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Ship Behavior in Ports and Waterways: An Empirical Perspective

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Ship Behavior in Ports and Waterways: An Empirical Perspective

Proefschrift

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door

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Dedicated to
My husband Wen Zhang

"*A time will come to ride the wind and cleave the waves,*
I'll set my sail and cross the sea which raves."
长风破浪会有时，直挂云帆济沧海。

—Bai Li (701–762)

Preface

Incredibly, it has been nine years since I started my PhD in 2013. Today, I received the approval of this dissertation in the last ten minutes of my 33rd birthday. Yes, my birthday wish just came true. Looking back this journey, it is a story of my personal growth and achievement with unexpected struggles and final survival. However, I can never make it without the encouragement and support from so many lovely people around me during these years. Now I would like to express my sincere gratitude to all of you.

First of all, I would like to say a huge thank you to my promoters, Winnie Daamen, Serge Hoogendoorn, and Tiedo Vellinga. Tideo, thank you for giving me the opportunity to start this amazing journey and the caring support from you and Rita to enjoy it. Through the connection with the port of Rotterdam, you always remind me to think about the practical application of the theoretical research. Serge, thank you for always providing the creative ideas and the impressive inspirations. Your enthusiasm also drives me during the research. Winnie, it is my great honor to be the first doctoral candidate having you as the corresponding promoter. Thank you for the critical but constructive comments and suggestions keeping me improving and shaping me into an independent researcher. Besides, special thank goes to your caring attention to my mood and gentle guidance to search for professional help. I really learned a lot from you which will benefit my future career.

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深深地感谢我的父亲周勇和母亲欧阳萍一直以来对我的关爱，过去的这些年，我的人生经历了太多波折，感谢你们对我每一次的决定都给予无条件的支持，也希望我已然成为你们最大的骄傲。感谢我所有的家人和朋友对我的关心。

Finally, to my beloved boyfriend, fiancé, husband, Wen, thank you for the trust, love, accompany, and support during all those laughters and tears in the past years. Side by side, we enjoy the sunshine; hand in hand, we face the storm. Now, let’s cheer up and carry on!

Yang Zhou,
Wuhan, September 2022

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1. Introduction

Waterborne transport has become one of the major freight transportation modes with great contribution to the global economy (United Nations Conference on Trade and Development, 2021). Due to the increasing ship size, the large amount of cargo carried by individual ships, and the high frequency of ships visiting the hub ports, the safety of ships and the capacity of ports have been global challenges with high priority for nautical traffic management and port authorities. Both efficient traffic management and predictive port design require a systematic and thorough understanding of ship behavior in port and inland waterways. This dissertation presents a comprehensive investigation of ship behavior in ports and waterways revealed by real-life data, which provides systematic insights into the influencing mechanisms of external factors in ship's navigation. In this chapter, the research motivation is elaborated based on the research background in section 1.1, followed by the formulation of research objectives and research questions in section 1.2, and the adopted research approach in section 1.3. In section 1.4, the contributions of this research are introduced from scientific and practical perspectives. Finally, the outline of this dissertation is described in section 1.5.

1.1 Research motivations

As one of the most important freight transportation modes, maritime transport has been the backstone of international trade and global economy. According to the annual report by the United Nations Conference on Trade and Development (2021), even under the impacts of the COVID-19 pandemic, maritime transport still carries more than 80% of international merchandise trade by volume, with an increase of 4.3 percent to the shock in the year 2020. For most of the countries all over the world, maritime transport is also crucial for their economic system as a fundamental role in import and export trading (Lee et al., 2019). From the cargo flow point of view, seaports and inland shipping link the individual countries to the global waterborne transportation networks. With the growing demand for maritime transport, the ship traffic flow is also expected to increase. For nautical traffic management in seaports and inland waterways, the understanding of ship behavior characteristics and the underlying mechanism is essential.

Due to its importance to global and domestic economy, the maritime transport related academic research has also attracted wide attention, aiming at improving its sustainable development with emerging technologies and increasing demand. Among the researches, Shi and Li (2017) identified three distinct research themes after reviewing 1,292 papers in the maritime transport domain, being maritime fleet, shipping, and port. By a structural topic model using text mining techniques, the topics and trends in the maritime transport are further identified (Bai et al., 2021). In the port related research, the most topical issues include port management, performance evaluation, port condition estimation, and terminal management as well. In the respect of shipping, the topics on ship trajectory analysis and prediction, ship risk prediction and safety management attract most attention, followed by the research on energy efficiency and ocean freight market analysis. Therefore, the researchers reach upon a consensus that achieving the objective of port development requires both ship safety and port capacity. Besides the constantly emerging technologies in reaching the objective, the analysis of ship behavior in the ports is also fundamental.

In the field of maritime transport research, as reviewed by Talley (2013), the proposition theoretical research is particularly used for which data are unavailable, unaccessible, insufficient, or of poor quality. However, over a decade, besides the classical approaches, such as literature review, survey, questionnaire, conceptual analysis, case study, more research adopted approaches using different sources of data, e.g., statistical analysis, simulation modeling, and techniques in the area of artificial intelligence (Yan et al., 2021). The main data sources include but not limited to Automatic Identification System (AIS) data for ship behavior record, ship specifications, port statistics, weather forecast information, maritime accident statistics and accident reports, etc. The core value of using data for maritime transport research can be generalized as an investigation of historical events to gain practical knowledge and a further application of theoretical methodologies to predict future scenarios. Thus, the knowledge derived from data becomes an important node of maritime transport research for different specific purposes, especially for the topics related to ship safety and port capacity. The statistical analysis approaches only using accident reports are rare due to a limited number of maritime accidents (Eleftheria et al., 2016; Sormunen et al., 2016). However, combined with AIS data in near-miss situations, the ship behavior and local risk in an area can be analyzed (Bye and Aalberg, 2018; Chen et al., 2019). Regarding the port capacity or the traffic state in an area, AIS data are mostly used to present the overall performance (Bellsolà Olba et al., 2017; Liu et al., 2020; Yip, 2013). AIS data, as a compulsory automatic record of ship behavior, also provide valuable information in the ship behavior related analysis, such as pattern recognition (Dobrkovic and Hillegersberg, 2018; Gao and Shi, 2020; Sun et al., 2018) and local traffic characterization (Rong et al., 2014; Wu et al., 2016). Therefore, when investigating the historical real-life ship behavior in an area, AIS data provide an important basic source.

In the current studies, the sailing environment of ships is simplified due to their specific analysis purposes (Qi et al., 2017a; Qu and Meng, 2012) or a lack of available data (Eldemir et al., 2013; Merrick et al., 2003; Shu et al., 2017). Moreover, since the maneuvering space in ports and waterways is confined by the physical boundaries, the ship behavior under the sailing environmental impacts is more complicated compared to open waters. The ships have to make the effort to control their position and speed for their own sailing safety and in case of unexpected emergency. The research focuses on ship behavior in ports and waterways is still limited (Z. Chen et al., 2018; Shu et al., 2013; Xiao et al., 2015). The depicted sailing environment in these studies is also far more simple than the real-life ports and waterways. Filling these research gaps is the motivation of this dissertation, which is to provide systematic insights into ship behavior in ports and waterways. On the one hand, the findings directly reveal the characteristics of ship behavior and the influencing factors and mechanisms, which explains the behavior under certain circumstances for port authorities. On the other hand, by further applying the acquainted practical knowledge of ship behavior, a new maritime traffic model can be developed. By incorporating the external impacts on ship behavior in real-life sailing environment in this dissertation, the developed model is expected to predict the future scenarios for port development.

1.2 Research objectives and questions

The main objective of this dissertation is *to gain empirical knowledge of ship behavior in real-life sailing environments and to empirically investigate the influencing mechanisms of intrinsic and external factors*.

In order to achieve the research objective, a series of questions should be addressed, which are formulated as follows:

1. For different specific research objectives in analyzing the maritime traffic, e.g., predicting future traffic state or assessing the port capacity, the ship behavior is required to different extents of details. Currently, simulation models are widely adopted to be applied in different waters, such as the open waters at sea or the confined waters in inland waterways. In such models, ship behavior is always included

considering their application purposes. Thus, a review on the maritime traffic models from the ship behavior modeling perspective depicts an overview of the ships sailing environment and the potential influencing factors. It also points out the scope when analyzing the ship behavior in real-life situations. Therefore, at the start of the dissertation, we propose the following questions: *What are characteristics and limitations of the current maritime traffic models in describing the ship behavior under external impacts and the interactions between individual ships?* (Chapter 2)

2. Starting from the simplest sailing environment, the ship behavior analysis focuses on the unhindered situation, in which the external impacts are mostly eliminated. Considering the potential behavior differences due to the inertia and maneuverability between ships with different sizes, ships are usually firstly classified into groups based on subjective selection of ship size attribute, e.g., Gross Tonnage (GT), deadweight tonnage (DWT), length, or TEU for container ships. However, from the objective behavior perspective, based on the quantitative investigation of the unhindered ship behavior, ships can be classified into clusters with similar behavior characteristics. The intrinsic ship size attribute can be adopted as explanatory variables to describe the ships in such clusters. To achieve the purpose, the following questions need to be answered: *Not considering external impacts, how to objectively classify ships using the intrinsic ship characteristics into clusters with similar behavior characteristics in unhindered situations?* (Chapter 3)

3. In respect of external influencing factors, we start from the most simplified situation of individual ships without interactions with other ships in ports and waterways under weak meteorological and hydrological conditions with no impact on ships. Under such circumstances, the impacts of static navigational infrastructures, such as the waterway layout and Aids to Navigation, on ship behavior patterns always exist. Besides the function of marking the boundaries of navigable waters, ship behavior might change due to the local good seamanship of officers on board along the distribution of navigational infrastructures, which is possibly habitual based on sailing experiences. Thus, from an empirical perspective, we investigate: *When individual ships sailing in ports and waterways, how do the static navigational infrastructures influence the ship behavior?* (Chapter 4)

4. Considering the real-life navigation in ports and waterways, the meteorological and hydrological conditions are never absolutely calm and ideal. Mostly, the impacts from environmental factors are simplified as random disturbances or specifically calculated for individual ships considering the detailed hydrodynamic processes. From the theory in dead reckoning, we also understand the observed ship behavior incorporates the impacts of wind and current on ship speed and leeway and drift angle. However, given specific wind and current conditions, when analyzing the ship behavior without detailed ship particulars in an area, the impacts on individual ships are required. To figure it out, using appropriate data to describe the sailing environment, we study: *How*

do the environmental factors, such as wind and current, influence the individual ship behavior? (Chapter 5)

5. So far, we have looked at the behavior of individual ships. However, a ship sails hardly alone, especially in hub ports. With the increasing traffic volume and ship density, the encounters between ships become more and more frequent. Besides the above-mentioned intrinsic and external factors, the encounters involve at least two ships with dynamic behavior during a changing process. Due to the limited maneuvering space in ports and waterways, the ship behavior considering the dynamic relative movement during the process should be analyzed. It formulates the question: *How do ships change the speed and/or course during encounters in ports and waterways?* (Chapter 6)

1.3 Research approach

This section explains how we empirically explore the ship behavior in ports and waterways using data analyses, including the basic introduction of the collected data and the adopted analysis techniques.

1.3.1 Data description

The Automatic Identification System is an automated tracking system onboard ships to automatically transmit information about the ship to other ships and coastal authorities. In 2000, the International Maritime Organization (IMO) issued an amendment adopting a new requirement regarding the introduction of AIS system in the International Convention for the Safety of Life at Sea (International Maritime Organization, 1974). By the end of 2004, the AIS system was mandatory for all ships of 300 GT and more engaged on international voyages, cargo ships of 500 GT and more not engaged in international voyages and all passenger ships irrespective of size. The AIS data in the research area (see Figure 1.1) have been collected for the whole year of 2014 from the port authority of Rotterdam. In the research area, every seagoing ship, even below the GT limit of IMO regulation, has installed AIS equipment and used it in all voyages. For the inland ships, both commercial and recreational ships, and sailing vessels longer than 20 meters are mandatory to use AIS since December 1st, 2014, according to the resolution of the Central Commission for the Navigation of the Rhine. Since the year of 2014 is still a transition period, the majority of the collected AIS data of 2014 are seagoing ships.

According to the guidelines by International Maritime Organization (2003), the AIS data contain three types of information: (1) static information (Maritime Mobile Service Identity number, IMO number, ship name, radio call sign, ship type, overall length, beam, etc.); (2) dynamic information (UTC time, ship position, speed over ground (SOG), course over ground (COG), heading, navigational status, etc.); and (3) voyage-related information (draught, destination, etc.). Therefore, AIS data provide both the basic intrinsic ship characteristics and the ship behavior through the voyages in the area.

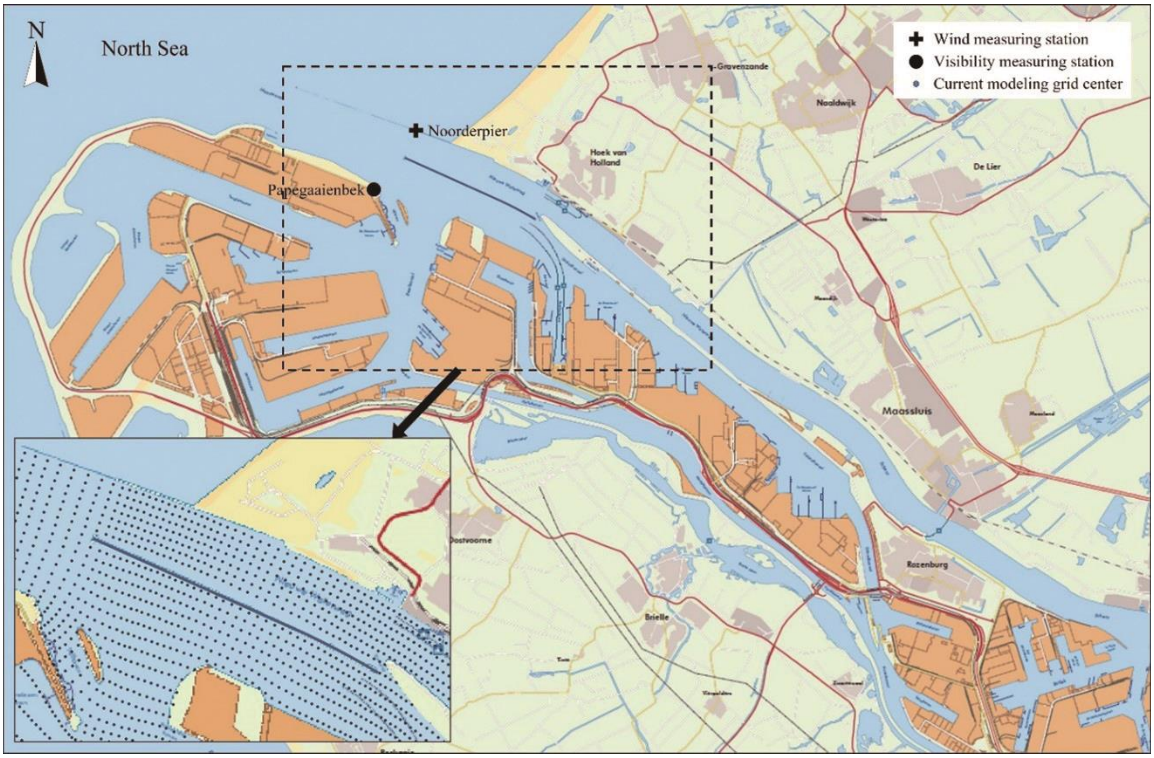

Figure 1.1. Location of the study area in the port of Rotterdam with the meteorological data measuring stations and the hydrological data modeling grid map.

To describe the external conditions of ship behavior, the meteorological and hydrological data during the same period as for which the AIS data have been collected from the port authority. The meteorological condition refers to wind and visibility, with the measuring stations marked in Figure 1.1. The hydrological condition refers to the current. Due to the propagation of flow and the velocity variation over the water-depth, the measured current velocity at a specific measuring station is not representative for the whole area. Thus, the current velocity in the research area is modeled in orthogonal curvilinear grids (see Figure 1.1) using the measured water level from eight stations around the port as input. The modeled velocity has been validated by comparing to the measured velocity in the area by the port authority.

1.3.2 Analysis techniques

To investigate the ship behavior in ports and waterways in a systematic way, different analysis techniques are adopted. The overall research approach in this research is illustrated in Figure 1.2.

