Journal of Marine Science and Technology

Volume 25 | Issue 2 Article 25

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Recommended Citation
Liu, Zhao; Liu, Jingxian; Li, Zongzhi; Liu, Ryan Wen; and Xiong, Naixue (2017) "CHARACTERISTICS ANALYSIS OF VESSEL TRAFFIC FLOW AND ITS MATHEMATICAL MODEL," *Journal of Marine Science and Technology*: Vol. 25: Iss. 2, Article 25.
DOI: 10.6119/JMST-017-0109-1
Available at: https://jmstt.ntou.edu.tw/journal/vol25/iss2/25

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Acknowledgements

The work described in this paper was supported by grants from the National Natural Science Foundation of China (Project No. 51179147, 51609195, 51479156 and 51479157), and a grant from the Fundamental Research Funds for the Central Universities (Project No. 2013-YB-004).

Journal of Marine Science and Technology, Vol. 25, No. 2, pp. 230-241 (2017)
DOI: 10.6119/JMST-017-0109-1

CHARACTERISTICS ANALYSIS OF VESSEL TRAFFIC FLOW AND ITS MATHEMATICAL MODEL

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Key words: vessel traffic flow, behavior characteristics, structure characteristics, characteristics model.

ABSTRACT

Vessel traffic flow (VTF) is crucial for navigation safety, navigation efficiency, and port planning. In this paper, we analyze the structure and behavior of VTF in terms of both static and dynamic aspects according to the characteristics of ship motion. Moreover, the microscopic and macroscopic characteristics of VTF are analyzed according to the characteristics of a single ship as well as those of a large number of ships. We propose a model of vessel traffic flow characteristics (VTFC) by using the AND-OR graph that can represent the type and structure and behavior of VTF and their relationships. The proposed model consists of three levels, and the relationship among these levels is mathematically rendered. We then construct a mathematical model of VTFC, and use an example from Tianjin Port to demonstrate the effectiveness of our model. Our research provides theoretical support for statistical analysis of VTF, and can be used in practical applications to ensure navigation safety, improve navigation efficiency, and guide port layout planning.

I. INTRODUCTION

1. Background and Related Work

With the growing number of ports worldwide and the development of shipbuilding technology, the number and types of ships at sea are rapidly rising, and ships are becoming larger and more specialized. In view of the limitations of the navigation environment and navigable water resources, there is a pressing need for better navigation safety and efficiency. Vessel traffic flow (VTF) is closely related to navigation safety and efficiency, as well as practical port planning, and has received considerable attention in the research field of marine traffic engineering.

VTF consists of ships, rows, rafts, and other marine vessels, and describes their motion. In maritime transportation, the VTF model is commonly composed of five basic elements: the location, direction, width, density, and velocity of traffic flow. To better understand this phenomenon, a mathematical model of VTF was initially developed using classical traffic flow theories (Yip, 2013). A ship traffic model for ports was also designed based on ship features (Pachakis and Anne, 2003). Furthermore, the ship behavior was clustered to study the traffic flow in terms of marine and ship manoeuvrability (Inaishi and Kawaguchi, 2004). To better understand the vessel traffic, the traffic event was divided into several terms, such as ship particulars (i.e., type, length and width), route, departure time and speed, to simulate the collision risk (Floris and Pentti, 2011). The combination of integrated bridge system with microcosmic cellular automata (CA) model was then proposed to simulate the VTF by taking the ship identity, type, position, course, speed, and navigation status into account (Feng, 2013).

Important features of VTF include the duality, limitation, and variability of traffic flow. The corresponding mathematical model should represent the relationship among traffic volume, speed, and density (Liu, 2009). The relationship between ship behavior and waterway transit capacity has been investigated, resulting in a model of waterway transit capacity based on ship behavior (Liu and Wen, 2009). The behavior characteristics of VTF have also been studied and analyzed, including the time pattern of traffic flow in port water and bridge areas (Liu and Li, 2008; Liu et al., 2008; Liu et al., 2010; Liu et al., 2013; Liu et al., 2014). In order to support inland waterway simulations, the differences between a narrow waterway in the Netherlands (the Port of Rotterdam) and a wide one in China (wide waterway of Yangtze River close to the Su-Tong Bridge) are compared to show that straightforward statistical distributions can be used to characterize lateral position, speed, heading and interval times for different types and sizes of ships (Xiao et al., 2015). Meanwhile, VTF is more complex, and a marine traffic complexity model is introduce to evaluate the status of traffic situation (Wen et al., 2015).

To ensure navigation safety and improve navigation efficiency,

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VTF has been surveyed and analyzed in certain waters, including the Japan Strait, Taiwan Strait, Bohai Strait, Taiwanese harbors and Laotieshan Waterway (Yamaguchi and Sakaki, 1971; Gao, 2005; Liu, 2008; Wan, 2010; Chou et al., 2015). VTF in the Chengshantou waters area has been studied based on Automatic Identification System data (Zhang, 2010). Traffic flow in the Istanbul Strait was also analyzed to enhance local traffic management and improve marine traffic safety (Aydogdu et al., 2012).

VTF has also been applied to simulate port systems in order to optimize their scheduling. For example, the simulation model of ship-berth links has been developed based on VTF data, enabling decision-support for terminal managers (Dragovic et al., 2005). Another proposed simulation model is unique in the scale and complexity of the waterway networks covered, the flexibility in defining traffic flow patterns, and the degree of accuracy demanded of navigational behaviors (Huang et al., 2013). A cellular automaton model containing rules of vessel movement and collision avoidance manoeuvers was also proposed. This model could describe different types of vessels, and provide the basis for simulation and vessel traffic management (Blokus-Roszkowska and Smolarek, 2014).

