further compounded and various in the bifurcated estuary region.

3.1 The Basic Model

Applying a basic traffic engineering principle to the unique characteristics of bifurcated estuary waterways, capacity is defined as the maximum throughput passing a given point of the waterway channel in a given unit of time, such as an hour, a day or a month. The ideal capacity may be affected by various geomorphological, weather, and operation regulations, which are reflected as modification factors. However, a mathematical model for estimating the capacity of waterways has been proposed by Wu and Zhu, shown in Equation (2). We follow this model to describe the basic throughput for bifurcated estuary waterways.

$$C_p = \eta \cdot W \cdot \rho_{\max} \cdot v = \eta \cdot W \cdot \frac{1}{r \cdot s} \cdot v \qquad (2)$$

Where

η: modification factor;

W: The width of the fairway;

ρ_{max}: Maximum ship density per unit length fairway;

r 、s: Long and short axis of the standard ship domain;

v: the speed of the vessel.

The modification factor is a product of many composite impacts from wind, fog, wave, and other nature conditions and is unique to a particular estuary. The width of the estuary channels may vary along the horizontal profile but remains stable for a given cross section. Another important factor is the ship domain, an oval denoted by the long axis—*r*, and the short one—*s*. The speed of the vessels is usually controlled by the channel conditions in the estuary, bounded by a low and high range, and generally collected in the AIS database.

3.2 Standard Ship Domain

There are many different ways to derive the dimensions of a ship domain. This approach measures the distance between the subject ship and adjacent ones. After plotting the relative positions for the target ship and surrounding ones, this study delineated the boundaries of the ship domain by excluding certain extreme values.

Analyzing all around ships is critical for the precision of our estimation, but due to the huge calculating burden and mountainous AIS data, we have divided the proximity of the target ship, 360 degrees, into 72 equal sectors, using 5 degrees as the step size in the computer-calculation program. The total number of ships in each sector is tallied and the distances between the target ship and surrounding ones are measured. Using a large quantity of ship positions collected in the AIS database, the authors have plotted the critical points of each sector and connected them into a closed polygon which is the size and shape of the ship domain for the target ship.

4. CASE STUDY

Many bifurcated estuary waterways play significant roles in transporting people and goods for large cities around the world. Each estuary is unique not only because of the geomorphological features, but also the traffic flow patterns, historical development, and vessel characteristics. The approach to calibrate capacity or maximum throughput is often associated with a particular bifurcated estuary region. In this case, the Yangtze River Estuary was chosen as a case study.

4.1 The Yangtze Estuary Waterways

As the longest and largest river in China and the third in the world, the Yangtze River has not only nurtured Chinese civilization from ancient times but also gathered the largest number of inland ports in China. Since its origination in the high mountains and plateaus of Sichuan province in southeast east China, the Yangtze river has traversed more than two thousand miles when it meets the ocean in the middle of the eastern China seaboard. As one of the largest bifurcated estuary systems, the Yangtze Estuary waterways have two main channels: the northern channel and the southern one as depicted in Figure 2.

Figure 2. Yangtze River Estuary

Due to its close proximity to Shanghai, the most powerful economic engine in China today, the Yangtze River Estuary waterways have been used by a large number of vessels of tremendous size and cargo loads. As shown in Figure 3, the vessel types in both northern and southern channels have been dominated by generally large cargo ships. With slightly deeper channels, the northern waterway has had an even higher share of general cargo ships, and the southern channel caters to a larger share of passenger ships.

The length of the vessels is generally concentrated at the longer end, between 90 to 180 meters and some of them longer than 180 meters as shown in Figure 4. Comparing the distributions of the vessel length in both channels, it seems that the southern channel has the largest share of larger ships between 90 to 180 meters while the northern channel accommodated more of the largest ships, over 180 meters in length. The travel speed of those vessels in both waterways ranges from 8 to 16 kn. The speed distribution in both channels follows a normal distribution but with the northern channel skewed more toward the higher speed. For example, the large share of speed for the northern channel is between 14-16 kn while the southern channel 10-12 kn. It is rare but there is a small percentage of vessels that travel above 20 kn.