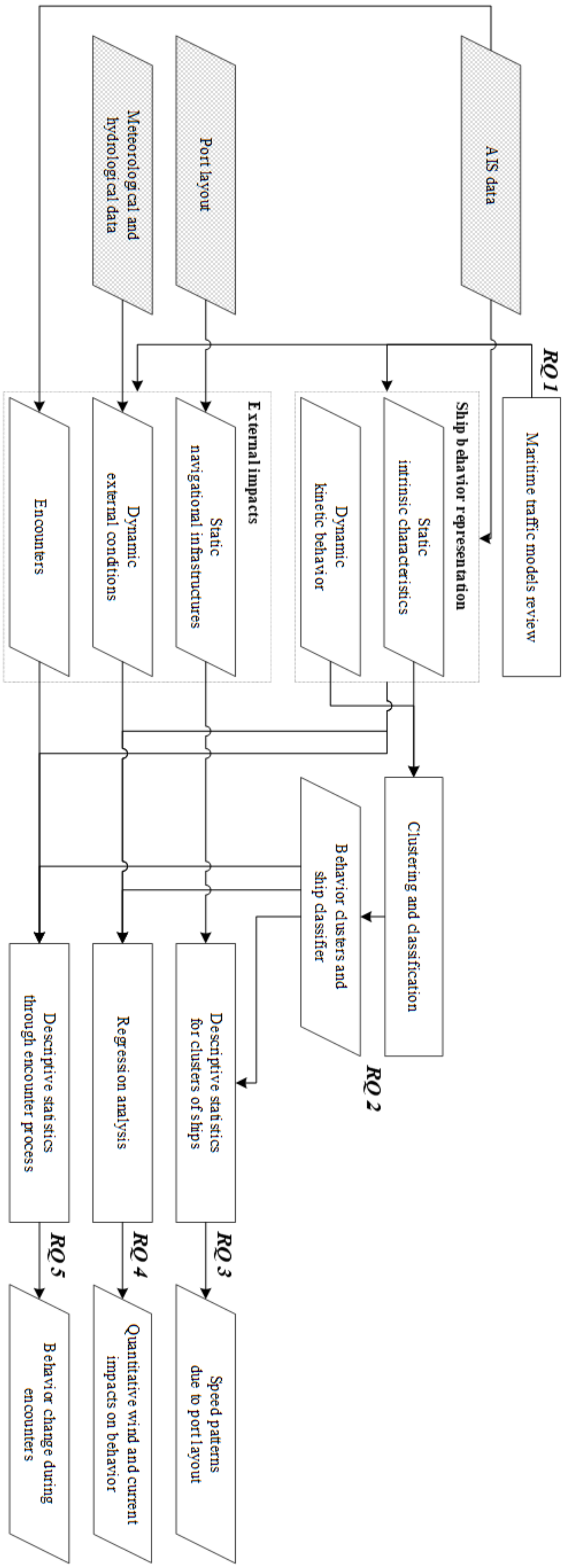

Figure 1.2. Research approach of the dissertation.

Firstly, to understand the overview of ship behavior in the real-life sailing environment, a review of the existing maritime traffic models over the last decades is performed to address research question 1. The review analyzes the modeling paradigms and assess their capabilities in accurately representing the ship behavioral details, which can be recorded by AIS data. The identified influencing factors and the impact mechanism are investigated in the remainder of this research.

To answer research questions 2–5, a series of empirical analysis using AIS data are carried out adopting different data analysis techniques. In research question 2, a two-step approach is proposed, including the ship behavior clustering and a ship classifier to categorize ships into such clusters using their own intrinsic characteristics. Regarding research question 3 on the impact of static navigational infrastructures, the descriptive statistics are used to show the speed patterns of ships in clusters along with the Aids to Navigation throughout the complex waterway layout. The other two research questions focus on the impacts of dynamic external factors. In research question 4 related to the wind and current impacts, a generic modeling paradigm is introduced based on the theory in dead reckoning to estimate ship position. The regression analysis method is adopted using the AIS data and the meteorological and hydrological data to quantify the impacts. To address research question 5, starting from the generic definition of encounters in ports and waterways, the pairs of ship trajectories are directly filtered from the viewpoint of the spatial-temporal co-existence of ships. An investigation into both ship behavior intensions and the corresponding relative movement conditions through the identified full process reveals the interactions between ships in different encounter situations.

1.4 Contributions

As introduced above, this dissertation is devoted to providing a comprehensive and deep investigation into ship behavior in ports and waterways, together with the influencing intrinsic and external factors. The research results contribute to both the scientific community and the practical operators, which are discussed in the subsections 1.4.1 and 1.4.2, respectively.

1.4.1 Scientific contributions

The most relevant scientific contributions of the dissertation are outlined as follows.

Identifying the representation details of ship behavior and the potential influencing factors in the sailing environment. Through an in-depth review focusing on the representation of ship behavior in the real-life sailing environment, we assess the stated performance of the existing maritime traffic models. The proposed assessment criteria systematically explain the details of ship behavior and the potential influencing factors, which are investigated in the remainder of this research and need to be considered for future research of ship behavior. We present a structure to investigate ship behavior from intrinsic to external factors and from static to dynamic ones. The overall findings of this research also explain the relationship between different factors leading to the final ship behavior.

Classifying ships into behavior clusters using the intrinsic ship characteristics. Instead of classifying ships based on subjective criteria before behavior comparison analysis, we directly investigate the ship behavior via clustering techniques to find out the clusters with similar behavior characteristics. The identified clusters objectively explain the underlying local behavior patterns, which also provides the basis for ship classification. The developed ship classifier only uses the intrinsic ship characteristics to classify ships into the clusters of behavior patterns. The coherent methodology explains the inherent ship behavior differences due to the individual ship size differences.

Quantifying the impacts of wind and current on individual ship behavior. We adopt the classical theory in dead reckoning to explain the mechanisms of wind and current impacts on ship speed and leeway and drift angle. Without a specific requirement on individual ship maneuvering particulars, the mathematical formulations of the ship behavior are identified with the estimated coefficients vis regression analysis using historical data. The quantification helps the understanding and modeling of wind and current impacts on ship behavior in a port area where the detailed individual ship maneuvering particulars are not always available.

Identifying ship behavior change and the corresponding relative movement conditions during encounter processes. Starting from the classification and constitutive elements of encounter situations in COLREGs, we define and categorize the generic encounters and their process in ports and waterways. Instead of focusing on the selected cases of ship encounters according to subjective risk judgement, we analyze the behavior of all encounters during the process. Therefore, the findings provide an overview of all possible ship behavior patterns in real-life sailing environment. The descriptive statistics of relative movement conditions help the understanding of the triggering point and the objective of behavior change from the perspectives of both ships. The results can also be used in future research to simulate the encounter processes.

Illustrating the impacts of navigational infrastructures on ship speed. Starting from the observed unexpected speed change phenomena when ships sailing alone in the waterway with complex layout, we identify the potential influencing factors considering the local sailing habits from the good seamanship perspective. We empirically illustrate the underlying impacts by analyzing the relationship between the speed change behavior and the distribution of navigational infrastructures. The findings help to understand the ship behavior in a complex waterway layout and draw attention to consider their impacts on ship speed in addition to marking the boundaries of navigable waters.

Identifying the modeling paradigms of existing maritime traffic models in respect of ship behavior modeling. In the review of maritime traffic models, from the perspective of their adopted methodologies, we systematically categorize the modeling paradigms for the first time in the field. This way, we point out the limitations of the existing models in simulating ship behavior due to the approaches and suggest the possible future research agenda. During the empirical investigation of ship behavior in this research, we adopt different analysis techniques for different factors which also considers the potential of integrating the impacts into modeling the final ship behavior.

1.4.2 Practical implications

The practical implications of this dissertation can be discussed from two aspects, being ship traffic management and port planning and design.

Firstly, the dissertation provides valuable empirical knowledge of ship behavior for the ship traffic management at port authority regarding operational decisions. Considering the practical application, the ship information in AIS data used in this dissertation is always available for port authority, either in historical data set or automatically reported during the voyage. When a ship is about to approach to or depart from a port, the port authority would be able to predict the behavior pattern based on the intrinsic ship characteristics, e.g., the possible speed range or lateral position in the waterway. Regarding the local environmental conditions, with the meteorological and hydrological forecast information, the results can provide theoretical references for traffic control measures regarding ship behavior suggestions along the navigational infrastructures (e.g., position control or speed limit). When the traffic density is high, the findings provide a better understanding of conventional sailing behavior during encounters in ports and waterways. Though the specific behavior cannot be accurately predicted for individual ships, from the perspective of traffic flow considering encounters, the traffic control measures appropriate to the circumstances can be expected.

Secondly, the overall findings of the dissertation can be used for port planning and design. Through the analysis of ship behavior in the environment from simple to complex, the impacts mechanisms from intrinsic distinction to external factors have been identified in this dissertation. When the port design needs to be assessed under specific circumstances, the corresponding finding can be applied. For example, when the composition of ship traffic in ship size is expected to change, the ship behavior pattern considering their intrinsic characteristics can be estimated. In case that the port layout, e.g., waterway width, is planned to change to fit the traffic demand, the ship behavior pattern can be generically predicted considering the local sailing habits along the designed navigational infrastructures.

1.5 Dissertation outline

An overview of the dissertation outline is illustrated in Figure 1.3. Chapter 2 reviews the existing maritime traffic models from the ship behavior modeling perspective, including the modeling paradigms and to what extent the behavior is included in models for different application purposes. The chapter provides an overview of ship behavior and the relevant influencing factors, which are further investigated in the remainder of the dissertation.

From the simple sailing environment to the complex one, the following four chapters investigate the influencing factors of ship behavior in ports and waterways and their influencing mechanisms. In chapter 3, starting from the unhindered situation without external impacts, the ship behavior is analyzed to reveal the *intrinsic factors* distinguishing ship behavior in straight waterway. For external influencing factors, they are divided into static and dynamic ones. Chapter 4 extends the waterway stretch to include richer navigational infrastructures, in which the impacts of the *static factors*, including waterway layout and Aids to Navigation, on ship behavior are introduced. The impacts of *dynamic factors* are studied in chapter 5 and 6. Still from simple to complicated sailing situations, among ships sailing alone in the waterway, the impacts of wind and current conditions on ship behavior are investigated in chapter 5. Chapter 6 focuses on the interactions between ships during the encounter process with other ships. Finally, chapter 7 summarizes the main findings, discusses the practical implications, and provides the recommendations for future research in the field of ship behavior analysis and modelling in ports and waterways.

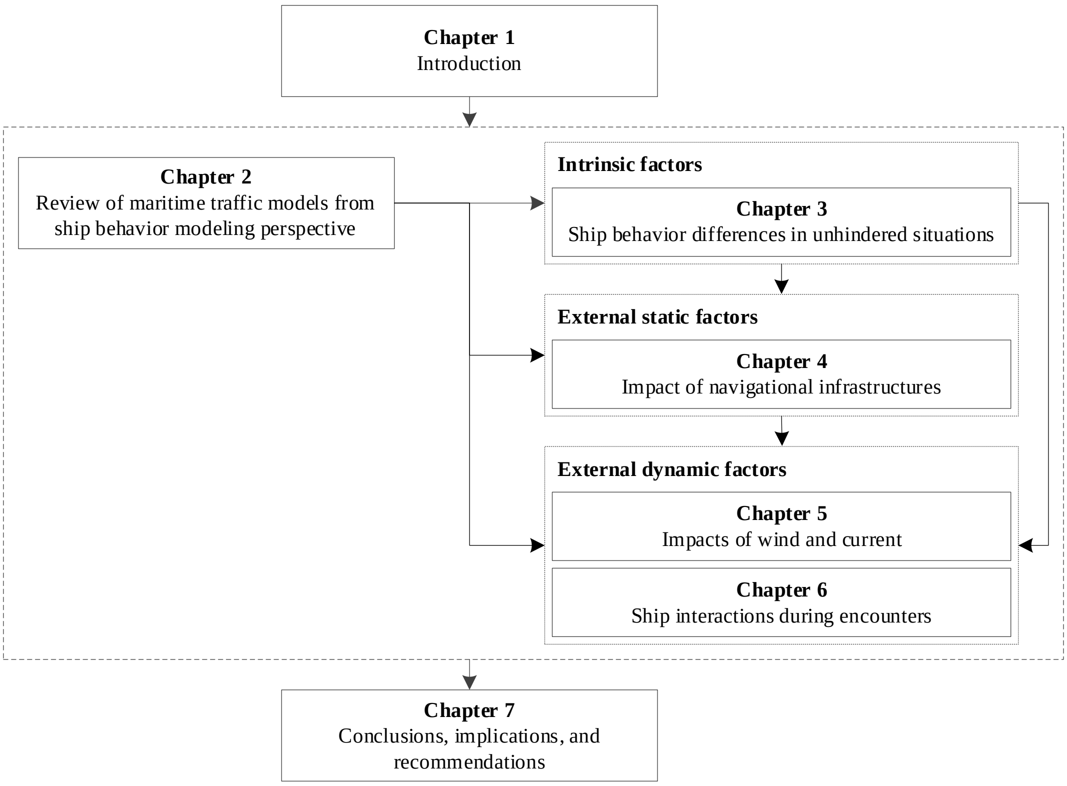

Figure 1.3. Outline of the dissertation.

2. Review of Maritime Traffic Models from Ship Behavior Modeling Perspective

This chapter reviews maritime traffic models from the ship behavior modeling perspective. The maritime traffic models include the models for ship traffic both at sea and in confined water area. The aim of this chapter is to depict the sailing environment of ships and figure out the limitations in representing the ship behavior.

To compare the capabilities of models in capturing the ship behavior characteristics, the considered models are assessed from different aspects of ship behavior representation, external impact modeling, and model applicability. The assessment shows that none of the existing models describe all dynamic kinetic information in detail for different ships and consider the impacts from a full range of external factors. The models developed for specific ships in specific situations ignore the irrespective behavioral details in other possible scenarios. Models without proper calibration and validation limit the applicability in other cases. It also indicates that few models can accurately simulate the different ship behavior at a microscopic level. To investigate the possible potential and limitations, the models have been assessed and discussed to indicate the underlying modeling paradigms based on the modeling characteristics.

This chapter is published as a journal article:
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2.1 Introduction

The importance of maritime transport keeps increasing with the trade globalization. Until 2017, over 80 percent of the global trade by volume and more than 70 percent of its value are carried by waterborne transport and handled by seaports worldwide (United Nations Conference on Trade and Development, 2017). According to the forecast of UNCTAD, the trade volume of seaborne transport will grow at an estimated compound annual growth rate of 3.2 percent between 2017 and 2022. The cargo flows will be expanded across the world with containerized dry bulk commodities. With such a growing demand for waterborne transport, the vessel traffic flow is also expected to increase. The safety of vessels and the capacity of different water areas have therefore drawn more attention from science. Currently, simulation models are widely used to represent the vessel traffic in different areas (at sea, in strait, in port, or in inland waterways). The purposes of developing such traffic models can be various, e.g., scenario research for the future traffic state, assessing the port design alternatives, or investigating the effects of introduction of autonomous vessels. However, the essential issue in common is to improve the capacity of the area while guaranteeing the safety of vessels.

To describe the models for vessel traffic, a lot of terms have been used, e.g. maritime traffic model (Bourdon et al., 2007; Mavrakis and Kontinakis, 2008; Or et al., 2007), marine traffic model (Hasegawa et al., 2001; Huang et al., 2016; Köse et al., 2003; Qi et al., 2017a; Yip, 2013), nautical traffic model (Xiao et al., 2013), ship or vessel traffic model (Groenveld, 2006; Pachakis and Kiremidjian, 2003; Qu and Meng, 2012; Wawruch and Popik, 2011). In this chapter, the term 'maritime traffic model' is adopted. Here, maritime traffic models include the models of vessel traffic at sea as well as the models for confined water areas. Thus, a maritime traffic model refers to a system of postulates, data, and inferences presented as a description of the state of vessels moving in a navigable area.