In general, current research on VTF concentrates on its definition, structure, spatial and temporal characteristics, ship behavior, and the macroscopic representation of traffic flow. These studies have illustrated the importance of VTF in the fields of navigation safety and efficiency, as well as port planning. However, the practical application of VTF analysis has thus far been limited by the absence of a mathematical model exhibiting VTFC.

2. Motivation and Contributions

In the literature, navigation safety and efficiency are evaluated by using the flow volume and type of VTF alone. This suggests that the function of VTF is not fully considered, e.g., the influences of speed and arrival time of VTF on navigation safety and efficiency are not shown. Moreover, the VTFC are not fully used to guide port layout planning systematically. Thus, to ensure that knowledge of VTF is appropriately used for navigation safety, efficiency, and port layout planning, it is necessary to investigate, analyze, and model VTFC.

In this paper, we develop a new mathematical model to investigate VTFC. This differs from previous research in the following aspects:

1. We analyze VTFC with regard to structure, behavior, and type, and construct a VTFC model by using the AND-OR graph to clearly represent these characteristics and their relationships.
2. We propose a mathematical model of VTFC by using vectors and matrices. Our model is thus conducive to data acquisition and storage, and forms the basis for the automatic provision of VTF statistics and analysis.
3. Our model clearly and fully exhibits VTFC.

The previous VTF model is composed of five basic elements: the location, direction, width, density, and velocity of traffic flow. It represents a visual performance of VTF, and hence lacks some important information about ships, such as their behavior and size. The main benefits of our proposed method are that it takes these ship characteristics into account, and clearly and fully exhibits VTF. Thus, the proposed model can effectively represent VTF in practice. For example, it can be used in certain aspects of navigation safety and efficiency, as well as in the systematic planning of port layouts.

3. Organization and Framework

The remainder of this paper is organized as follows: The next section contains a description of the notation used in this paper. We then introduce the AND-OR graph and characteristics model, and describe the vessel traffic flow modelling process. Next, we detail VTF and its characteristics. The characteristics are then analyzed in terms of both static and dynamic aspects from microscopic and macroscopic perspectives. We then construct a model by using the AND-OR graph to express VTFC, and construct a relationship model to express the relationships among the characteristics. Finally, we design a mathematical model to express the characteristics and their relationships in abstract form. The mathematical model expresses the state of VTF in vector space. This mathematical model is used to analyze VTF at Tianjin Port. Our contributions are summarized and directions for future work discussed at the end of the paper.

II. NOTATION

The following symbols are used throughout this paper:

(1) $VTFC$, I, A, T, S, B, and I are matrices.
(2) $VTFC$ expresses vessel traffic flow characteristics.
(3) I expresses microscopic characteristics of VTF.
(4) A expresses macroscopic characteristics of VTF.
(5) T expresses type characteristics of VTF.
(6) S expresses structure characteristics of VTF.
(7) B expresses behavior characteristics of VTF.
(8) Tr, Tc, To, Si, Bi, Sa, and Ba are vectors.
(9) Trj ($j = 1, 2, 3, \ldots, n$) and Tcj ($j = 1, 2, 3, \ldots, n$) are categories of VTFC.
(10) Sij ($j = 1, 2, 3, \ldots, n$) and Bij ($j = 1, 2, 3, \ldots, n$) are sets of ship data that represent the values of different microscopic characteristics of VTF.
(11) Saj ($j = 1, 2, 3, \ldots, n$) and Baj ($j = 1, 2, 3, \ldots, n$) are sets of statuses of different macroscopic characteristics of VTF.

III. METHODS AND PROCESSES

1. AND-OR Graph and Characteristics Model

The AND-OR graph is a new representation of Boolean functions that does not always have to be constructed to its full size to be useful in solving different problems. In many applications, it is sufficient to enumerate the AND-OR graph only partially in order to extract valuable information about the given problem (Stoffel et al., 1995).

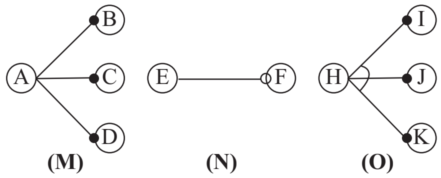

Fig. 1. Model of characteristics. (M) shows the required characteristics model, where *B, C,* and *D* are indispensable to *A*. (N) shows the optional characteristics, where *F* may appear in *E*. (O) shows the XOR characteristics model, where only *I, J,* and *K* appear in *H*.

AND-OR graphs contain the AND, OR, and XOR gates (Chen, 2007). All gates in the characteristics model have a unique Boolean label according to how their output is realized. The required characteristics are proposed based on an AND gate, meaning that the sub-characteristics must exist. Optional characteristics are proposed based on an OR gate, which means that the sub-characteristics need not exist. The XOR characteristics are proposed based on the XOR gate, whereby only one sub-characteristic can exist.

Thus, the required characteristics are indispensable, and are represented by a line ending at a solid point. There are no strings on their own line segment. The required characteristics model is shown in Fig. 1. (M). The optional characteristics are not indispensable, and are represented by lines ending at a hollow point; the optional characteristics model is shown in Fig. 1. (N). The XOR characteristics indicate that there is only one sub-characteristic included, and these are represented by a line ending at a solid point with a single sideband string. The XOR characteristics model is shown in Fig. 1. (O).

2. Modelling Process of VTFC

The modelling process of VTFC has three stages:

Stage 1

definition and connotation of VTFC. The definition and connotation of VTFC are proposed based on the connotation of VTF itself. These provide the foundation for the identification and analysis of VTFC.