Figure 3. Vessel Type Distributions

Figure 4. Distribution of Ship Length

Figure 5. Distribution of Ship Speeds

4.2 Typical Ship Domain for the Yangtze River Estuary

Given the higher share of large cargo ships with a typical length of 90 to 180 meters as shown in Figure 3 and Figure 4, a general cargo ship, ranging in length from 90 to 180 meters, is the standard or typical ship chosen as the basis for ship domain estimation. Applying the approach presented in Section 3, the ship field has been divided into 72 equal sectors and the distances between the target ship and adjacent reference ships were plotted

Utilizing the AIS data for the past three years, the detailed locations of more than 150,000 vessels have been plotted according to the methodology introduced in Section 3. As shown in Figure 6, a typical ship domain was derived for the northern and southern fairways respectively. Confirming to the predictions by Fujii and Tanaka, the standard ship domain is very similar to an ellipse with long axis tilted to the right slightly. Using a 95% confidence interval, the boundary values for the long axis of a standard ship domain in the northern fairway is about 10 times the ship length, and the short axis 4 times the ship length. If the 99% confidence interval is applied, the boundary values for the long axis of the standard ship domain in the northern fairway becomes 6 times the ship length and the short axis 3 times the ship length. Detailed boundary values for both long and short axes for the northern and southern fairways are listed in Table 1. The experiment values fall well into the range of 3-8 times the ship length for the long axis and 1.6 times the ship length for the short axis, which are provided in existing literature. But the actual derivation of the specific typical ship domain for the northern and southern fairways respectively provided researchers a highly accurate base for further capacity analyses.

Table 1. Typical Ship Domain

confidence coefficient	Northern Fairway	Southern Fairway
95%	$10L\times4L$	$8L\times3L$
99%	$6L\times3L$	$6L\times2L$

Figure 6. Standard Ship Domain for Northern and Southern Fairways

4.3 Ship Density Calculations

Regarding ship domains, the travel speed is another important characteristic that affects the capacity or throughput of a particular waterway. The speed distribution in both northern and southern channels has been tested using a KS test and normal fitting curves as demonstrated in Figure 7. As mentioned before, the speed distribution for the southern fairway follows a typical normal distribution while the northern fairway skewed toward the higher speed categories. The larger concentration of vessel speed around 14-16 kn and the very small share for all speed categories greater than 16 kn is caused by the traffic control regulations.

Given the skewed distribution of speed in the northern fairway, the typical or standard speed cannot be represented by a simple mode, mean or average value alone. A statistical analysis of the speed profile for the northern fairway was performed and presented in Table 2. To avoid abnormal value, the derived median speed, 12.3 kn and 11.1 kn for vessels traversing the northern and southern fairways respectively, is used to substitute the “v” in Equation 2.

Figure 7. Normal Fitting of Speed Distributions

Table 2. The Statistical Analysis of Speed Distributions

	Northern Fairway	Southern Fairway		Northern Fairway	Southern Fairway
mean	11.8	10.9	kurtosis	179.66	272.0541
median	12.3	11.1	minimum value	1.7	0.3
mode	14.8	11.9	maximum value	26.9	26.8
Standard deviation	4.33	3.75	observed value	2119	3852
variance	18.71	14.08	Confidence (95.0%)	0.18	0.12

The width, *W* denoted in Equation 2, represents the width of waterway channels. In the Estuary context, the width of the channel is often increasing when approaching the ocean. However, given the traffic management conditions, the traffic flows are usually divided in two directions; therefore, *W* can be simplified as two times the short axis of the ship domain ellipse.