The science of maritime traffic modeling started by Davis et al. (1980) adopting the concept of ship domain by Fujii and Tanaka (1971) and Goodwin (1975). According to the different requirements of application purposes, a broad range of models describing maritime traffic at different levels of vessel behavioral details has been developed. From the viewpoint of collective traffic flows, the maritime traffic flow of a port (Bellsolà Olba et al., 2017; Groenveld, 2006; Pachakis and Kiremidjian, 2003), a canal (Franzese et al., 2004), a strait (Köse et al., 2003) or an area (Yip, 2013) is modeled to present the overall performance. However, in such models, the details of individual vessel behavior are simplified to a large extent. To investigate the traffic state involving different type of vessels, agent-based models are developed for waterway networks (Merrick et al., 2003) or open sea (Vaněk et al., 2013). Different types of vessels are defined as distinctive agents. However, in the model by Vaněk et al. (2013), the sailing behavior of each type of agent (merchant vessel, navy vessel, and pirate vessel) in the models is simplified as an event with origin and destination over a period of time. The behavior of individual vessels can hardly be modeled. Aiming to represent the details of vessel traffic, the detailed behavior of every single vessel in the area is modeled by describing the time-space state (Cheng et al., 2017; Hasegawa et al., 2001; Miyake et al., 2015). To further consider the safe passage of vessels during encounters, the evasive behavior of vessels is included (Qu and Meng, 2012; Watanabe et al., 2008). Qu and Meng (2012) and Qi et al. (2017) introduce the impact of weather and sea state on sailing behavior. Such models considering individual vessel behavior show the interaction between vessel and surroundings (both external environmental factors and other encountering vessels).

Two groups of researchers have reviewed (a subset of the) available models before. Szlapczynski and Szlapczynska (2017) present a systematic review of the models using ship domain for whatever application purposes. However, other models, which are not based on the ship domain but potentially interesting in our application, are not assessed. Bellsolà Olba et al. (2018) review port simulation models adopting different methods and focus on the vessel traffic from a port operations viewpoint. The underlying modeling methodology and the corresponding application limitations are, however, not discussed in detail. The models developed for other areas have not been assessed, either. Therefore, none of the existing reviews analyzes the full range of the maritime traffic models from the viewpoint of vessel behavior modeling. The underlying evolution in methodologies is not discussed, either. However, vessels are the basic elements of maritime traffic. To investigate the models from the vessel behavior perspective allows an overview of how the maritime traffic is described. This way, all involved approaches can also be revealed.

The scope of this review covers all maritime traffic models describing the behavior and interactions of individual vessels, irrespective of the application area. This chapter provides a broad, but not exhaustive overview of the current literature on maritime traffic models of the last decades. Commercial models are not included due to the limit of information about the underlying methods. The aim of this chapter is to analyze the modeling paradigms and assess the capabilities of maritime traffic models in accurately representing the vessel behavioral details. Within this chapter, the performance of the maritime traffic models has been assessed with a series of criteria regarding the capability of modeling vessel behavior in different circumstances. Moreover, the modeling characteristics are also analyzed to indicate the underlying paradigms and implementation issues. The review result will provide suggestions for the future development of a maritime traffic model considering individual vessel behavior.

The rest of the chapter is organized as follows. Section 2.2 explains the research methodology from literature search to model selection and model assessment. Section 2.3 identifies the criteria to assess the models with detailed explanation. Section 2.4 categorizes and elaborates upon the model characteristics based on their underlying methodologies. In section 2.5, all models are discussed with respect to the criteria described in section 2.3. Finally, section 2.6 concludes the chapter based on the assessment results.

2.2 Research methodology

The goal of this review is to provide an overview and discussion of all maritime traffic models considering the vessel behavior. Figure 2.1 illustrates the steps of this review from literature search to model selection and assessment. The detailed methodology is further explained in this section. In section 2.2.1, the literature search method and process are presented. Section 2.2.2 introduces the criteria to select models from the search result. Finally, the selected models are assessed according to the criteria explained in section 2.2.3.

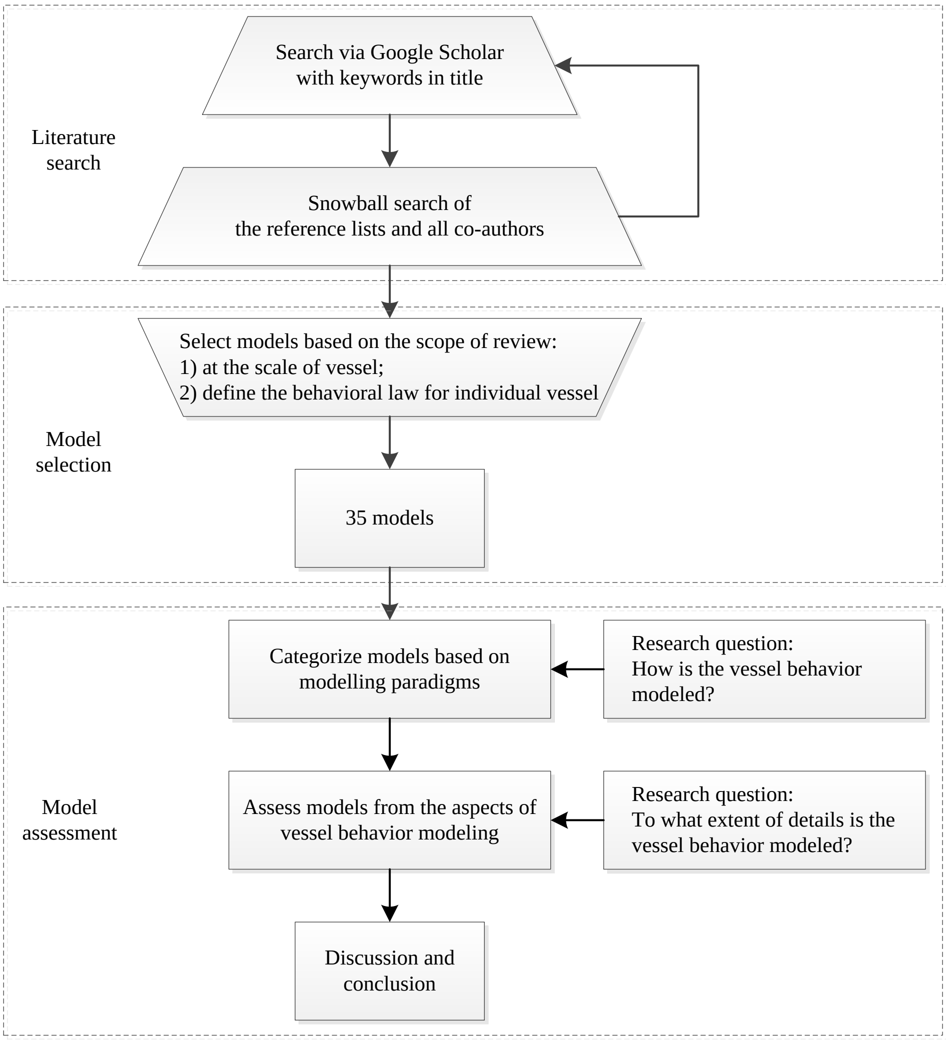

Figure 2.1. Steps of literature search and model review (The dashed rectangles refer to the steps corresponding to the sub-sections in section 2.2).

2.2.1 Literature search

Maritime traffic models have been developed for different purposes of application. The literature search in this chapter is firstly performed through Google Scholar to include both peer-reviewed journal articles and conference chapters. Included in this chapter were articles dated up to December 2018 with the keyword: “traffic model(s)”. This way, all types of models are covered, including conceptual models, analytical models, statistical models, data-driven models, and simulation models. Besides, at least one of the following keywords should also be contained in the title of the article: “marine”, “maritime”, “nautical”, “ship(s)”, “vessel(s)”, “port(s)”, “waterway(s)”, “channel(s)”, “canal(s)”, “strati(s)”, “gulf(s)”, “bay(s)”. All articles in the search results focusing on maritime traffic are deemed as relevant articles for further review. In case of other unexpected keywords, the snowball search is conducted in two ways: (1) searching all of the relevant articles in the references; (2) searching all of relevant articles of all co-authors. Only the articles in English have been assessed. The process and findings of the literature search have been presented in Figure 2.2. As a result, 66 maritime traffic models in 112 articles are collected for further model selection in section 2.2.2. The cloud of words in the title and key words of the 112 articles gives an overview of the issues that the studies on maritime traffic models have focused on (see Figure 2.3). It can be observed that the initially proposed key words for literature search can cover the majority of the relevant papers.

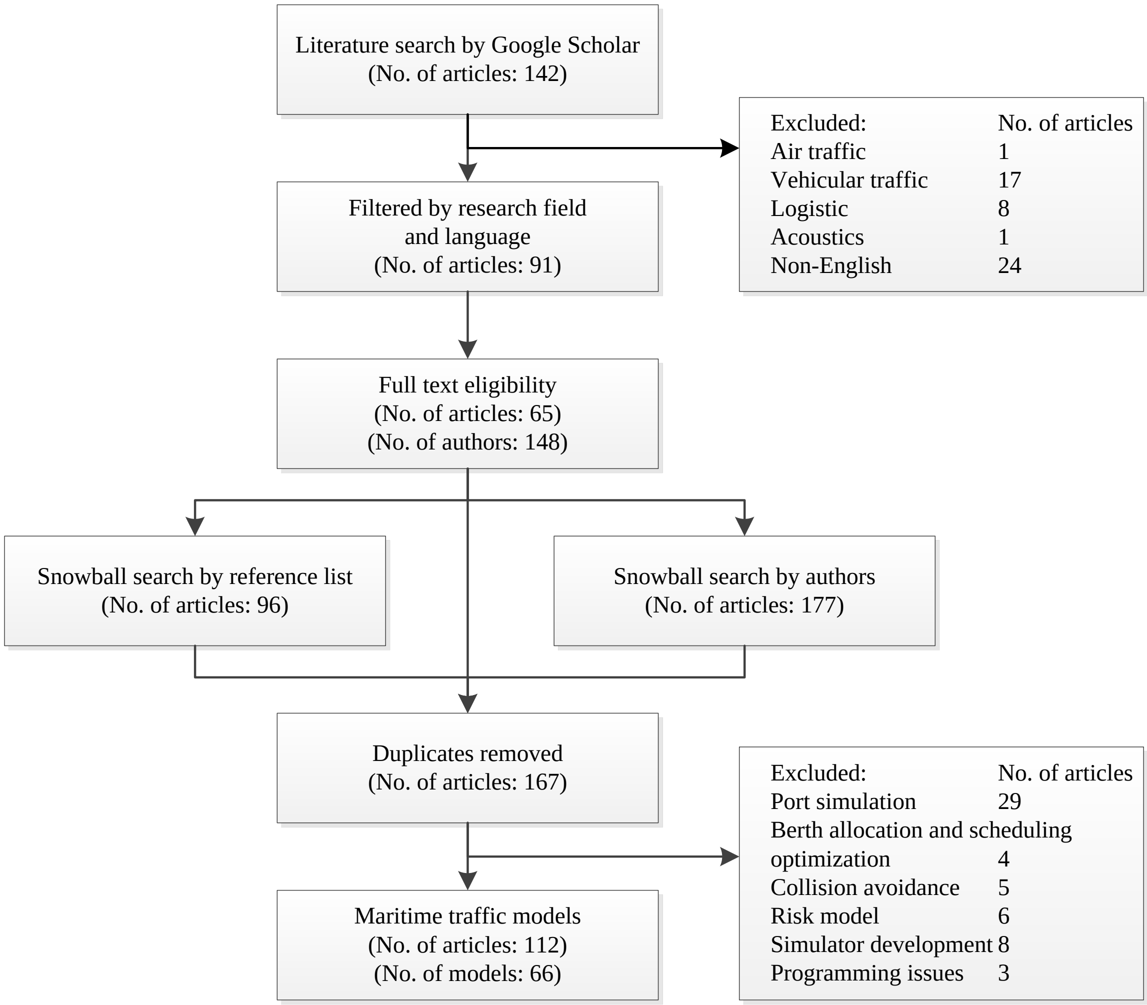

Figure 2.2. The process and findings of the literature search step.

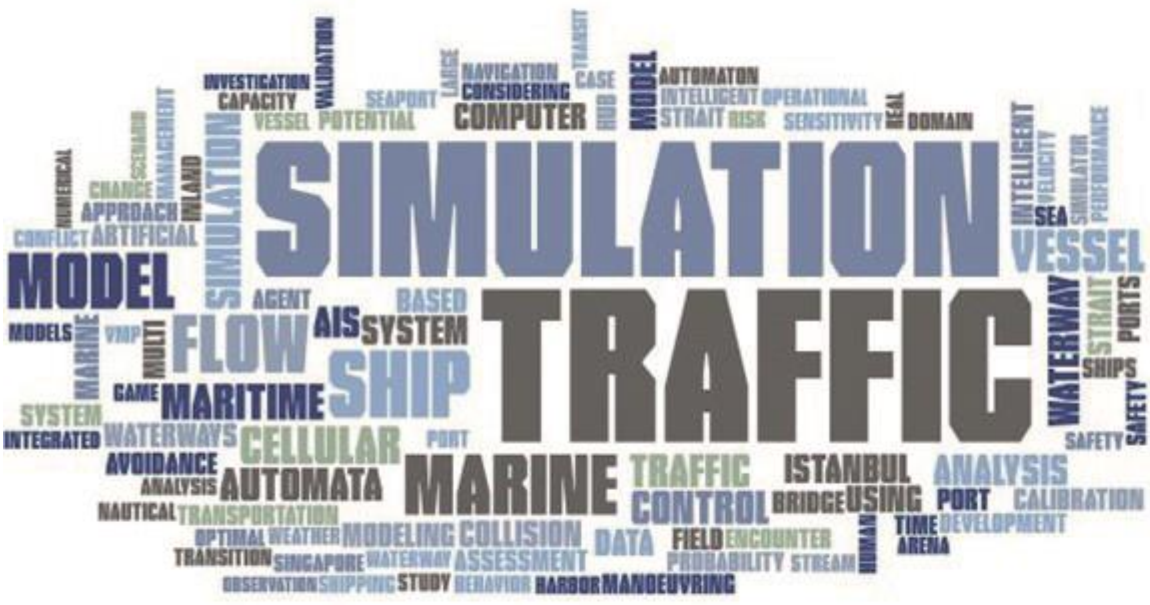

Figure 2.3. The cloud of words in the title and key words of the 112 articles on maritime traffic models.

2.2.2 Model selection

Based on the requirements of the application, the models need to describe different aspects of the maritime traffic flow by considering the dynamic kinetic information of individual vessels or not. The dynamic kinetic information of vessel behavior includes, but is not limited to, position, speed, course, and heading. Starting from this point of view, models are defined to be either microscopic maritime traffic model or macroscopic ones. However, the scale is not explicitly explained. In vehicular traffic analysis, Lesort et al. (2005) also point out that the usual micro/macro classification is not sufficient to identify the characteristics of the models. They proposed a new classification method based on two criteria, being the behavioral law (individual or collective) and the representation scale (vehicle or flow) (Bourrel et al., 2003).

From the vessel behavior modeling perspective, the collective behavioral law at the flow scale only describes the evolution of maritime traffic at an aggregated level. The detailed information of individual vessels and their dynamic behavior is neglected. In order to compare and assess how the vessel behavior is modeled, the criteria to select models for assessment in this review are identified: (1) representing the maritime traffic at the scale of vessels; and (2) defining the behavioral law of individual vessels. According to this definition, 35 models from the search results in the previous step are selected and reviewed in this chapter. Among the other models, there are mainly four reasons for the exclusion from the review. Considering the first selection criterion, 10 traffic flow-based models and 3 network-based models are excluded. According to the second criterion, 17 models without a definition of behavioral law for individual vessel are excluded from the review. Besides, one commercial model with brief introduction is excluded, as well.

The statistics of descriptive background information of the selected models is provided in Table 2.1, with the full list in Appendix. Among the selected publications, it happens that both articles and thesis describe the same model. In this case, the thesis is deemed as the reference which explains the model in a systematic manner. In respect of the collected data sources, AIS data is the most common type to use after its introduction. Regarding the countries of the author's affiliations, European and Asian countries account for the majority.

Table 2.1. The statistics of descriptive background information of the selected models.

Descriptive information	Categories	No. of articles/models	Descriptive information	Categories	No. of models
Type of publication	Journal articles	24 articles	Country and region	NLD	7
	Conference proceedings	14 articles		CHN	7
	Thesis	6 theses		POL	4
Stated application area	Confined water	28 models		JPN	3
	Open water	7 models		SGP	3
Collected data type	AIS data	14 models		TUR	3
	Traffic data	5 models		BEL	2
	Radar data	3 models		GBR	2
	Ship maneuvering data	3 models		DEU	1
	GPS data	1 model		FIN	1
	Cine film of radar screen	1 model		NOR	1
	Questionnaire	1 model		PRT	1
	No data collected	10 models		USA	1

2.2.3 Model assessment

The model assessment in this review is performed in two parts, to answer two questions. The first one (section 2.2.3.1) is to evaluate what kind of vessel behavior related information is included in each model. The comparison results will show to which extent the models describe the vessel behavior and the relevant external impacts. The other one (section 2.2.3.2) is to discuss how the vessel behavior is modeled, which is to reveal the underlying paradigms in vessel behavior modeling.