Stage 2

identification and analysis of VTFC. The identification and analysis of VTFC is the foundation for our construction of a VTFC model.

Stage 3

construction of VTFC model and its relationship and mathematical models. The VTFC model is based on the analysis of VTFC by using the AND-OR graph. The relationship model is constructed based on the VTFC model, and finally the mathematical model is proposed on the basis of the relationship model by using vectors and matrices.

IV. VESSEL TRAFFIC FLOW CHARACTERISTICS

1. Vessel Traffic Flow

VTF describes the properties and state of a ship as well as its movement. The features of VTF include duality, limitation, variability, and complexity. The duality of VTF means that not only is traffic flow affected by traffic management constraints, but also that the flow can change the velocity of ships and their relative positions. The limitation of VTF refers to restrictions imposed by channel conditions, water conditions, the natural environment, and so on. Furthermore, there exists mutual interference between any two ships. The variability of VTF implies that traffic flow will change with time in the same waters, and that traffic flow in different waters will have different characteristics. The complexity of VTF means that ship movement is under human control, and thus velocity and direction are adaptive under the manipulation of a human operator.

2. Definition and Connotation of VTFC

VTF incorporates ship movement and ship properties, which are affected by relatively stable natural factors. The VTFC include static inherent characteristics (called structure characteristics) and dynamic characteristics (called behavior characteristics).

Structure characteristics are determined by the ship properties, and are relatively stable at a given place and time. These include microscopic structure and macroscopic structure characteristics. Behavior characteristics of traffic flow may change at different points or at different times, and include macroscopic behavior characteristics and microscopic behavior characteristics.

In general, VTFC are the sum of the structure characteristics and behavior characteristics of the ships. In narrow terms, VTFC refer to a large number of ships, but do not actually include a single ship. In this paper, the VTFC include single ship characteristics.

V. CHARACTERISTICS ANALYSIS OF VTF

VTFC are clustered as structure or behavior characteristics depending on whether they are static or dynamic, respectively. Similarly, they can be identified as microscopic or macroscopic characteristics for a single ship or a large number of ships, respectively.

1. Structure Characteristics of VTF

The structure characteristics of VTF include both the structure characteristics of the relevant ship and the distribution of these characteristics. In other words, the structure characteristics of VTF consist of macro-structure and micro-structure characteristics. The structure characteristics include the ship type, tonnage, age, nationality, and scale (draft, length, and breadth).

2. Behavior Characteristics of VTF

For safe and efficient movement, ships must act and react at different points and times to adapt to their navigation environment. Hence, the behavior characteristics of VTF include the ship behavior, the distribution of ship behavior, and other dynamic characteristics reflecting the movement of a large number of ships. In other words, the behavior characteristics of VTF con-

Table 1. Microscopic characteristics of vessel traffic flow.

Category	Characteristics				
Structure	Type	Tonnage	Scale	Vessel Age	Nationality
Behavior	Position	Speed	Heading	Distance or Time Distance Between the Ships	Draft

Table 2. Macroscopic characteristics of vessel traffic flow.

Category	Characteristics					
Structure	Ship Number	Type Distribution	Tonnage Distribution and Representative Values	Scale Distribution and Representative Values	Age Distribution and Representative Values	Nationality Distribution
Behavior	Position Distribution	Speed Distribution and Representative Values	Temporal Distribution and Representative Values	(Time) Distance Distribution and Representative Values	Draft Distribution and Representative Values	Heading Distribution and Representative Values

sist of macro-behavior and micro-behavior characteristics. Ship behavior refers to its position, velocity, direction, distance, and the time between any two neighbouring ships.

3. Microscopic Characteristics of VTF

The microscopic characteristics of VTF are the objects of its statistical characteristics. These are also called micro-characteristics in this paper. Microscopic characteristics include micro-behavior and micro-structure characteristics. To determine the micro-characteristics of VTF, we must collect and store data related to the structure characteristics and the ship behavior. Structure characteristics mainly refer to those essential characteristics of a ship that are relatively stable at a given point in space and time. Behavior characteristics mainly refer to the changing behavior of ships during movement, and thus vary at different points in space and time. Microscopic characteristics of VTF are listed in Table 1.

4. Macroscopic Characteristics of VTF

The macroscopic characteristics of VTF combine the characteristics of a large number of ships. These characteristics include both macro-behavior and macro-structure characteristics.

The macroscopic characteristics of VTF, also called macro-characteristics in this paper, are derived from statistical analysis of large amounts of ship data. In general, the macroscopic characteristics of VTF can be obtained from the microscopic characteristics. Macroscopic characteristics can be further divided into macro-structure and macro-behavior characteristics, which can be represented by distribution and representative values (i.e., mean value, min-value, and max-value). Macro-structure characteristics are determined using data related to ship properties (ship, type, tonnage, age, nationality, and scale), and are composed of data regarding the micro-static characteristics of VTF. Macro-behavior characteristics of VTF are determined by the behavior data of the ship. The macroscopic characteristics of VTF are listed in Table 2.

VI. MATHEMATICAL MODEL OF VESSEL TRAFFIC FLOW CHARACTERISTICS

1. Clustering Vessel Traffic Flow Characteristics

Structure and behavior characteristics can be further divided into microscopic characteristics and macroscopic characteristics respectively. Moreover, VTFC vary with region and ship type. Thus, VTFC should consist of traffic flow type, along with characteristics related to the structure and behavior of the VTF.