Given the diversified ship length, shape and operating characteristics, a statistical analysis was also performed to identify the typical ship length to be used to calculate capacity in bifurcated estuary channels. Applying the same approaches presented earlier, Shanghai Maritime Safety Administration has developed and adopted a set of conversion factors to identify a typical or standard ship. As presented in Table 3, the same conversion factors were applied and the typical ship length was identified as 175 and 121 meters for the northern and southern channels, respectively.

Once the standard ship domains are determined, it is straightforward to derive the ship density, which was included in Equation 2. Bringing the values of long and short axes of an ellipse to the density function ρ_{max} , the ship density was calculated for both northern and southern fairways for both 95% and 99% boundary conditions.

Table 3 Conversion Factor of Standard Ship (MSA of Shanghai)

The Length of Ship (m)	<30	30~50	50~90	90~180	>180
Conversion Factor	0.30	0.50	1.00	2.00	3.50

Proportion of ships in different lengths

The Length of Ship (m)	<30	30~50	50~90	90~180	>180
Northern Fairway (%)	2.95%	1.19%	0.54%	56.50%	38.82%
Southern Fairway (%)	6.32%	1.64%	19.64%	67.92%	4.48%

4.4 Modification Factors

Once all the parameters are estimated, the maximum capacity under ideal conditions can be calculated. However, the real world operations of inland or estuary waterways are far from perfect or ideal. The maximum capacities are often modified or impacted by weather conditions such as wind, wave, fog, and uneven distribution of vessel fleets. For example, there were 117 days in 2010 when the wind reached level 7 on the Beaufort scale; the wind speed was greater than 13.9 m/s, the ability of navigation was blocked; therefore, the capacity of the fairways was reduced to zero. Similarly, when the visibility is less than 1000 meters, no vessel is allowed to travel along the deep waters of the northern channel which reduces the throughput of the channel significantly. Table 4 presents the values of modification factors.

Table 4. Modification Factors

Modification Factors					
η_f	η_w	η_h	η_y	η_s	η
0.885	0.904	0.993	0.85	0.9	0.608

4.5. The Capacity Calculations

Applying the ship domain dimensions, speed distribution, and typical ship length derived from AIS data for the Yangtze estuary channels, the maximum capacity was derived for the northern and southern channels under ideal conditions. Further modified by the modification factors provided by the local marine management authority, the estimated maximum capacities for the northern and southern channels are 159,432 and 259,296 vessels per year respectively. The total throughput when both directions are combined is about 418,728 vessels per year.

Comparing the maximum capacities for both northern and southern channels with their respective observed throughput in the past three years, utilization rates for both channels can be derived. As presented in Figure 8, the traffic volume in the northern channel is fairly stable, hovering around 36 percent of the saturated capacity. The traffic volume in the southern channel experienced significant growth since 2011, and it reached almost 57 percent in 2014.

These facts could be possibly explained by the reason that a number of large projects, such as a 10.5-meter channel and 12.5-meter channel development had been invested in the pipelines. Compared with the actual data, the calculated capacity of the Yangtze River Estuary channel can meet current requirements, and there is still a large increase in the number of vessels. Accurate and timely estimation of the throughput for bifurcated estuary channels is the basis for planning long-term investment, optimizing operations, and improving water conditions in the near future.

Figure 8. Volume to Capacity Ratio for Northern and Southern Channels

5. CONCLUSION

The capacity estimation process documented in this manuscript took advantage of a large amount of AIS data collected in a particular location. The ever-increasing contributions and accumulations of AIS data and computation approaches will provide great opportunities to a further improvement in the ship domain estimation, which is useful not only for the safe movements of vessels but also maximization of capacity and/or optimization of marine transportation operations.

In the next-step research, more complicated methodologies for the ship domain in this estuary will be discussed. Moreover, the AIS data will be collected and evaluated for a more accurate estimation. Based on accurate capacity estimation, Maritime Administration may develop long range waterway plans, improve operations and ensure and/or improve the safety and efficiency of waterway systems.

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