2.2.3.1 Vessel behavior modeling assessment criteria

Maritime traffic models have the requirement to accurately represent the evolution of the maritime traffic state, for every application purposes. Hence, the selected models are compared with respect to their capabilities to represent vessel behavior in maritime traffic. The authors understand that each model is developed with a specific goal and are not expected to capture all details of vessel behavior as is in real-life situations. To fully evaluate the performance of the models, the proposed assessment criteria will cover a wide variety of characteristics of vessel sailing behavior that can be observed in real-life, as shown in Figure 2.4.

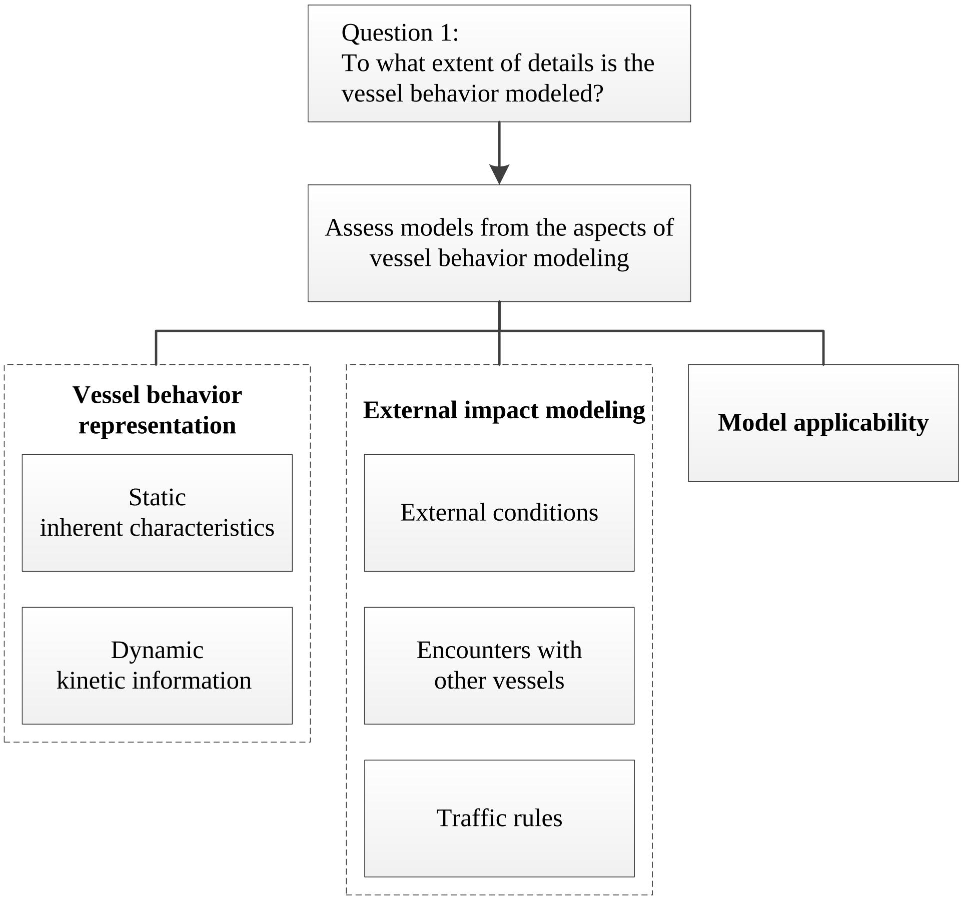

Figure 2.4. Structure of vessel behavior modeling assessment criteria.

Firstly, the way of representing vessel behavior is assessed in two aspects. The static inherent characteristics indicate how a model distinguish different vessels and whether a model can capture the differences among vessels or at least groups of vessels. To show how the vessel behavior is described in a model, the dynamic kinetic information adopted in a model should be compared.

Since the vessel behavior is highly affected by external conditions as studied by Shu et al. (2017), the way of modeling such external impacts should be evaluated. The external factors include external environmental conditions, encounters with other vessels, and traffic rules as well. The assessment aims to indicate to what extent the details of vessel behavior and the relevant external factors are included in the models. It means there could be some factor that no model has considered yet. Therefore, the existing maritime traffic models are not only compared, the possible limitations of all models could also be revealed.

Additionally, the capability of models to capture different vessel movement base cases is also investigated to show the model applicability. The full range of assessment criteria is explained in section 2.3.

2.2.3.2 Modeling paradigm categorization

To elaborate and discuss the possible potential and limitations of the models, the models are categorized based on their underlying modeling paradigms (see Figure 2.5) and introduced in section 2.4. The common feature of maritime traffic models is that most of the models represent the vessels as agents. Only a few models considering detailed maneuverability with sub-modules are developed. Thus, agent-based modeling is not a suitable criterion to define the modeling paradigms in maritime traffic models.

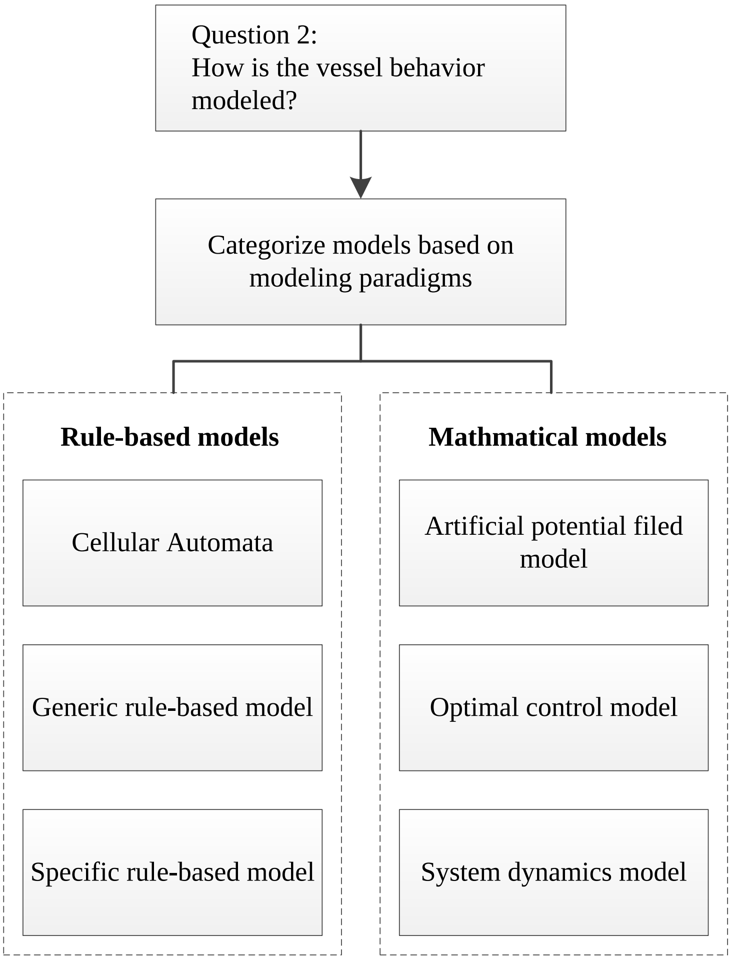

Figure 2.5. Categorization of modeling paradigms.

Investigating the structure of all maritime traffic models, they can be generically categorized by rule-based models to describe the behavioral law by rule sets and the mathematical models to present the state of vessels in form of differential equations. In the rule-based models, one specific category is cellular automata. The water area is discretized into cells, and the rules are defined to update cell state at time steps. For the other rule-based models, two types of rule sets are distinguished. One type of rules is generically defined for all vessels applying under whatever circumstances, while the other type of rules considers the differences between vessels and the possible interaction between vessels and the circumstances. Based on these differences in rule sets, the rule-based models are further categorized into generic rule-based models and specific rule-based models.

Among the other mathematical models, three typical types are identified. The artificial potential field models calculate the attractive or repulsive potential between the vessels and the circumstances to represent the interacting behavioral laws. The optimal control models describe the system of maritime traffic via a set of differential equations with an optimization criterion as the objective function. Lastly, the system dynamics models describe the vessel behavior by state-space functions. Therefore, the six modeling paradigms identified in this review are cellular automata, generic rule-based model, specific rule-based model, artificial potential field model, optimal control model, and system dynamics model.

The information of all traffic models used in this review is taken from the respective papers proposing or applying the corresponding models. Since the authors cannot implement all models for comparison, we assume that the description of the models presented in the papers agrees with their implementation. Thus, the authors do not implement all models to compare their performance or modeling accuracy. However, even if the model is developed for a specific purpose, the capability of the model to simulate other situations is also assessed with respect to its potential in describing the characteristics and the sailing rules in other types of water area.

2.3 Assessment criteria — vessel behavior modeling

To compare the capability of vessel behavior modeling, the maritime traffic models are assessed from three aspects, including vessel behavior representation, external impact modeling, and model applicability, as shown in Figure 2.4. The assessment criteria are described in more detail in this section. Besides an explanation of the criteria, a rating scale is introduced for each criterion to compare the models. For some criteria, the models are only marked as “yes” or “no” to indicate whether such a factor is included or not. For other criteria, the models are rated to the extent that the models can represent the behavior or the impact.

2.3.1 Vessel behavior representation

The first group of assessment criteria focuses on the representation of vessel behavior, which is the basis of a maritime traffic model. We identify two criteria to assess the representation of vessel static characteristics and dynamic behavior. One criterion investigates how different vessels are defined or classified based on their inherent static characteristics (e.g., vessel type, geometric sizes, or tonnage), and the other criterion assesses how the vessel dynamic kinetic movement is described during modeling.

2.3.1.1 Static inherent characteristics

The behavior of each individual vessel is unique, even in the same area. The reasons are diverse, including the maneuverability of the vessels, the impacts of external factors, and the decisions and behavior of the bridge team. From the aspect of the vessels, the type, geometric size, or tonnage could influence the maneuverability. Thus, the ability to simulate different vessels in the models has been indicated by the method of vessel classification based on static inherent characteristics, as listed in Table 2.2. With more characteristics involved, the differences between vessel behavior can be better presented.

Table 2.2. Explanation of abbreviation to describe static inherent vessel characteristics.

Abbreviation	Description of the static inherent vessel characteristics
T	Vessel types
GT	Gross tonnage, which is a measure of the vessel’s internal volume
DWT	Deadweight tonnage, which is a measure of the weight that a vessel can carry without her own weight
L	Length overall, which is the maximum length of a vessel
B	Breadth, which is the greatest breadth of a vessel
S	Specific vessels including all detailed vessel characteristics
(Blank)	No static inherent characteristics, the vessels are equally modeled without classification

2.3.1.2 Dynamic kinetic information

The vessel motion can be described in six degrees of freedom considering hydrodynamic forces, including surge, sway, heave, roll, pitch, and yaw (Sandurawan et al., 2012). However, from the viewpoint of other vessels or the traffic manager, the detailed motion cannot be observed. For example, the information on the rate of turn can only give a generic impression of fast or slow turning behavior to the other vessel, since the real maneuverability of each individual vessels is unknown. Therefore, only the directly observable dynamic kinetic information is selected as assessment criteria. The behavior of an own vessel can only be observed by position, speed over ground, course over ground and heading. For a detailed assessment, the vessel movement in the models is rated from these four aspects based on the criteria in Table 2.3.

Table 2.3. Rating scales for the dynamic kinetic information of vessel movement.

Abbreviation	Rates	Description of the rates
Position (P)	!	Two-dimensional space (both longitudinal and lateral position)
	√	One-dimensional space (only longitudinal position)
Speed (S)	!	Dynamic freedom of speed choice at each time step or continuously
	√	Several fixed speed choices
	×	Fixed speed through the voyage
Course (C)	!	Dynamic freedom of course choice at each time step or continuously
	√	Fixed course to follow the designed routes
	(blank)	Not included
Heading (H)	!	Dynamic freedom of heading choice at each time step or continuously
	√	Same as the course
	(blank)	Not included

2.3.2 External impact modeling

As mentioned above, vessel behavior is always influenced by external factors in real-life situations. From the viewpoint of each individual vessel, three types of external factors will be assessed in the maritime traffic models, including external conditions, encounters with other vessels, and traffic rules. The criteria will be explained in more detail in this section.

2.3.2.1 External conditions

The external conditions refer to the meteorological and hydrological factors and the geographical waterway layout which affect vessel navigation. Instead of summing up the external factors already mentioned in the existing models, all external factors relevant to vessel behavior will be included explicitly. Besides the normal conditions, the adverse weather condition is also included as an external factor for vessel behavior, which has been proven to restrict the vessel maneuverability (Bitner-Gregerse et al., 2016). The assessment criteria of external factors are listed in Table 2.4.

Table 2.4. Rating scales for the conditions of external factors.

Abbreviation	Rates	Description of the rates
Visibility (V)	!	Included with scales of visibility
	√	Included as good or restricted visibility
	(blank)	Not included
Wind (W)	!	Included with scales of the wind velocity and direction
	√	Included as “yes” or “no”
	(blank)	Not included
Tide (T)	√	Tidal chart included for water level or direction of the main stream
	(blank)	Not included
Current (C)	!	Included with scales of the current velocity and direction
	√	Included as “yes” or “no”
	(blank)	Not included
Adverse weather (A)	!	Included with scales
	√	Specific adverse condition included
	(blank)	Not included
Bank (B)	√	Defined geographical boundaries (bank) with impact on the vessel behavior
	×	Defined geographical boundaries (bank) without impact on the vessel behavior
	-	Not applicable for open water or confined water area with specific routeing scheme

2.3.2.2 Encounters with other vessels

When two or more vessels encounter each other during navigation, the vessels will possibly take actions to avoid collision and guarantee safe passage. Using a distance of safety in the model is the most generic way to model vessel encounters. However, vessels sailing at sea should comply with the rules in the International Regulations for Preventing Collisions at Sea (COLREGs) (International Maritime Organization, 1972), and vessels sailing in port area should additionally comply with the local rules regarding the responsibility of vessel behavior during encounters. Thus, the inclusion of vessel behavior during typical encounters can be assessed. This is to distinguish the impacts of different encounters on vessel behavior. According to COLREGs, three types of vessel encounter are identified, being head-on situation, crossing situation, and overtaking. Besides the basic types of two-vessel encounter, the multi-vessel encounter (more than two vessels involved) is also considered to indicate the capability of a model dealing with such more complex situations. The detailed rating scales for vessel encounter in the models are explained in Table 2.5.

Table 2.5. Rating scales for the description of vessel behavior during encounter with other vessels.

Abbreviation	Rates	Description of the rates
Distance of Safety (DS)	√	Generic or situation-specified distance of safety
	(blank)	No distance of safety
Head-on situation (HO)	!	Both normal (port-to-port) and dangerous (starboard-to-starboard) head-on situations with specified rules
	√	Specified with same rules for both vessels
	(blank)	Not specified
Crossing situation (CS)	!	Specified rules for stand-on vessel and give-way vessel
	√	Specified with rules for only one vessel
	(blank)	Not specified
Overtaking (OT)	!	Specified rules for both overtaking and overtaken vessel
	√	Specified with rules for only one vessel
	(blank)	Not specified
Multi-vessel encounter (MV)	√	Specified rules among vessels
	(blank)	Not included

2.3.2.3 *Traffic rules*

As mentioned in the impacts of vessel encounter, the traffic rules, such as COLREGs, may affect the vessel behavior in some circumstances. Besides the regulations issued by IMO, the local authority of government or port can set special rules for the reasons of security, safety or environment protection. In addition to the responsibility of vessels during encounters, these rules may also include speed limit, and waterway usage, etc. The inclusion of traffic rules at different levels of details is assessed based on the classes in Table 2.6.

Table 2.6. Rating scales for the inclusion of traffic rules in the model.

Rates	Description of the rates
!	Specified rules by local authority
√	Only COLREGs
(blank)	Not specified

2.3.3 Model applicability

With specific purpose of model development, not all models can be applied in all types of water area. Thus, the applicability of models is assessed by looking at the application area, listed in Table 2.7.

Considering the navigable waters for vessel maneuvering, the water area can be distinguished by open water area and confined water area. For confined waters, the boundary can be geographical bank or virtual waterways, e.g., the area with traffic separation scheme. The authors realize that, besides the specific application as stated in the papers, models can be used in more situations considering whether and how the impact of the sailing area boundaries is included. Therefore, the models are not only assessed according to the situation referred to in the papers but also with respect to the application area potential of the models.

Table 2.7. Explanation of abbreviation to describe the model application area.