The type of VTF is determined according to the region or the statistical object (ship type). The VTF type may be inland, coastal, open water, port water, reservoir water, etc., according to the region. Furthermore, VTF type should consider the object at hand, i.e., tanker, container ship, bulk-cargo ship, integrated VTF, etc.

Structure characteristics describe the type, tonnage, age, nationality, and scale (draft, length, and breadth) of the ship, as well as the distribution and representative values of these factors.

Behavior characteristics include the ship position, velocity, direction, distance, time between ships, and the distribution and representative values of these factors. In particular, the ship spatial distribution can be regarded the ship position distribution which could be statistically analyzed from two scenarios. First, the ship position distribution at a specific time point could illustrate the corresponding maritime traffic situation. On the other hand, the ship position distribution calculated from the massive historical data could represent the spatial density of cumulative traffic flow in a specific waters.

2. Construction of VTFC Model

The VTFC model consists of three levels. The first level considers the VTF type, structure characteristics, and behavior characteristics.

It is important to determine the type of VTF in order to study its characteristics. Because the gap between different ship types and regions is large, VTFC are divided into region characteristics, classification characteristics, and other characteristics.

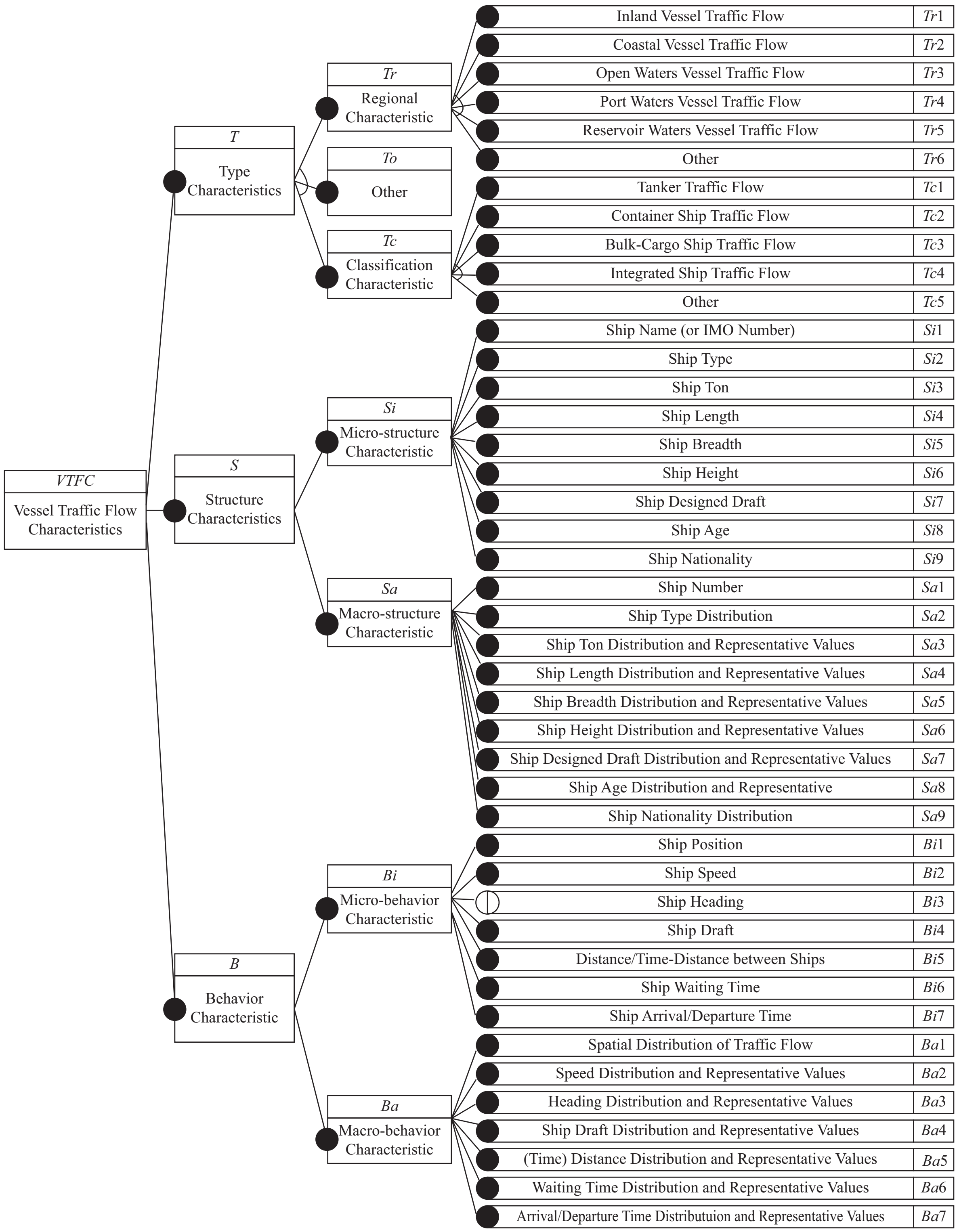

Fig. 2. Model of VTF characteristics. VTF characteristics are expressed as *VTFC*. The first level consists of type characteristics, structure characteristics, and behavior characteristics, expressed as *T*, *S*, and *B*, respectively. The second and third levels are shown in the third and fourth columns, respectively.

These three groups are XOR characteristics. That is to say, we should have characteristics from only one of these groups.

Structure characteristics form an important part of traffic flow characteristics. These consist of macro-structure and micro-structure characteristics, both of which include lower-level characteristics.