Abbreviation	Description of the water area
OW	Open water area
CW_G	Confined water area with geographical boundaries, e.g., inland waterway or coastlines
CW_V	Confined water area with virtual boundaries, e.g., specific routeing scheme
?	Unclear area of application

For vessel behavior in the confined water area, different vessel movement base cases have been identified. The cases have been defined as the predominant sailing situation that might occur in a confined area (e.g., sailing in a straight waterway, turning at an intersection, crossing an intersection, etc.). The movement base cases are expected to cover the whole range of vessel behavior in confined water area with either geographical or virtual boundaries. Thus, the vessel traffic can be a combination of such generic base cases. Figure 2.6 presents the categories of vessel movement base cases.

Instead of identifying the vessel movement in different waterway layout, the specific traffic flow is considered to indicate the base cases. Firstly, the vessel movement is distinguished by uni-directional and multi-directional flows. The category "uni-directional flow" splits into three separate categories, namely straight flow, bending flow and turning flow. The distinction between straight flow and bending flow is whether the vessel shall take a series of course change actions to follow the route. The distinction between bending flow and turning flow depends on the total course change when passing the area without the course steady in between. If the course change is less than or equal to 90 degrees, the vessel movement is deemed as bending flow. If the course change is larger than 90 degrees, the movement is deemed as turning. The lower figure in Figure 2.6 (UT_3) under the turning flow indicates the vessel movement in turning basin close to the berth. In the movement cases in turning flows, the ship turning maneuverability usually needs to be concerned. Next to that, the category "multi-directional flow" is further distinguished by bi-directional flows, merging flows, diverging flows and crossing flows. The distinction between crossing flows and the other three categories is the potential route conflict among the flows. Bi-directional flows in a straight waterway (MB_1) or a bending waterway (MB_2) occur due to the local rules, which can be a traffic separating scheme or made by the local port authority. Meanwhile, the merging and diverging flows are mainly due to the layout of such intersection (MM_1 and MD_1). If there is a third vessel from the opposite direction (MM_2 and MD_2), multi-directional flows occur additionally due to the local rules of bi-directional sailing. For crossing flows (MC_1 and MC_2), the waterway layout plays a basic role in the case, while the local traffic rules or the traffic separation scheme also leads to the multi-flows.

The capability of a model to capture such base cases depends on whether the vessel behavior is specified in different situations.

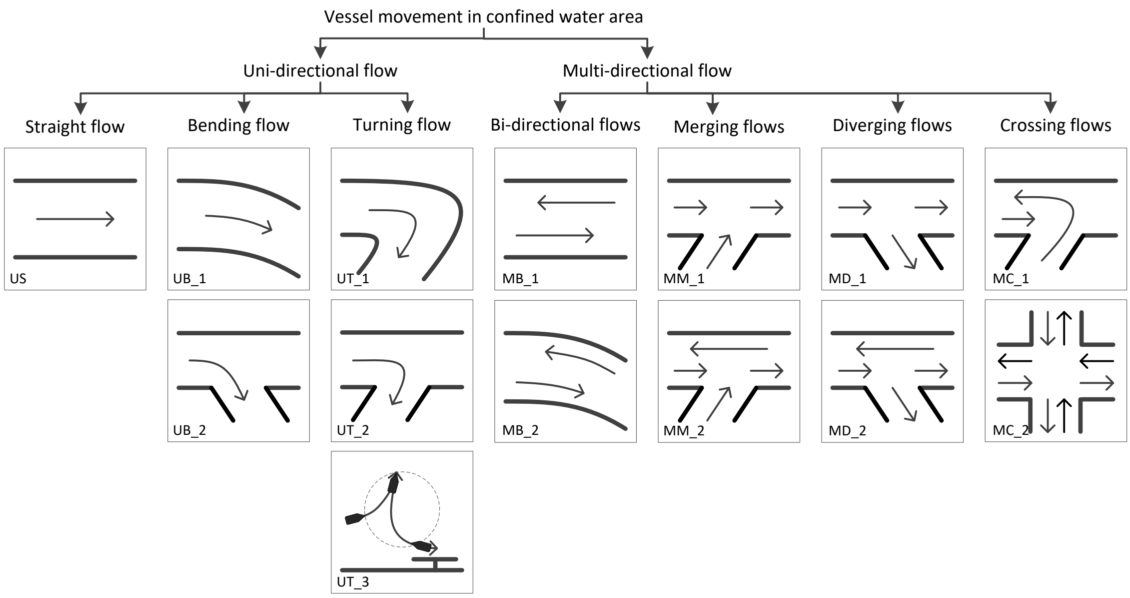

Figure 2.6. Vessel movement base cases in confined water area.

2.4 Model categorization — vessel behavior modeling

All of the maritime traffic models, excluding the commercial ones due to a lack of sufficient information about the methodology, will be categorized based on their modeling paradigms as presented in Figure 2.5. To illustrate the development of maritime traffic models with their corresponding modeling paradigms, the timeline of the models is presented in Figure 2.7. It can be observed that the rule-based models (either specific or generic) are adopted throughout the development of maritime traffic models. With the introduction of AIS data and the development of computer science, the trend moves from generic rules to specific rules and from one-dimensional model to two-dimensional ones. The optimal control model and system dynamics model for maritime traffic are first proposed in the 1990s at a conceptual level, due to a lack of data availability. Afterward, both methods are not often adopted, compared to rule-based models. However, in recent years, with the research trend of mathematical models and the various data sources, both modeling paradigms are developed again. Cellular Automata and Artificial Potential Field are adapted to maritime traffic from other fields, namely vehicular traffic flow modeling and robot path planning. Both paradigms have been continuously adopted and developed by different researchers since its first application in maritime traffic models. By categorizing the models into paradigms, the introduction of individual models will also indicate the development within each paradigm.

Before the detailed introduction, an overview of the models regarding the characteristics of model development is also presented in Table 2.8. The model characteristics include the following aspects:

a) *Dimension* indicates how the vessel motion is specified in space.

b) *Scale of time* refers to how is the vessel movement modeled in time, i.e., continuous or discrete. A time-discrete model can be obtained by discretizing the time-continuous model, or directly developed to update vessel movement at time steps.

c) *Scale of space* indicates how is the water area defined in the model (continuous or discrete).

d) *Calibration* refers to the process to find an optimum set of model parameters by minimizing the differences between simulation results and the observed data.

e) *Validation* is the process using an independent data set compared to the one used in calibration, in order to check whether the model replicates reality or not.

f) *Category*: Six modeling paradigms are identified in this chapter. The categories are described in the order indicating the potential to capture more details of vessel behavior.

Since all of the reviewed models are stochastic, it is not included as a criterion in the table. In the following sections, Cellular Automata (section 2.4.1), Generic Rule-Based model (section 2.4.2), Specific Rule-Based model (section 2.4.3), Artificial Potential Field model (section 2.4.4), Optimal Control model (section 2.4.5), and System Dynamics model (section 2.4.6) are introduced. Section 2.4.7 provides a discussion on the overview of the modeling paradigms.

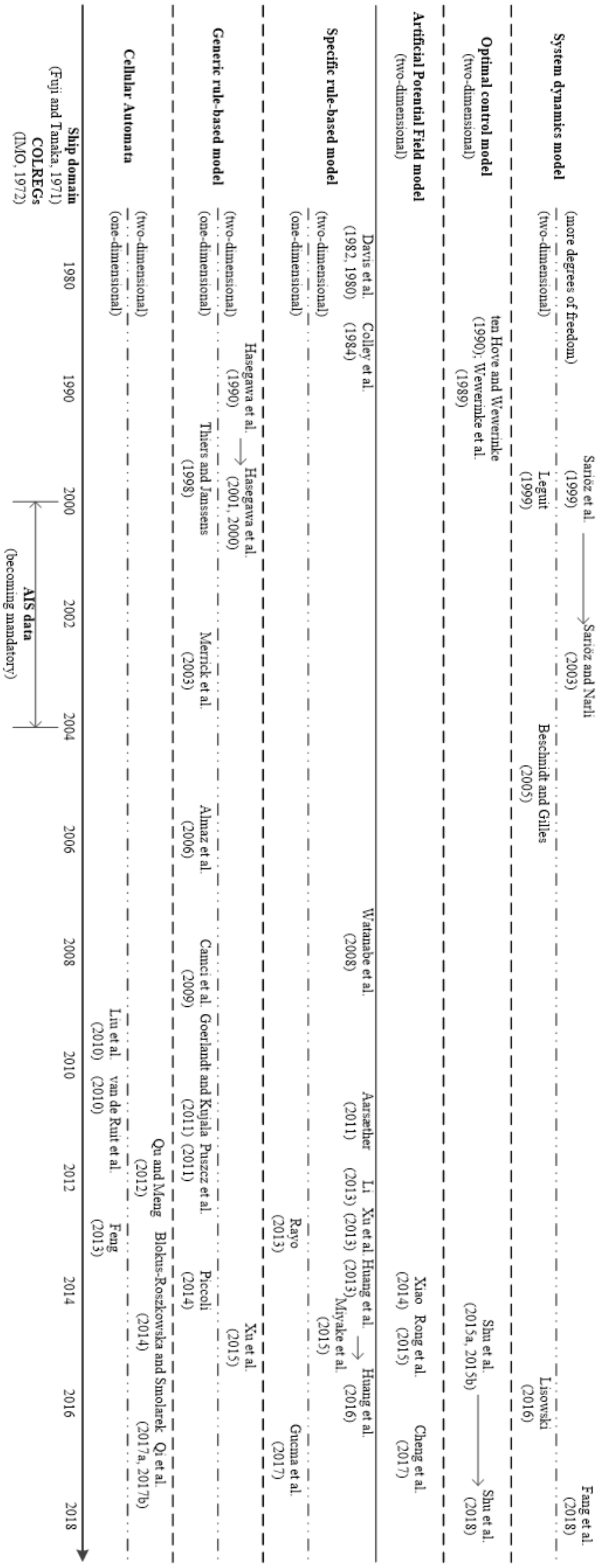

Figure 2.7. Timeline of the maritime traffic models with corresponding modeling paradigms.

Table 2.8. Overview of maritime traffic models with respect to the model characteristics.

No.	Model	Dimension	Scale		Calibration	Validation	Category
			Time	Space			
1	Liu et al. (2010)	*1*	*dt*	*d*	×	√	CA
2	Feng (2013)	*1*	*dt*	*d*	×	×	CA
3	van de Ruit et al. (2010)	*1*	*dt*	*d*	×	√	CA
4	Qu and Meng (2012)	*2*	*dt*	*d*	×	√	CA
5	Blokus-Roszkowska and Smolarek (2014)	*2*	*dt*	*d*	×	×	CA
6	Qi et al. (2017a, 2017b)	*2*	*dt*	*d*	×	√	CA
7	Thiers and Janssens (1998)	*1*	*dt*	*d*	×	√	GRB
8	Merrick et al., (2003)	*1*	*dt*	*c*	×	√	GRB
9	Almaz et al. (2006)	*1*	*dt*	*c*	×	√	GRB
10	Camci et al. (2009)	*1*	*dt*	*c*	×	√	GRB
11	Goerlandt and Kujala (2011)	*1*	*dt*	*c*	×	√	GRB
12	Puszcz et al. (2011)	*1*	*dt*	*c*	×	√	GRB
13	Piccoli (2014)	*1*	*dt*	*c*	×	√	GRB
14	Hasegawa (1990); Hasegawa et al. (2001, 2000)	*2*	*dt*	*c*	×	√	GRB
15	Xu et al. (2015)	*2*	*dt*	*c*	×	√	GRB
16	Gucma et al. (2017)	*1*	*dt*	*c*	×	√	SRB
17	Rayo (2013)	*1*	*dc*	*c*	×	×	SRB
18	Davis et al. (1982, 1980)	*2*	*dt*	*c*	×	×	SRB
19	Colley et al. (1984)	*2*	*dt*	*c*	×	√	SRB
20	Watanabe et al. (2008)	*2*	*dt*	*c*	×	×	SRB
21	Li (2013)	*2*	*dt*	*c*	×	×	SRB
22	Xu et al. (2013)	*2*	*dt*	*c*	×	√	SRB
23	Miyake et al. (2015)	*2*	*dt*	*c*	×	√	SRB
24	Huang et al. (2016, 2013)	*2*	*dt*	*c*	√	√	SRB
25	Aarsæther (2011)	*2*	*dc*	*c*	×	√	SRB
26	Xiao (2014)	*2*	*dt*	*c*	√	√	APF
27	Rong et al. (2015)	*2*	*dt*	*c*	×	√	APF
28	Cheng et al. (2017)	*2*	*dt*	*c*	×	√	APF
29	ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	*2*	*dc*	*c*	×	×	OC
30	Shu et al. (2018, 2015a, 2015b)	*2*	*dc*	*c*	√	√	OC
31	Leguit (1999)	*2*	*dt*	*c*	×	×	SD
32	Lisowski (2016)	*2*	*dc*	*c*	×	×	SD
33	Beschnidt and Gilles (2005)	*2*	*c*	*c*	×	×	SD
34	Sariöz et al. (1999); Sariöz and Narli (2003)	*>2*	*c*	*c*	√	×	SD
35	Fang et al. (2018)	*>2*	*dc*	*c*	√	×	SD

Dimension: 1=one-dimensional, 2=two-dimensional, *>2*=including more degrees of freedom of vessel motion;

Scale of time: *dt*= discrete-time model, *dc*=discretized from a continuous-time model, *c*=continuous time;

Scale of space: *d*=discrete, *c*=continuous;

Category: CA=Cellular Automata, GRB=generic rule-based, SRB=specific rule-based, APF=artificial potential field, OC=optimal control, SD=system dynamics.

2.4.1 Cellular Automata

The Cellular Automata (CA) model is a specific type of rule-based model. It is discrete both in time and space to describe the discrete movement of vessels through grids of cells. The waterway or traffic route is discretized into cells with a predefined size. The vessels are assigned a certain number of cells according to the length. The states of cells are assumed to be either available or occupied. For all CA models, the decision of vessel behavior depends on the status of neighboring cells. However, the moving direction and the moving speed differ according to the rules defined in different models.

The position of the vessel is updated at each time step. The vessel speed is modeled generally in two ways. In the simplified method, the speed of the vessels is constant through the voyage, which can be the same for all vessels (Liu et al., 2010) or dependent on vessel type (Blokus-Roszkowska and Smolarek, 2014). Alternatively, the speed of the vessels is decided by rules of following behavior (Feng, 2013; Qi et al., 2017b; Qu and Meng, 2012; van de Ruit et al., 2010).

Regarding the external impacts, Qu and Meng (2012) and Qi et al. (2017a) adopt random variables to represent the impacts of weather and sea state on vessel speed. The interactions with other vessels are considered by defining deceleration rules when another vessel is within a distance of safety (Feng, 2013; Qi et al., 2017a). Blokus-Roszkowska and Smolarek (2014) consider the relative course of the other vessel to determine the reacting behavior, which could be acceleration or course change. Qu and Meng (2012) define crossing rules for vessels about to enter the main traffic route from the branch waterways and rules for overtaking situation.

Since CA models present the dynamics of traffic flow based on vessel speed and position in cells, the detailed behavior of vessels can hardly be simulated. The impacts of external factors are simplified, either.

2.4.2 Generic rule-based models

In generic rule-based models, it is assumed that the details of the individual vessel behavior (position, speed, course) are simplified as generic movement rules for all agents. In such models, the rules for different vessels are defined as the same under any circumstances.

Most of the generic rule-based models present the maritime traffic in one-dimensional space, i.e. the lateral position of vessels in waterway is not included (Almaz et al., 2006; Camci et al., 2009; Goerlandt and Kujala, 2011; Merrick et al., 2003; Piccoli, 2014; Puszcz et al., 2011; Thiers and Janssens, 1998). The routes are predefined in the models, and with waypoint coordinates if needed. The behavior rule of the agents is to follow the routes and turn instantly at the waypoints. In other models in two-dimensional space, the lateral position of vessels at waypoints is defined to follow specific distribution or the distribution from historical data (Hasegawa, 1990; Hasegawa et al., 2001, 2000; Xu et al., 2015). The vessel speed is defined as the same for all vessels (Piccoli, 2014), or dependent on the vessel classification (Almaz et al., 2006; Camci et al., 2009; Goerlandt and Kujala, 2011; Hasegawa, 1990; Hasegawa et al., 2001, 2000; Merrick et al., 2003), or generated from historical distribution (Puszcz et al., 2011; Xu et al., 2015). Thiers and Janssens (1998) determine the vessel speed for each waterway segment, thus the vessels change the speed immediately when entering a new segment.

The conditions of external environmental factors are considered by defining different vessel speed (Almaz et al., 2006; Camci et al., 2009; Merrick et al., 2003; Puszcz et al., 2011), or generating vessels according to tidal window (Piccoli, 2014; Thiers and Janssens, 1998). Qu and Meng (2012) and Xu et al. (2015) define the rules of overtaking by a distance of safety. None of the models define detailed behavior rules for collision avoidance during other encounters. However, Distance of Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA) are calculated for risk analysis (Goerlandt and Kujala, 2011; Hasegawa et al., 2001). The traffic rules regarding speed limit or overtaking prohibition are also included for all vessels (Qu and Meng, 2012; Thiers and Janssens, 1998; Xu et al., 2015).

Therefore, the differences in unhindered behavior among different vessels and the external impacts under different circumstances cannot be presented in the generic rule-based models. When applying for macroscopic statistical analysis for a large area as presented in the referenced papers, the models are well applicable.

2.4.3 Specific rule-based models

Similar to generic rule-based models, the dynamic vessel behavior (position, speed, course, heading) is assumed to be described by a set of rules. However, the specific rule-based models consider the differences between vessels and the possible interaction between vessels and the circumstances. The unhindered behavior of different vessels is usually distinguished. The impacts of the geographical layout can also be included by defining behavior rules. The vessel behavior during an encounter can be determined according to a situation-based calculation.

In respect of the rules for basic behavior, the course of the vessels is designed to follow the route and instantly turn at the waypoints in most of the models, except for Aarsæther (2011). In this model, the course is proportional feedback of the rate-of-turn when the course of the route is changing. The speed of the vessels are constant through the voyage, which can be dependent on vessel classification (Miyake et al., 2015; Watanabe et al., 2008), or have a specific distribution (Gucma et al., 2017), or a distribution derived from historical data (Colley et al., 1984; Davis et al., 1980; Huang et al., 2016, 2013; Li, 2013; Xu et al., 2013). In other models, the speed of the vessels is determined by the maximum or minimum of the speed limitations (Rayo, 2013). Aarsæther (2011) defines the vessel behavior as a first-order model between the current and desired speed.

Regarding the impacts of external environmental factors, only two models include the corresponding behavior rules. For the impact of bank, Davis et al. (1980) define the domain of bank, while the vessels will change course to sail parallel to the bank and decelerate. Watanabe et al. (2008) assume the waterway bank to be a virtual agent with the same speed parallel to the vessel agent or on the opposite direction.

Nearly all models include the interactions between vessels for collision avoidance, except for Xu et al. (2013). Rayo (2013) and Gucma et al. (2017) only define a distance of safety to determine whether a vessel should decelerate or not, in which course change is not considered in the one-dimensional space. The remaining models adopt different criteria to judge the encounter situation between vessels and calculate DCPA and TCPA to trigger the evasive actions. Aarsæther (2011) only defines a distance of safety as the only criterion. Davis et al. (1980) adopt the ship domain to indicate the timing when the domain is infringed by the other vessel, in which the size is decided by statistical data. Colley et al. (1984) further considers the relative speed of the other vessel and defines the concept of range to domain over range rate (RDRR) in the calculation. This way, the three types of encounters can be distinguished. The behavior rule during dangerous head-on situation (starboard-to-starboard) is also defined. Li (2013) and Miyake et al. (2015) trigger the collision avoidance behavior with an increase of DCPA and TCPA. Watanabe et al. (2008) adopt the concept of CR by Hasegawa et al. (2001) to judge the situation and calculate the timing for the vessel to turn back to the original route. Huang et al. (2016) use DCPA and the Separating Axis Theorem (Eberly, 2001) to detect the collision candidate. All of them assign the responsibility of taking actions among vessels in encounter based on the rules of COLREGs. The resulting evasive behavior is mainly to change course or to change both course and speed. The magnitude of the behavior is decided to best decrease DCPA and TCPA.

In the models by Davis et al. (1982), Colley et al. (1984) and (Miyake et al., 2015), the multi-vessel encounter situation is assumed to be a series of two-vessel encounters. The most dangerous vessel to avoid collision first is chosen with the earliest TCPA. In this case, if the most dangerous vessel is the give-way vessel, and she does not take evasive actions within a certain time, the stand-on vessel at liberty should take action by a round turn. During the collision avoidance, DCPA and TCPA are calculated at each time step to judge the situation.

The specific rule-based models represent the interaction between vessels better than the aforementioned two approaches. However, in most of the pre-defined rules, the safety distance or other parameter value to trigger the evasive maneuver for collision avoidance is subjectively determined by the user for a specific area during model development. It limits the applicability of models in other areas. The impact of environmental external factors is not included yet. To present such impacts on different vessels by specific rules, the detailed maneuvering particulars for specific vessels may be needed.

2.4.4 Artificial potential field models

An Artificial Potential Field (APF), also known as artificial force field, has been implemented in three maritime traffic models for different types of water area. In these models, vessels are defined as agents. APF provides the course of the vessel subjected to a force which is derived from the sum of the attractive potential and the repulsive forces. All models by APF present the vessel behavior in two-dimensional continuous space. The models are designed to calculate the potential and forces to decide the speed and course at each time step.

The definition of attractive and repulsive potential varies among the models. Xiao (2014) adopts APF to simulate the impacts of banks and encounters (head-on and overtaking situation) on vessel behavior in straight waterways. A similar model is developed by Rong et al. (2015) for traffic in the river, where the boundaries of the traffic lanes are represented by a series of points with the repulsive potential to the vessels. In the model by Cheng et al. (2017), the impacts from fixed obstacles in the multi-bridge area are simulated using APF. The repulsive potential field around fixed obstacles is assumed to be rectangle or circle with three layers, in which the most inside layer is set with the largest repulsive potential. The potential of the three layers is defined separately as a function of distance, speed, and course, while the potential within each layer is the same.

In the models by Rong et al. (2015) and Cheng et al. (2017), the speed of vessels changes only during the encounter with other vessels or obstacles. Otherwise, vessels keep a constant speed determined when generating the vessel in the beginning. Neither of them includes the impact of external conditions, e.g. wind or current. Xiao (2014) developed a sub-model for the behavior of vessels by the Nomoto model (Kawaguchi et al., 2004) based on basic maneuverability. The impact of wind and current is indicated by a variation in course and heading, without influencing the speed of vessels.

APF shows its potential in modeling the course choice under the external impacts from sailing boundaries or other encountering vessels. It can be expected that the method could represent the impacts of external factors as repulsive potential based on the hydrodynamical calculation or sufficient data analysis to calibrate the parameters in the function. However, the method of APF itself hardly simulates the unhindered vessel speed, which is so far derived from historical data or modeled separately.

2.4.5 Optimal control models

The optimal control models present the vessel behavior in two-dimensional continuous space. The models are designed to continuously describe the behavior, though discretized during implementation. In different models, the objective function and the constraints are defined differently. The vessel behavior is decided by solving the optimization problem.

Wewerinke et al. (1989) first presented the maritime traffic modeling as a nonlinear control problem. The dynamic vessel behavior of speed and position is to minimize the cost function. The state of the system is defined as a function of speed, rate of turn, heading, position. For any encounter, DCPA and TCPA are calculated. Once the DCPA is less than a certain threshold, the vessels will change their behavior as a state change in the system control. The principle of behavior change is to minimize both DCPA and TCPA. All of the functions are provided as a theoretical study without further calibration or validation.

Another simulation model using optimal control is developed by Shu et al. (2015) to predict the vessel behavior in the port area. The vessel behavior in the model is described at the tactical level to generate vessel route choice and operational level to include the dynamics of the vessel sailing behavior. The impacts of bank and waterway bending on vessel behavior are considered in the route choice model. The optimal vessel course is based on the approach presented by Hoogendoorn et al. (2013), which is the solution to minimize the cost (utility) to the destination for a vessel located at a specific position at the moment of time. But the desired speed of vessels on specific cross-sections are generated from the historical data. But the impacts from other external factors and the interaction with other vessels are not included in the model. The model has been calibrated with Automatic Identification System (AIS) data.

The approach with optimal control provides the possibility to model the real-life sailing environment, by changing the objective function or the constraints. Based on the calibration for optimized parameters, the model can be expected to be applied to any other area.

2.4.6 System dynamics models

The last modeling paradigm is to describe the vessel movement in state-space representation, which is expected to most capture the details of vessel behavior in maritime traffic. The system dynamics models are designed to present the process of vessel behavior in a system as it is in reality.

Leguit (1999) determines the vessel behavior by a PID controller considering the forces on different modules of vessels (i.e., hull, rudder, and propeller). Other models define the vessel behavior state by differential equations in two-dimensional space (Beschnidt and Gilles, 2005; Lisowski, 2016) or in more degrees of freedom (Fang et al., 2018; Sariöz and Narli, 2003; Sarıöz et al., 2002).

Regarding the external environmental factors, Lisowski (2016) distinguishes the vessel behavior in different visibilities. The impacts of wind and/or current are investigated by including the corresponding forces on the vessel (Beschnidt and Gilles, 2005; Leguit, 1999; Sariöz and Narli, 2003; Sarıöz et al., 2002). Sariöz et al. (1999) and Sariöz and Narli (2003) consider the bank effects by hydrodynamic calculation along the length of the vessel. With respect to the vessel interaction during encounters, a defined distance of safety needs to be maintained by the vessels to avoid collision (Fang et al., 2018; Lisowski, 2016). Fang et al. (2018) further distinguish the responsibilities of the stand-on vessel and give-way vessel according to the encounter situation.

In the current system dynamics models, only the two models presented in more degrees of freedom are calibrated by full-scale maneuvering simulation result or maneuvering data for specific vessels (Fang et al., 2018; Sariöz and Narli, 2003; Sarıöz et al., 2002). It also indicates the limitation in applying such models for an area with a large number of different vessels due to a lack of data for model parameter calibration. The computation load is also expected to be the largest, compared to the aforementioned paradigms.

2.4.7 Discussion on model characteristics and paradigms

Regarding the dimension of models, most of them simulate the vessel motion in two-dimensional space, which describes the longitudinal and lateral position in the water area. Besides the CA models, only one model discretizes the waterway into segments. All other models simulate vessel movement in continuous space. Meanwhile, only two models are designed to be continuous in time to describe the vessel maneuvering, which are both system dynamics models. Other models update the vessel behavior at time steps or calculate the state-space model discretely. With respect to the calibration and validation processes, more models focus on the validation, while only five models are calibrated to obtain the optimum parameter sets. The model parameters are mostly determined by the users for specific water area or based on historical data.

The overall comparison of the six modeling paradigms based on the proposed assessment criteria is presented in Table 2.9. Rather than a summary of the existing models' characteristics, the comparison also considers the potential and limitation of the paradigms. It can happen that a modeling paradigm is capable of modeling the vessel behavior under specific external impact, but none of the existing models has implemented it due to the specific application purposes. The applicability of the model is not limited by modeling paradigms, i.e., any paradigm can be applied in open or confined water area. Thus, the model applicability is not compared for the paradigms. To further investigate the details of each model, the selected maritime models are individually assessed in section 2.5.

Table 2.9. Overall comparison of the characteristics of the six modeling paradigms.

Modeling paradigms (no. of models)		Vessel behavior representation					External impact modeling											
		Static inherent characteristics	Dynamic kinetic information				External conditions						Encounters with other vessels					Traffic rules
			P	S	C	H	V	W	T	C	A	B	DS	HO	CS	OT	MV	
Rule-based models (25)	CA models (6)	T, GT, DWT, L, B	!	!	!		!	√	√	√			√		!	!		!
	Generic rule-based models (9)	T, GT, DWT, L, B	!	!	!		!	√	√	√			√		!	!		!
	Specific rule-based models (10)	T, GT, DWT, L, B	!	!	!	√	!	√	√	√		√	√	!	!	!	√	!
Mathematical Models (10)	APF models (3)	T, GT, DWT, L, B	!	!	!	√	!	!	√	!	√	√	√	!	!	!	√	!
	Optimal control models (2)	T, GT, DWT, L, B	!	!	!	!	!	!	√	!	√	√	√	!	!	!	√	!
	System dynamics models (5)	S	!	!	!	!	!	!	√	!	!	√	√	!	!	!	√	!

The rating scales are explained in section 2.3, except for the use of blank cell. All blank cells here indicate the kinetic information or external factor cannot be included due to the limitation of this paradigm.

From Table 2.9, it can be found most of the maritime traffic models are rule-based, either with generic rules or specific ones. CA models and generic rule-based models can hardly distinguish the vessel heterogeneity and human behavior differences between vessels or represent the external impacts on vessel behavior. However, even with the simplification of the maneuvering processes and the interaction with surrounding environment, the models are well applicable for macroscopic analysis of traffic flow. The specific rule-based models can further describe the evasive maneuvering behavior based on the specific encounter situations. However, the behavior differences between vessels and the impacts of external environmental factors cannot be properly handled, unless the detailed maneuvering particulars for specific vessels can be provided.

The mathematical models (APF models, optimal control models, and system dynamics models) pose their potential in capturing the behavioral differences between vessels and the specific external impacts. The APF models and optimal control models describe the behavior variation between groups of vessels with similar inherent characteristics. The system dynamics models are even capable of simulating the individual vessel behavior in detail considering the whole sailing processes. However, the specific maneuverability of each individual vessel in an area is rarely known. The application purpose of a maritime traffic model is mostly for an area, without strict requirement on individual behavior accuracy. Thus, for the mathematical models, the trade-off between generic application and vessel behavior variation needs to be balanced, and the necessary data for model calibration should be available.

2.5 Discussion on vessel behavior modeling

In this section, the maritime traffic models described in section 2.4 will be individually assessed using the criteria introduced in section 2.3. The comparison results are displayed in Table 2.10. The performance and potential of models will be discussed from the four aspects, being the vessel behavior representation, the potential to modeling external environmental impacts, the modeling of impacts during encounters, and the model applicability.

Table 2.10. Assessment of maritime traffic models with respect to the capability of modeling vessel behavior.

No	Model	Vessel representation	Static inherent characteristics	Dynamic kinetic info.			External conditions						Encounter with other vessels					Traffic rules	Area of application	Movement base cases (for confined water area)	Stated application purpose
				P	S	C	H	V	W	T	C	A	B	DS	HO	CS	OT	MV			
1	Liu et al. (2010)	a	T, GT	√	×								-	√						CW_V	US	
2	Feng (2013)	a		√	!								-							CW_V	US, MM_1, MD_1	
3	van de Ruit et al. (2010)	a	T	√	√	√							-	√						CW_V	US, UB_2, UT_2	Flow analysis
4	Qu and Meng (2012)	a	T	!	!	!		√	√	√	√		-	√		√	√		!	OW, CW_V	US, MM, MC_2	Traffic volume
5	Blokus-Roszkowska and Smolarek (2014)	a	L	!	!	!							-	√		√				CW_V	US, MM, MD, MC_2	
6	Qi et al. (2017a, 2017b)	a	L	!	!	√			√	√	√		-	√			√			CW_V	US, MM_1	Flow analysis
7	Thiers and Janssens (1998)	a	T, GT	√	!	√				√			×	√		√	!		!	CW_G, CW_V	US, UB_1, UT_1, MB, MM, MD	Flow analysis
8	Merrick et al., (2003)	a	T	√	√	√		√					-	√						OW, CW_V	US, MM_1, MD_1	Density analysis
9	Almaz et al. (2006)	a	T, L	√	!	√		!			√		-				√		!	OW, CW_V	US, UB_1, MB	Flow analysis
10	Camci et al. (2009)	a	T, L	√	!	√		!			√		-						!	OW, CW_V	US, UB_1, MB	Flow analysis
11	Goerlandt and Kujala (2011)	a	T, L, B	√	×	√							-							OW, CW_V	US, UB_2, MB, MM, MD	Collision probability
12	Puszcz et al. (2011)	a	T, L	√	√	!		√					-							CW_V	US, UB, MB, MM, MD, MC_1	Flow analysis
13	Piccoli (2014)	a	T, DWT	√	!	√				√			-	√			√		!	CW_V	US, MB, MM, MD	Flow analysis
14	Hasegawa (1990); Hasegawa et al. (2001, 2000)	a	GT, L	!	!	!							-	√					√	OW, CW_V	US, UB_2, MB, MC	Risk assessment
15	Xu et al. (2015)	a	T, L, B	!	×	!							-	√			!		!	CW_V	US, MB_1	Flow analysis
16	Gucma et al. (2017)	a	L	√	√	√							-	√			√			CW_V	US, MB_1	Flow analysis
17	Rayo (2013)	a	S	√	√	√							×	√			√		!	CW_G, CW_V	US, MB_1	Flow analysis
18	Davis et al. (1982, 1980)	a		!	!	!	√						√	√	√	!	√	√	√	OW	-	
19	Colley et al. (1984)	a	T	!	!	!	√						-	√	!	!	!	√	√	OW	-	