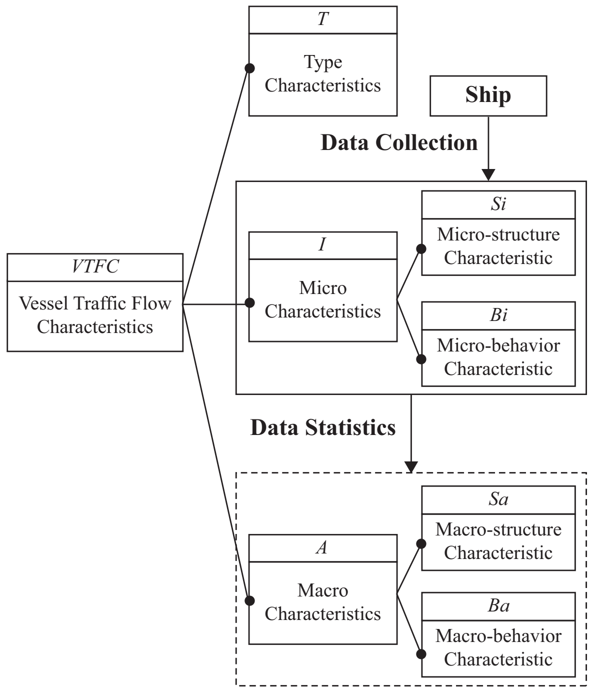

Fig. 3. Relationship model for VTF characteristics. The characteristics of VTF are denoted by *VTFC*. The type, microscopic, and macroscopic characteristics are expressed as *T*, *I*, and *A*, respectively. *I* can be collected from ships, and *A* can be obtained using statistics related to *I*.

Behavior characteristics are another important aspect of VTFC. Likewise, their lower-level characteristics include macro-behavior and micro-behavior characteristics. However, some lowest-level characteristics are optional.

Using the type of VTF, behavior and structure characteristics, and macroscopic and microscopic characteristics, we can form a VTFC model. The characteristics model (shown in Fig. 2) is constructed by using the AND-OR graph based on the categorization of VTFC.

To use VTFC appropriately, we must set up a suitable relationship model on VTFC. Microscopic characteristics form the basis of macroscopic characteristics, and macroscopic characteristics can be obtained from the data related to microscopic characteristics. Data related to microscopic characteristics can be collected from ships in turn. Thus, the relationship model for VTFC can be designed using microscopic and macroscopic characteristics. The relationship model is shown in Fig. 3.

The data of micro-structure characteristics, dependent on the target ship properties, can be obtained by recording the ship name, type, ton, length, breadth, height, designed draft, age, and nationality. In addition, the data of micro-behavior characteristics, dependent on the target ship behavior and the corresponding navigation environment, can be obtained by recording the position, speed, heading, draft, distance between two ships, ship waiting time, and arrival time.

3. Mathematical Model of VTFC

In the characteristics model (Fig. 2) and the relationship model (Fig. 3), *VTFC, T, S, B, I, A, Tr, To, Tc, Si, Sa, Bi,* and *Ba* are vectors. *Trj*, *Tcj*, *Sij*, S*aj*, *Bij*, and *Baj* ($j = 1, 2, 3, \ldots, n$) express third-level characteristics, with *Sij* and *Bij* representing the values of microscopic characteristics, and *Trj*, *Tcj*, *Saj*, and *Baj* denoting the status of the macroscopic characteristics. The relationships among the characteristics of vessel traffic flow can then be written as follows:

$$VTFC = T \cup S \cup B = T \cup I \cup A \tag{1}$$

$$T = Tr \text{ or } Tc \text{ or } To \tag{2}$$

$$S = Si \cup Sa \tag{3}$$

$$B = Bi \cup Ba \tag{4}$$

$$I = Si \cup Bi \tag{5}$$

$$A = Sa \cup Ba \tag{6}$$

$$Tr = Trj\ (j = 1, 2, 3, \ldots, 6) \tag{7}$$

$$Tr = Tcj\ (j = 1, 2, 3, \ldots, 5) \tag{8}$$

$$Si = S \cap I = Si1 \cup Si2 \cup \ldots \cup Si9 \tag{9}$$

$$Sa = S \cap A = Sa1 \cup Sa2 \cup \ldots \cup Sa9 \tag{10}$$

$$Bi = B \cap I = Bi1 \cup Bi2 \cup \ldots \cup Bi7 \tag{11}$$

$$Ba = B \cap A = Ba1 \cup Ba2 \cup \ldots \cup Ba7 \tag{12}$$

The VTFC model can be expressed as a matrix consisting of microscopic and macroscopic characteristics. Because microscopic characteristics form the basis of VTF, which is expressed by macroscopic characteristics, the characteristics model of VTF should consist of microscopic characteristics, expressed by *I*, and macroscopic characteristics, expressed by *A*. The mathematical model of the VTFC can thus be expressed as follows:

$$VTFC = (T, I, A) \tag{13}$$

$$I = (Si, Bi) \tag{14}$$

$$A = (Sa, Ba) \tag{15}$$

$$Si = (Si1, Si2, \ldots, Si9)^T \tag{16}$$

$$Sa = (Sa1, Sa2, \ldots, Sa9)^T \tag{17}$$

Table 3. Ship lengths processing.