Table 2.10. *(continued)*

No	Model	Vessel representation	Static inherent characteristics	Dynamic kinetic info.				External conditions						Encounter with other vessels					Traffic rules	Area of application	Movement base cases (for confined water area)	Stated application purpose
				P	S	C	H	V	W	T	C	A	B	DS	HO	CS	OT	MV				
20	Watanabe et al. (2008)	*a*	S	!	!	!	√						√	√	√	√	√		√	OW, CW_G	US, UB_1, UT_2, MB, MM, MD	
21	Li (2013)	*a*		!	!	√							-	√	!	!	!			CW_V	US, UB_1, MB, MM_1, MC_1	Collision analysis
22	Xu et al. (2013)	*a*	L	!	√	√							-							CW_V	US	
23	Miyake et al. (2015)	*a*	GT, L	!	!	!	√						-	√				√	√	OW, CW_V	US, UB_2, MB_1, MC	Collision avoidance
24	Huang et al. (2016, 2013)	*a*	T, L, B	!	×	√	√						-	√	√	√	√		√	OW, CW_V	US, UB_1, MB, MC_2	Flow analysis
25	Aarsæther (2011)	*a*		!	!	!	√						-	√	√	√	√		√	CW_V	US, UB_1, MB, MM, MD	
26	Xiao (2014)	*a*	T, GT, L	!	!	!	√		!		!		√	√	√		!		√	CW_G, CW_V	US, MB_1	
27	Rong et al. (2015)	*a*	T	!	!	!							-	√	√		!			CW_V	US, UB_1, MB	Flow analysis
28	Cheng et al. (2017)	*a*		!	!	!	√						√							CW_G, CW_V	US	
29	ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	*a*		!	!	!	!						-	√	√	√	√		√	?		Conceptual model
30	Shu et al. (2018, 2015a, 2015b)	*a*	T, GT	!	!	!							√							CW_G, CW_V	US, UB_1, MB	
31	Leguit, (1999)	*m*	S	!	!	!			!				×							CW_G	US, UB_2, MB_1	Risk assessment
32	Lisowski (2016)	*a*		!	!	!	√	√					-	√	√	!	!			?		Sensitivity analysis
33	Beschnidt and Gilles (2005)	*a*		!	!	!	!		!		!		-							OW, CW_V	US, UB_1	
34	Sariöz et al. (1999); Sariöz and Narli (2003)	*m*	S	!	√	!			!		!		√							CW_G, CW_V	US, UB_1	
35	Fang et al. (2018)	*m*	S	!	!	!	!						-	√	!	!	!			OW	-	Collision avoidance

Abbreviations:
Vessel representation: *a*=agent, *m*=sub-modules based on vessel structure;
Static inherent characteristics: T=type, GT=gross tonnage, DWT=deadweight tonnage, L=length, B=breadth, S=specific vessels;
Dynamic kinetic information: P=position, S=speed over ground, C=course over ground, H=heading;
External conditions: V=visibility, W=wind, T=tide, C=current, A=Adverse weather, B=bank;
Encounter with other vessels: DS=distance of safety, HO=head-on, CS=crossing, OT=overtaking, MV=multi-vessel encounter;
Area of application: OW=open water area, CW_G=confined water area with geographical boundary (bank), CW_V=confined water area with virtual boundary (routeing scheme);
Movement base cases (for confined water area): see Figure 2.6.

2.5.1 Vessel classification method

The assessment on static inherent characteristics shows that most models define some classification criteria to simulate the vessel behavior per class or analyze the statistical data to derive behavioral model parameters for each group of vessels. Among the vessel inherent characteristics, the vessel type is mostly chosen as the criterion or one of the criteria for vessel classification. Regarding the characteristics of geometric size, the length has been more adopted than the breadth. For all of the models using breadth, the length and type are also chosen as the criteria. This way, the horizontal shape of the vessel can be outlined, which best supports the modeling of positional relation between the vessel and the surrounding circumstances. With respect to the characteristics of tonnage, both gross tonnage and deadweight tonnage are adopted as part of the classification criteria to generally categorize the large and small vessels. The inclusion of different classes of vessels presents the diversity of vessels in the area, which has been proven by vessel behavior analysis (de Boer, 2010; Mascaro and Korb, 2010; Silveira et al., 2013; Zhou et al., 2019a). Or a specifically developed model can be dependent on the data of vessel particulars based on application purposes.

2.5.2 Modeling of dynamic kinetic information

All models include position and speed to different extents. Most of the models present the vessel position in two-dimensional space. However, for the models developed for collective traffic flow analysis, the position is simplified into one-dimensional movement. For the vessel speed, besides the way of free speed choices, two other ways of simplification have been implemented in the presented models. One is to determine the vessel speed as a constant variable upon vessel generation based on the historical distribution. The other is to set several choices of fixed speed for maneuvering simulation or theoretical analysis. However, to fully indicate the behavior differences among vessels and the behavior changes under external impacts, the vessel should be able to maintain or change speed under any circumstances through the voyage. For the purpose of emission control, Fagerholt et al. (2015) propose the method of maritime routing and speed optimization. In the studies on waterborne automated guided vehicles, the vessel’s path is modeled by a successive linearized prediction by model predictive control (Zheng et al., 2016). In maritime traffic models by optimal control, both methods can be considered by changing the corresponding objective functions to obtain the optimal speed and course, respectively.

Considering the course of the vessel, nearly all of the models include this kinetic information. A simplified way to include the course is that the routes are determined at the beginning, and all of the vessels follow such routes without course changes. In such models, the course is included as a constant. However, under the good seamanship in COLREGs, course change is prior to speed change during encounters considering the vessel maneuverability and the effects of collision avoidance. It has been realized by the other models adopting the principle that vessels normally follow the designed route and change course under external impacts from the encountering vessel or other factors.

As for the heading of the vessels, only a limited number of models consider the heading changes during vessel encounter or route changes. The other models include heading for DCPA and TCPA calculation, but the heading is deemed the same as course. In order to explicitly reflect the vessel behavior changes during encounter and external impacts, heading should be included in a model to indicate the detailed vessel movement.

2.5.3 Impacts of external environmental conditions

The impacts of external factors on vessel behavior have been proven (Shu et al., 2017), which cannot be ignored in maritime traffic models when considering the individual vessel behavior. However, external conditions have seldom been considered in the models. Generally speaking, two ways have been adopted to indicate such impacts. The first one is to introduce random variables (Qi et al., 2017a; Qu and Meng, 2012) or generic rules (Almaz et al., 2006; Camci et al., 2009; Merrick et al., 2003). It shows the variation of vessel movement under external impacts. The other way is to consider the vessel maneuverability under specific wind and current conditions to model the corresponding behavior (Beschnidt and Gilles, 2005; Leguit, 1999; Sarıöz et al., 2002; Xiao, 2014). Instead of using specific weather conditions, Kepaptsoglou et al. (2015) introduces the method to consider the weather impacts on container vessel speed as a chance-constrained model, which provides another option. None of the models includes the impact of adverse weather conditions, which implies the models assume the adverse weather condition is excluded in the application. As for the impact of banks, most of the models have included it as a push force from the bank using different methods as introduced in section 2.4. The method of integrating such impacts on vessel behavior still needs to be investigated.

2.5.4 Impacts of vessel encounters/interaction between vessels

The impact from encountering vessels on the evasive behavior of the own vessel has been considered in most of the reviewed models. The main method is to define a distance of safety to trigger and calculate the evasive behavior. The distance can be the direct distance between vessels or the size of ship domain. Besides the distance, the relative sailing direction of the other vessels is considered, by calculating DCPA and TCPA, to further distinguish different encounter situations. Specifically, Colley et al. (1984) define behavior rules in the dangerous head-on situation (starboard-to-starboard). All of the models adopt the responsibility of conducts regulated by COLREGs. Regarding the multi-vessel encounters, only Miyake et al. (2015), Davis et al. (1982) and Colley et al. (1984) include the rules to decide the priority of collision avoidance. From the aspect of vessel encounter, the models by Davis et al. (1982) and Colley et al. (1984) can be deemed as the most comprehensive ones. However, the quantification of collision avoidance behavior still needs to be investigated (Fang et al., 2018). Currently, in the field of vessel collision avoidance, the algorithm of generalized velocity obstacle has been developed (Huang et al., 2019), and applied to detect collision candidate (Chen et al., 2018). Instead of the traditional method of calculating DCPA and TCPA, the emerging method can also be applied in maritime traffic models to simulate the vessel behavior during encounters. In a waterway network area with multiple waypoints, Chen et al. (2018) propose the distributed model predictive control for a cooperative multi-vessel situation. Similarly, the method can be adopted to model the vessels' interaction in maritime traffic models.

2.5.5 Model application area

Currently, most of the maritime traffic models are developed for specific application purposes. However, the capability of the model to simulate other situations (the so-called generalization of the model) is also assessed considering its potential according to the proposed assessment criteria of model applicability. Firstly, the definition of navigable water area in the model implies whether the model can describe the characteristics of other types of water area. Secondly, the corresponding sailing rules of the vessels in such an area indicate the capability of modeling the specific traffic flow. As listed below "area of application" in Table 2.10, 16 out of 35 models have been considered to be applicable in more areas than stated in the original paper.

From the perspective of the area of application, three types of water area have been identified in section 2.3.3. The first one with the largest space for vessel maneuvering is open water area. In this type of area, the vessels are sailing with auto-pilot most of the time to follow the designed route. Only during vessel encounters, the vessels should take actions by the bridge team to avoid collisions. All of the encounter types stated in COLREGs should be considered, which have been presented in the models by Davis et al. (1980) and Colley et al. (1984). When the weather or sea state is bad, the behavior is mostly determined by the vessel maneuverability, which is dependent on individual vessels. Therefore, models which are not developed for vessels in open waters can be applied in such a way, provided the behavior during vessel encounters is modeled.

For the confined waters either with routeing scheme or geographical boundaries, the traffic density is usually higher than in open water. The vessel behavior would be expected to be more detailed, including the position in two-dimensional space, speed choices with dynamic freedom, course with free choices, and heading with free choices. This way, the behavioral details between vessels and the external impacts can be presented. Compared to the models for water area with routeing scheme, the impacts of the bank should be considered in the models for physically confined water. However, such impacts are missing in the models designed for port or inland water area (Leguit, 1999; Rayo, 2013; Thiers and Janssens, 1998).

Considering the vessel movement base cases in confined water area (see Figure 2.6), all of the models are capable to model the vessel behavior in uni-directional straight flow. None of the models describe the turning behavior close to berth, since it is fully dependent on individual vessel maneuverability and maneuvering habit of the bridge team. Compared the applicability of models between modeling paradigms, the generic rule-based models can include more movement base cases. The models based on APF, optimal control or system dynamics require a more specific description of the boundary impacts and the interaction with other vessels in such situations. From this viewpoint, to capture more details of vessel behavior and to be applicable in more situations can be a trade-off according to the application purposes.

2.6 Conclusions and recommendations

This chapter provides a review of the literature on maritime traffic models from the vessel behavior modeling perspective. The maritime traffic models include the models applicable both at sea and in confined water area. The scope of this review is the models representing the maritime traffic at the scale of vessels considering the individual vessel behavioral law. To provide a structured overview of the underlying paradigms, a categorization method is proposed to classify the models into six categories, including Cellular Automata, generic rule-based models, specific rule-based models, artificial potential field models, optimal control models, and system dynamics models. All presented models are assessed and compared based on a set of criteria, namely the vessel behavior representation, external impact modeling, and model applicability.

2.6.1 Current status of maritime traffic models

All maritime traffic models can describe the traffic state to different levels of details. As indicated by the articles, the models can fulfill the specific application purposes they are designed for. From Figure 2.7, it can be found that before 2010, a majority of the maritime traffic models are developed only to simulate the generic traffic state in one-dimensional space. The idea of mathematical models is seldom adopted and developed mostly at a level of conceptual model. Afterwards, with the mandatory use of AIS equipment onboard and the improvement of computer science, the models are developed with calibration and/or validation to capture more details of vessel behavior when modeling the maritime traffic. However, two types of limitations are also discovered in the current models.

Firstly, for models with a generic description of maritime traffic state, the behavior variation between vessels and the external impacts are simplified to a large extent. As presented in Table 2.10, none of the existing models describe all dynamic kinetic information in detail for different vessels and consider the impacts from the full range of external factors. One of the reasons is the current models are developed for a specific purpose. The details of vessel behavior or external impacts have been simplified according to the application area or purpose. For the impact of adverse weather condition, none of the models consider the behavior in such a situation, which implies the models assume that the adverse weather condition is excluded from their application. On the contrary, comparing the model paradigm categorization in

Table **2.8** and the model assessment results in Table 2.10, the existing models capturing more details of vessel behavior and the external impacts can be applied in less sailing situations. Such models focusing on individual vessel behavior also require the specific vessel maneuvering data for calibration and validation, which also limits the model applicability.

Therefore, a model capable of simulating different vessel behavior in different situations is still missing. Such a model considers the commonality of vessels in classes based on the vessel characteristics. The behavior characteristics in different types of water area or under different external conditions are also analyzed for vessels in classes. For some specific application purposes, the vessel behavior can be simplified. Thus, the balance between generic application and vessel behavior variation can be handled.

2.6.2 Future research agenda

Based on the results of the review, the possible future research paths are outlined considering the use of different data sources in the era of big data. Future development of maritime traffic models regarding vessel behavior modeling can focus on several directions, which are the main gaps for the current models as mentioned above.

Firstly, the behavior of different vessels should be able to be modeled through the calibration of parameter sets in a generic model. So far, each maritime traffic model is only developed for a specific purpose. The behavior differences between vessels are either ignored or simplified as assumptions of different behavior based on vessel type or size. The general behavior commonality of vessels in classes based on vessel characteristics is still unknown. Thus, a generic model needs to classify the vessels in a systematic way to cover all vessels while identify the vessel behavior differences. When the generic model is applied in different areas or for different purposes, the local AIS data can be used to obtain the optimal parameter sets.

Secondly, the external impacts from external conditions, vessel encounters, and traffic rules need to be integrated into the vessel behavior. Since the vessel behavior is highly influenced by the surrounding sailing environment, the external impacts should not be ignored or simply assumed as a given distribution without detailed study. This way, the meteorological and hydrodynamic data corresponding to the period of AIS data can be coupled to explain the behavior under specific circumstances. The emerging algorithms in the waterborne automated guided vehicles and collision avoidance can be adopted to model the vessel interaction during encounters. However, the method of including such external impacts on vessel behavior is needed, especially for the (geographically and virtually) confined water areas.

Finally, the maritime traffic in different water areas and different vessel movement base cases in confined water area should be considered. Based on a systematic description of the vessel behavior characteristics in different areas, a generic model identifies the vessel behavior under different circumstances. Meanwhile, for model users, the model can be specified based on the application purposes.

Such a generic model would meet both requirements of capturing different vessel behavioral details and being applicable for different purposes in different area. The source of AIS data also makes calibration and validation of the models possible.

Appendix

The full list of descriptive background information for the selected models is provided in Table 2.11, which is in addition to the statistical information in Table 2.1.

Table 2.11. Overview of the descriptive background information of the selected models in this review.