Length (m)	2010	2011	2012	2013	2014
0-50	15	6	9	17	57
50-100	10037	8436	6827	6141	6140
100-150	5839	6421	5827	5555	5283
150-200	4350	4850	5303	5087	5211
200-250	1192	1118	1063	1365	1454
250-300	1069	1217	1281	1384	1640
300-350	456	334	358	321	321
350-400	105	132	241	326	334
Ave. length (m)	137.66	142.8	149.73	153.7	155.8

$$Bi = (Bi1, Bi2, \ldots, Bi7)^T \tag{18}$$

$$Ba = (Ba1, Ba2, \ldots, Ba7)^T \tag{19}$$

We make the assumption functions F:

$$F\begin{pmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{pmatrix} = \begin{pmatrix} f_{11}(x_{11}) & \cdots & f_{1n}(x_{1n}) \\ \vdots & \ddots & \vdots \\ f_{m1}(x_{m1}) & \cdots & f_{mn}(x_{mn}) \end{pmatrix} \tag{20}$$

The relationship between the macroscopic and microscopic characteristics, and the mathematical model of VTFC, can then be written as follows:

$$A = F(I) = F(Si; Bi) = F(Si1, \ldots, Si9; Bi1, \ldots, Bi7) \tag{21}$$

$$VTFC = F\begin{pmatrix} T; & I \\ T; & A \end{pmatrix} = \begin{pmatrix} T; & Si; & Bi \\ T; & f_{22}(Si); & f_{23}(Bi) \end{pmatrix} \tag{22}$$

From Eqs. (1) to (22), *VTFC* represents data matrices including all information of vessel traffic flow characteristics, which can be divided into *T*, *S* and *B*. Here, *T* represents type of vessel traffic flow, *S* denotes the structure of vessel traffic flow, *B* is related to the behavior of vessel traffic flow. In addition, *VTFC* can also be divided into *T*, *I* and *A*. Here, *I* denotes the micro-characteristics of vessel traffic flow, *A* denotes the macro-characteristics of vessel traffic flow. *Tr* represents the geographic region of VTF, *Tr*1 denotes the inland vessel traffic flow, *Tr*2 denotes the coastal vessel traffic flow, *Tr3* represents the vessel traffic flow in open waters, *Tr*4 denotes the vessel traffic flow in port waters, *Tr*5 represents the reservoir vessel traffic flow, *Tr*6 is related to other region vessel traffic flow; *Tc* represents the classification of vessel traffic flow, *Tc*1 denotes the tanker vessel traffic flow, *Tc*2 denotes the container vessel traffic flow, *Tc*3 denotes the bulk-cargo vessel traffic flow, *Tc*4 denotes the integrated vessel traffic flow, *Tc*5 denotes other classification vessel traffic flow; *To* is other type of VTF. *Si* represents micro-structure characteristics, *Si*1 is ship name or ship IMO number, *Si*2 is ship type, *Si*3 is ship ton, *Si*4 is ship length, *Si*5 is ship breadth, *Si*6 is ship height, *Si*7 is ship designed draft, *Si*8 is ship age, *Si*9 is ship nationality; *Sa* represents macro-structure characteristics, *Sa*1 is ship number, *Sa*2 is ship type distribution, *Sa*3 is ship ton distribution and representative values, *Si*4 is ship length distribution and representative values, *Sa*5 is ship breadth distribution and representative values, *Sa*6 is ship height distribution and representative values, *Sa*7 is ship designed draft distribution and representative values, *Sa*8 is ship age distribution and representative values, *Si*9 is ship nationality distribution. *Bi* represents micro-behavior characteristics, *Bi*1 is ship position, *Bi*2 is ship speed, *Bi*3 is ship heading, *Bi*4 is ship draft, *Bi*5 is distance or time-distance between two ships, *Bi*6 is ship waiting time, *Bi*7 is ship arrival or departure time; *Ba* represents macro-behavior characteristics, *Ba*1 is ship spatial distribution of traffic flow, *Ba*2 is ship speed distribution and representative values, *Ba*3 is ship heading distribution and representative values, *Ba*4 is ship draft distribution and representative values, *Ba*5 is distance or time-distance distribution and representative values, *Ba*6 is ship waiting time distribution and representative values, *Ba*7 is ship arrival or departure time distribution and representative values.

VII. EXAMPLE OF VTFC MODEL

We used data related to ships at sea around Tianjin Port, China, to analyze the performance of the proposed VTFC model.

1. Tianjin Port

Tianjin Port is the largest port in northern China and the main maritime gateway to Beijing. In 2013, it handled 500 million tons of cargo and 13 million twenty-foot equivalents (TEUs) of containers, making it the world's fourth-largest port according to throughput tonnage and ninth in container throughput. The data used in this paper are ship data for Tianjin New Port

Table 4. Ship breadth processing.

Breadth (m)	2010	2011	2012	2013	2014
0-10	804	707	458	325	381
10-20	12660	11254	9788	9139	8957
20-30	5570	6261	5919	5459	5402
30-40	3095	3460	3782	4191	4465
40-50	802	696	790	876	946
50-60	122	125	159	179	255
60-70	10	11	13	27	34
Ave. width (m)	20.91	21.68	22.69	23.34	23.75

Table 5. Ship nationality processing.

Nationality	2010	2011	2012	2013	2014
China Ships	14913	14681	12759	11885	12303
Others	8150	7833	8150	8311	8137

Table 6. Ship draft processing in 2014.

Draft (m)	2010	2011	2012	2013	2014
0-5	7961	8256	6636	6673	6319
5-10	12884	11841	11399	10419	11164
10-15	1876	2063	2423	2548	2286
15-20	342	354	451	556	671
Ave. draft (m)	6.26	6.33	6.7	6.82	6.87

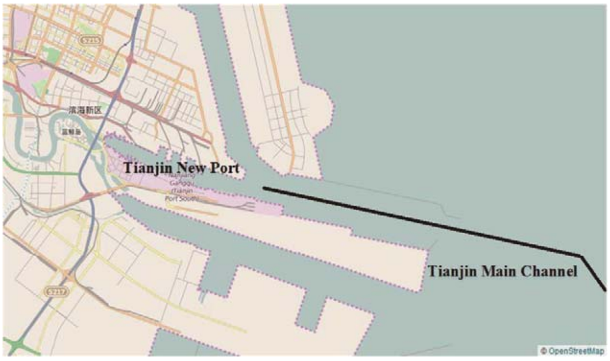

Fig. 4. Tianjin port. Channels and anchorages are shown in the figure.

(Tianjin Main Channel) obtained from the Vessel Traffic Service Center of the Tianjin Maritime Safety Administration. The port is shown in Fig. 4.

2. Source of Ship Data

The incoming ship data were recorded from 2010-2014. The recorded data consist of the name, International Maritime Organization (IMO) number, nationality, arrival time, length, breadth, and draft of each ship at Tianjin Port.

3. Ship Data Processing

Because the data relate to ships at Tianjin Port, the VTF type is 'port waters'.

(1) Number of ships

Data related to 107122 ships at Tianjin Port from 2010-2014 were analyzed.

(2) Ship length

The maximum recorded ship length in our dataset was 399.67 m and the minimum was 22.3 m. Ships lengths were processed in units of 50 m. The ship lengths are shown in Table 3.

(3) Ship width

The maximum recorded width was 60.14 m and the minimum was 3.5 m. The widths were processed in units of 10 m. The recorded ship widths are shown in Table 4.

(4) Ship nationality

The ship nationalities are shown in Table 5.

(5) Ship draft

The maximum recorded draft in our dataset was 18.32 m and the minimum was 1 m. The drafts were processed in units of 5 m. The ship drafts are listed in Table 6.

Table 7. Ship arrival time processing.

Time	2010	2011	2012	2013	2014
January	1823	1935	1506	1554	1573
February	1356	1411	1656	1157	1171
March	1946	2164	1912	1804	1741
April	2026	2096	1792	1663	1771
May	2273	2100	1873	1815	1795
June	2057	1969	1680	1631	1754
July	2044	1989	1755	1681	1752
August	1978	1909	1725	1769	1772
September	1882	1882	1918	1707	1807
October	1909	1963	1798	1709	1819
November	1971	1732	1677	1871	1769
December	1798	1364	1617	1835	1716
Ave. number	1922	1876	1742	1683	1703

Table 8. Ship heading processing.

Heading (°)	273	274	275	276	277	278	279
Number of Ship	11	18	18	30	53	117	281
Heading (°)	**280**	**281**	**282**	**283**	**284**	**285**	**Ave. (°)**
Number of Ship	401	290	108	37	20	18	279.8

Table 9. Ship speed processing.

Speed (kn)	6	7	8	9	10	11
Number of Ship	53	95	111	127	403	286
Speed (kn)	**12**	**13**	**14**	**15**	**Ave. speed (kn)**	
Number of Ship	198	115	8	5	10.6	

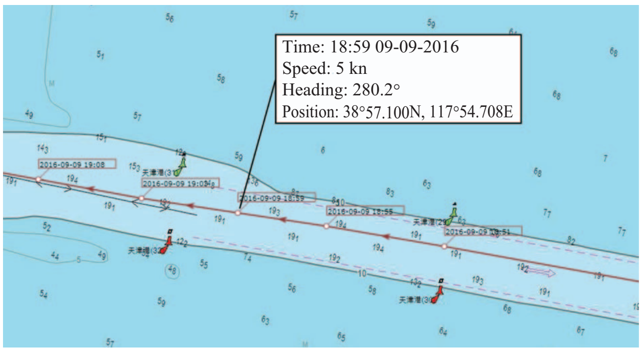

Fig. 5. An example of micro-behavior characteristics of vessel traffic flow in Tianjin port. More details about the micro-characteristics are available at http://www.shipxy.com/.

(6) Ship arrival time

Ship arrival time data should consist of month, day, and hour, or other units of time. We selected months as the ship arrival time units here. Ship arrival times are listed in Table 7.

(7) Other micro-behavior characteristics

Besides arrival time and draft of the ship, the ship position, heading and speed are also important characteristics of ship behavior. The recorded position, heading and speed data can be used to assist maritime supervision in practice. An example of micro-behavior characteristics of VTF in Tianjin port is visually illustrated in Fig. 5.

(8) Other macro-behavior characteristics

The statistical distributions and mean value on ship speed and heading can be obtained by analyzing the recorded micro-behavior characteristics of VTF from the incoming ship in December 2014. The main channel route is 99.6°-279.6° near data collection area. The ship heading and speed are respectively shown in Tables 8 and 9.

4. Mathematical Description of the VTFC

Using the VTFC model and the Tianjin Port ship data, the relevant characteristics of the Tianjin Port VTF can be expressed by a mathematical model in 2014. The relevant characteristics are as follows:

$$Tr = Tr4 \tag{23}$$

$$S = (Ti1, Ti4, Ti5, Ti9; Sa4, Sa5, Sa9) \tag{24}$$

$$B = (Bi4, Bi7; Ba4, Ba7) \tag{25}$$

$$Sa1 = (20400) \tag{26}$$

$$Sa4 = (57, 6140, 5283, 5211, 1454, 1640, 321, 334; 155.8) \tag{27}$$

$$Sa5 = (381, 8957, 5402, 4465; 946, 25, 34; 23.75) \tag{28}$$

$$Sa9 = (12303, 8137) \tag{29}$$

$$Ba4 = (6319, 11164, 2286, 371; 6.87) \tag{30}$$

$$\begin{aligned} Ba7 = (&1573, 1171, 1141, 1771, 1795, 1754, \\ &1752, 1772, 1807, 1819, 1769, 1716; 1703) \end{aligned} \tag{31}$$

$$A = (Sa1, Sa4, Sa5, Sa9; Ba4, Ba7) \tag{32}$$

$$\begin{aligned} VTFC = (&Tr4; Si1, Si4, Si5, Si9; Bi4, Bi7, Tr4; \\ &Sa1, Sa4, Sa5, Sa9; Ba4, Ba7) \end{aligned} \tag{33}$$

$$VTFC_{2014} = \begin{array}{c} \left(\begin{array}{ccccccc} Tr4 & tianrong & 96 & 16.2 & China & 3 & 1 \\ & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \hdashline Tr4 & 20400 & 155.8 & 23.7 & 0 & 6.87 & 1703 \\ & & 57 & 381 & 12303 & 6319 & 1573 \\ & & 6140 & 8957 & 8137 & 11164 & 1171 \\ & & 5283 & 5402 & & 2286 & 1741 \\ & & \vdots & \vdots & & \vdots & \vdots \end{array} \right) \end{array} \begin{array}{l} \text{Micro-} \\ \text{characteristics} \\ \text{Macro-} \\ \text{characteristics} \\ \\ \\ \\ \end{array} \tag{34}$$

The representative matrix in Eq. (34) describes the VTFC of Tianjin port in 2014. It can be observed that both micro- and macro-behavior characteristics, including information on ship type, ship length, ship breadth, ship nationality, ship draft, ship arrival time, and the number of ships in the traffic flow, can be represented simultaneously. Similarly, the VTFC of

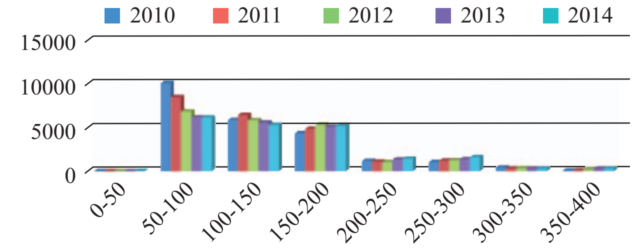

Fig. 6. The length distribution of ships from 2010 to 2014. This is a simple example about the characteristic distribution of VTF. The statistical result can be used to illustrate that the *VTFC* information is available for evaluating the characteristic evolution of VTF.

Tianjin port from 2010-2013 can be expressed using the Eq. (33). Essentially, VTFC can be quantitatively represented as a time-dependent data series. Therefore, the same VTFC extracted from the representative matrices with respect to 2010-2014 can be further visually displayed using the figures. The visual results can make people better understand VTFC, and illustrate the dynamic evolution of VTF. As shown in Fig. 6, the length distribution of ships in Tianjin port from 2010-2014 is visually demonstrated as a realistic example.

5. Discussion

The recorded data of VTF, extracted from the Tianjin Port during the period 2010-2014, was used to construct a simplified mathematical model to represent the VTFC. The model contained basic data and state data regarding the relevant VTFC. Thus, the sample data and processed data could be easily stored and retrieved from the VTFC matrix. And the characteristics can be shown in time series by using some models of VTFC.

However, our model used only the number of ships, their length, width, nationality, draft, and arrival time. The data processing was slightly simplified. For instance, the magnitude of length was set in units of 50 m, the magnitude of breadth was set in units of 10 m, and the magnitude of length was set in units of 50 m. In addition, the simplified mathematical model (34) do not include the statistical data on ship speed and heading because that the data of ship speed and heading are not obtained completely. Our current work suffers from some potential limitations, but it is still worthy of consideration because the effectiveness of the proposed method has been demonstrated using the realistic data. We believe the proposed method can be further improved data records and analysis of VTF to increase the application value of the VTF in navigation safety, navigation efficiency, and port planning.

VIII. CONCLUSIONS AND FUTURE WORK

1. Conclusions

In this paper, we constructed a relationship model and a mathematical model of VTFC, and analyzed its components in detail. Our conclusions are as follows:

(1) We analyzed the structure and behavior of VTF in terms of both static and dynamic aspects according to the properties and characteristics of ship motion. Furthermore, we analyzed microscopic and macroscopic characteristics, which represent single ship characteristics and those of a large number of ships, respectively.
(2) We developed a three-level model representing VTFC according to the type of flow, dynamic and static characteristics, and macroscopic and microscopic characteristics of VTF. The first level considers the VTF type, as well as the structure and behavior characteristics of VTF. The second level of the model consists of subclasses of vessel type, along with further structure and behavior characteristics. The third level incorporates specific characteristics of VTF.
(3) A relationship model for VTFC was constructed to express the relationship between macroscopic and microscopic characteristics of traffic flow, and this reflects the relevant basic data.
(4) We constructed a mathematical model representing VTFC using matrices and vectors. The model is useful for storing data and representing VTFC.
(5) We used ship data from waters around Tianjin Port during the period 2010-2014, to construct a simplified model representing VTFC.

2. Future Work

The VTFC model plays an important supporting role in the statistical analysis and prediction of VTF, as well as the storage and retrieval of VTF data. We proposed models for the characteristics and relationships of VTF. However, we did not undertake a detailed statistical analysis of the individual characteristics, and did not reflect on the practical applications of these models in a systematic or comprehensive manner. Hence, our next study will investigate these aspects.

ACKNOWLEDGEMENTS

The work described in this paper was supported by grants from the National Natural Science Foundation of China (Project No. 51179147, 51609195, 51479156 and 51479157), and a grant from the Fundamental Research Funds for the Central Universities (Project No. 2013-YB-004).

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