No.	Model	Type of publication	Country and region	Stated application area	Collected data type	Data source
1	Davis et al. (1982, 1980)	J	GBR	OW	Questionnaire	Interview
2	Colley et al. (1984)	J	GBR	OW	Cine film of radar screen	National Maritime Institute
3	ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	C	NLD	CW	-	-
4	Thiers and Janssens (1998)	J	BEL	CW	Traffic data	Local observation
5	Leguit (1999)	T	NLD	CW	Traffic data and ship maneuvering data	Not mentioned
6	Hasegawa et al. (2001, 2000); Hasegawa (1990)	C	JPN	OW	GPS and AIS data	Not mentioned
7	Sariöz and Narli (2003); Sariöz et al. (1999)	J	TUR	CW	Ship maneuvering data	Not mentioned
8	Merrick et al., (2003)	J	USA	CW	Traffic data	San Francisco VTS
9	Beschnidt and Gilles (2005)	J	DEU	CW	Radar and AIS data	Not mentioned
10	Almaz et al. (2006)	J	TUR	CW	Traffic data	Not mentioned
11	Watanabe et al. (2008)	C	JPN, BEL	CW	-	-
12	Camci et al. (2009)	C	TUR	CW	Traffic data	Not mentioned
13	Liu et al. (2010)	C	CHN	CW	-	-
14	van de Ruit et al. (2010)	J	NLD	CW	-	-
15	Aarsæther (2011)	T	NOR	CW	AIS data	Norwegian Coastal Administration
16	Goerlandt and Kujala (2011)	J	FIN	OW	AIS data	Finnish Transport Agency
17	Puszcz et al. (2011)	C	POL	CW	AIS data	HELCOM
18	Qu and Meng (2012)	J	SGP	CW	AIS data	Lloyd MIU ship movement database
19	Feng (2013)	J	CHN	CW	-	-
20	Huang et al. (2016, 2013)	J, C	SGP	CW	Radar data	Not mentioned
21	Li (2013)	T	SGP	CW	-	-
22	Rayo (2013)	T	NLD	CW	-	-
23	Xu et al. (2013)	C	CHN	CW	AIS data	Self-installed receivers
24	Blokus-Roszkowska and Smolarek (2014)	C	POL	CW	-	-
25	Piccoli (2014)	T	NLD	CW	-	-
26	Xiao (2014)	T	NLD	CW	AIS data	MARIN(NLD) & MSA(CHN)
27	Miyake et al. (2015)	J	JPN	OW	AIS data	Not mentioned
28	Rong et al. (2015)	J	PRT	CW	AIS data	Not mentioned
29	Xu et al. (2015)	C	CHN	CW	AIS data	Self-installed receivers
30	Lisowski (2016)	J	POL	OW	-	-
31	Cheng et al. (2017)	C	CHN	CW	Radar data	Self-installed receivers
32	Gucma et al. (2017)	J	POL	CW	AIS data	VTS center in Szczecin Harbour
33	Qi et al. (2017a, 2017b)	J	CHN	CW	AIS data	Not mentioned
34	Shu et al. (2018, 2015a, 2015b)	J	NLD	CW	AIS data	MARIN
35	Fang et al. (2018)	J	TWN (CHN)	OW	Ship maneuvering data	Experiment and sea trial

Type of publication: J=journal article; C=conference proceedings; T=thesis;
Country and region: marked by the affiliation of all authors in abbreviations from country codes of ISO 3166;
Stated application area: OW=open water; CW=confined water;
Collected data type and data source: the models without historical or experimental data input are marked with a dash '-'.

3. Ship Classification Based on Ship Behavior Clustering

The current studies in ship behavior analyze the behavior patterns either with a subjective choice of classification for behavior differences among the groups of ships or without any classification at all. In order to fill this gap, a new methodology for ship classification in ports based on the unhindered behavior clustering is developed in this chapter.

Besides a proper data preparation, the proposed methodology consists of two steps: step I, clustering ship behavior in a port area and identifying the characteristics of the clusters; step II, classifying ships to such behavior clusters based on the ship characteristics. The clustering results present both the behavior patterns and the behavior change patterns for ship path and speed over ground, which are the dominant behavior attributes for ships in ports. Some patterns of integral ship behavior can also be revealed by investigating the correlation between the two behavior attributes. The results has shown that length and beam can be adopted as explanatory variable to classify ships to the corresponding behavior clusters. The results provide a systematic understanding of unhindered ship behavior in a port area and can be used to predict the ship behavior pattern based on their intrinsic characteristics.

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3.1 Introduction

Waterborne transport has become an increasingly important means of international freight transport. Due to a large amount of cargo carried by individual ships and the high frequency of ships visiting the hub ports, the safety of ships and the capacity of ports have been global challenges with high priority for nautical traffic management and port authorities. Both efficient traffic management and predictive port design require a systematic and thorough understanding of ship behavior in port and inland waterways. For individual ships, the behavior is always different due to the officers on board and the different sailing situations. However, it is assumed to exist some behavior patterns for the total ship traffic in an area. The ship behavior patterns in an area are revealed by clusters of similar ship behavior, while the clusters are distinctive with each other over the area. For the macroscopic ship traffic flow, the behavior patterns show the characteristics of the ship behavior in the area. For the individual ships, the behavior patterns indicate the range that the ships will behave. accurate behavior pattern prediction will support the port operation and the maritime surveillance. As only static ships characteristics are known before the ships enter a port area, a relation between these ship characteristics and the behavior patterns needs to be found. Therefore, ships are classified according to such patterns based on the ship characteristics.

Currently, in the field of ship behavior analysis, Automatic Identification System (AIS) data has proven to be a valuable source of big data. Many researchers have used AIS data for general behavior pattern recognition and anomaly detection, without a clear classification of the involved ships (Gunnar Aarsæther and Moan, 2009; Pallotta et al., 2013; Ristic et al., 2008). In these studies, the behavior differences of individual ships are ignored. However, such individual differences have been revealed in other studies, in which a ship classification is pre-defined before analyzing the ship behavior using AIS data. Silveira et al. (2013), Goerlandt and Kujala (2011), and Mascaro et al. (2010) classify ships based on their type, while not considering the size of ships. For the purpose of ship behavior investigation, this classification method lacks a detailed description of the behavior differences within the same ship type. De Boer (2010) proves behavior differences of container ships with different deadweight tonnages (DWT). However, the classification thresholds are determined such that approximately the same amount of available trajectories is included in every data set. This classification method only explains the behavior differences when comparing groups of ships, without a clear recognition of the actual behavior patterns in the area. The results of behavior comparison depend on the choice of classification criterion. The same drawback holds for the studies of Shu et al. (2013) and Xiao et al. (2015), which classify ships according to gross tonnage (GT). Moreover, the GT is a measure of ship's overall internal volume without information on ship's size which seems to be relevant to the behavior. Both classifications are based on the presence frequencies of ships with different GT in the data set. In the study for ship behavior during collision avoidance based on AIS data by Mou et al. (2010), the overall length is selected as the criterion to distinguish ship size and investigate the correlation between ship length and the closest point of approach (CPA). However, the reason for choosing such a criterion is not explicitly explained. Thus, in the studies of predefined classification for ship behavior, the choice of the classification criterion would result in a subjective explanation of the ship behavior patterns. It would be better to recognize the patterns of ship behavior directly from the behavior clusters, which then form the basis of ship classification.

To the best of the authors' knowledge, there is no dedicated research on the methodology of ship classification based on their behavior in a port or waterway. In our preliminary research on ship classification methodology (Zhou et al., 2015), ships are classified based on the relation between ship characteristics and behavior when passing a specific cross-section. However, the proposed method cannot be applied in a waterway or port area since it cannot handle the behavior in time series. The behavior patterns are not recognized, either. In a recent study, ship trajectories in a coastal area have been classified to predict ship type (Sheng et al., 2018). However, the classification only considers two types of ships (cargo ships and fishing ships) without other ship characteristics, and the method cannot be applied in a port area since detailed paths and speeds are not analyzed. In real-life port operations or maritime traffic management, the general ship classification in a port, a water area, or a country is subjectively determined by the local port authority or other equivalent parties for the purpose of port dues calculation or ship registration. Ship classifications based on guidelines or rules will not support the accurate prediction of port operations with respect to maritime traffic.

The objective of this chapter is to develop a ship classification method based on ship behaviors revealed by AIS data, using static ship characteristics as explanatory variables. The first contribution is to develop a methodology to cluster ship behavior using AIS data. The resulting ship behavior patterns form the classification basis. The second contribution is the development of a ship classifier able to predict the ship behavior based on the static ship characteristics. To apply clustering and classification techniques in the domain of maritime traffic, existent methods in data mining will be modified and improved according to the characteristics of the data. The research result will support the behavior pattern recognition from AIS data and simulate the behavior in a systematic way considering the differences of ship characteristics. From the practical application perspective, the port authority would be able to predict the behavior pattern based on the available ship characteristics from AIS data or Vessel Traffic Services (VTS) report when a ship is about to approach. In case of special circumstances, the prediction can provide theoretical references for traffic control measures regarding ship behavior suggestions (e.g., position control or speed limit). In this chapter, the data sets are introduced in section 3.2 to give an overview of the characteristics of maritime traffic in ports. Section 3.3 explains the proposed methodology for behavior clustering and ship classification. The clustering results and the classifier performance are presented and discussed in section 3.4. Finally, section 3.5 concludes the chapter with recommendations for further research.

3.2 Data description

The study area is a nearly straight waterway, Nieuwe Waterweg, located at the entrance of the port of Rotterdam, the Netherlands, as shown in Figure 3.1. The reason for choosing a straight waterway for behavior clustering is to eliminate the impact of a specific waterway layout on ship behavior. Thus, the proposed methodology is expected to be generically applicable in other (straight) waterways. This study focuses on ship behavior in unhindered situations, as it is assumed that ships with the same behavior pattern in an unhindered situation would behave similarly when under the impacts of external factors, such as encounters, wind, and current. Based on such behavior clustering and ship classification, the behavior in other waterway layout or hindered situation can be systematically analyzed. The length of the study area is 2300 m, and its width is about 650 m. For the inbound traffic (sailing from the sea towards the port of Rotterdam), the Maasgeul channel (see Figure 3.1) splits into Nieuwe Waterweg and Calandkanaal, which are physically separated by a slightly bent mole, named the Splitsingsdam.

The X-Y coordinate system in Figure 3.1 corresponds to the Dutch geographical coordinate system, the Rijksdriehoeksmeting (RD system), with the origin located in the southwest of the study area. In order to facilitate the analysis of ship behavior, the coordinate system is transposed to a local reference system. The transposed origin lies at the bottom left corner of the study area, which corresponds to the west end of the Splitsingsdam.

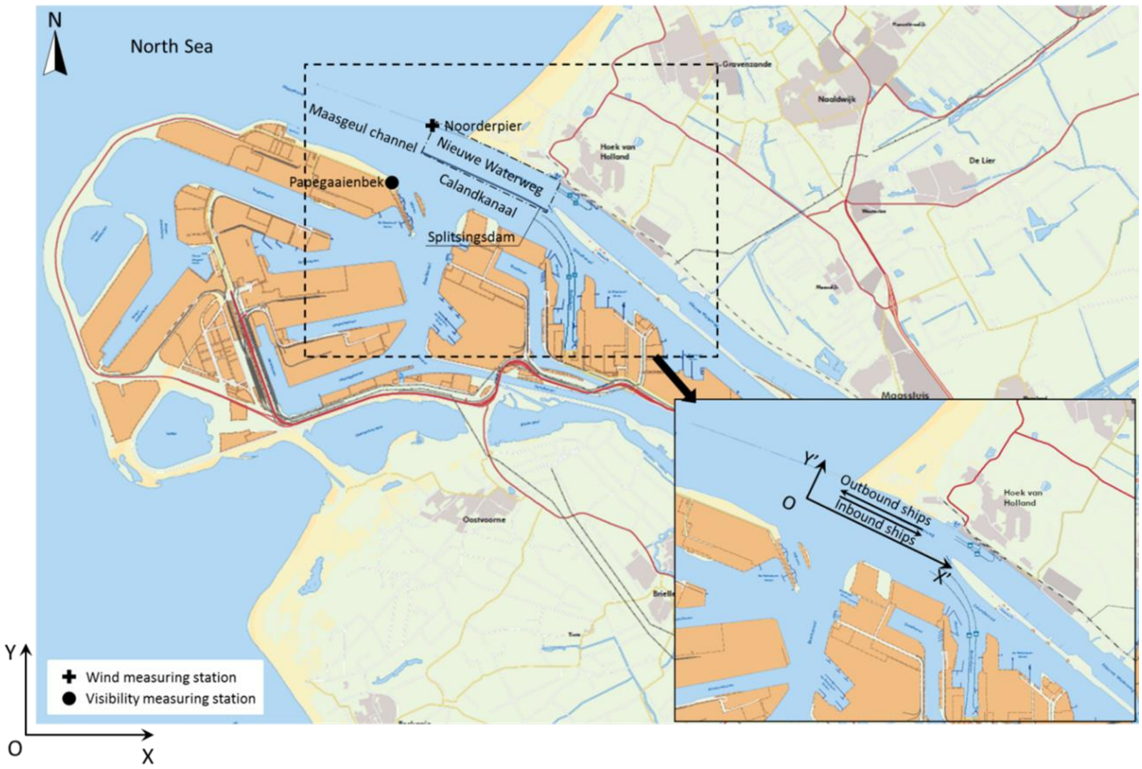

Figure 3.1. Location of the study area and the wind and visibility measuring stations in the port of Rotterdam. The X-Y coordinate system is RD system. In the cutout area, the transposed system is indicated, so the inbound ships sail in the X'-direction, while the lateral deviations from the straight path are visible in Y'-direction.

The data for the whole year of 2014 have been collected from the port authority of Rotterdam, including the ship behavior records and the data of external environmental factors. The raw AIS data reveal the ship behavior in the study area, while the meteorological and hydrological data present the external conditions, including visibility, wind, and current. In this section, the collected data are introduced.

3.2.1 AIS data

The AIS system is an automated tracking system onboard ships, which is designed to automatically provide information about the ship to other ships and to coastal authorities. In 2000, International Maritime Organization (IMO) issued an amendment adopting a new requirement regarding the introduction of AIS system in the International Convention for the Safety of Life at Sea (SOLAS) (IMO, 1974). The AIS system is mandatory by the end of 2004 for all ships of 300 Gross Tonnage (GT) and more engaged on international voyages, cargo ships of 500 GT and more not engaged in international voyages and all passenger ships irrespective of size. In the study area, every seagoing ship, even below the GT limit of IMO regulation, has installed AIS equipment and used it in all voyages. For the inland ships, both commercial and recreational ships, and sailing vessels longer than 20 meters are mandatory to use AIS since December 1st 2014 according to the resolution of the Central Commission for the Navigation of the Rhine. The regulation applies to most of the inland vessels in the Netherlands. Since the year of 2014 is still a transition period, the majority of the collected AIS data of 2014 are seagoing ships.

According to the guidelines by IMO (2003), the AIS data contain three types of information: (1) static information (Maritime Mobile Service Identity (MMSI) number, IMO vessel number, ship name, radio call sign, ship type, overall length, beam, etc.); (2) dynamic information (UTC time, ship position, speed over ground (SOG), course over ground (COG), heading, navigational status, etc.); (3) voyage-related information (draught, destination, etc.). The static information is entered into the AIS system by the equipment provider when the equipment is initially installed or after a major change of the ship structure. The dynamic information is updated automatically based on the sensor data. The update time interval of dynamic information depends on the speed of the ship according to the regulation by the International Telecommunication Union (ITU, 2014). The time interval is short when the SOG is high, and vice versa. The voyage-related information should be manually updated to the real-time situation by the officers onboard. The actual draught may indicate the loading condition of the ship, which affects the ship's maneuverability. However, in the collected data set, errors are found in the voyage-related information. For most of the ships in the data set, the draught is not updated in each voyage. For some ships, the value of draught equals the molded draught in the registration. Other ships are recorded with a draught of 0 meter in the data set. This implies that the data of ship draught are not reliable, thus these are not analyzed.

Since the port authority of Rotterdam only stores the mandatory fields of static information in AIS data, the ships characterization is limited to type, length, and beam. In the collected

AIS data set (2,299,842 messages), numerous ship types occur, including cargo ships, tankers, passenger ships, pilot ships, tugs, and dredgers. For the specific purpose ships (pilot ships, tugs, and dredgers), their working status is not indicated in the AIS messages. However, their behaviors in working and non-working states are different, and as such, these ships are excluded from this research. Thus, only three main types of ships are analyzed in this research, being cargo ships (993,566 messages), tankers (522,614 messages) and passenger ships (77,724 messages). Since the cargo ships are not further categorized (e.g., into container, general cargo ship or bulker), the ship type is not included as a characteristic to classify the ships, even though it is assumed that the behavior of these types of cargo ships vary considerably. Therefore, the static ship characteristics to classify ships are length and beam in this research. The ratio between length and beam is also considered as a characteristic, as it is one of the ship dimension ratios indicating ship maneuverability. The ratio is calculated with an accuracy of 0.1 considering the rules of significant figures in division calculation (Harris and Stöcker, 1998), since the length and beam are registered with an accuracy of 0.1 meter in AIS data.

In the AIS data, the dynamic ship behavior is recorded through four behavior attributes (see Figure 3.2): position, heading, COG, and SOG. Since the study area is a straight waterway, the COGs of the ships mostly follow the direction of the waterway. The headings of the ships change seldom, either. Thus, in this research, the ship position and SOG are the main behavior attributes to be analyzed and clustered. Based on the transposed coordinate system (see Figure 3.1), the ship position is represented by the distance to the Y'-axis (the northwest boundary of the study area) and the lateral distance to the X'-axis (the southwest boundary). Since the Splitsingsdam is a slightly bent mole, the lateral distance to the X'-axis does not exactly correspond to the distance to the dam.

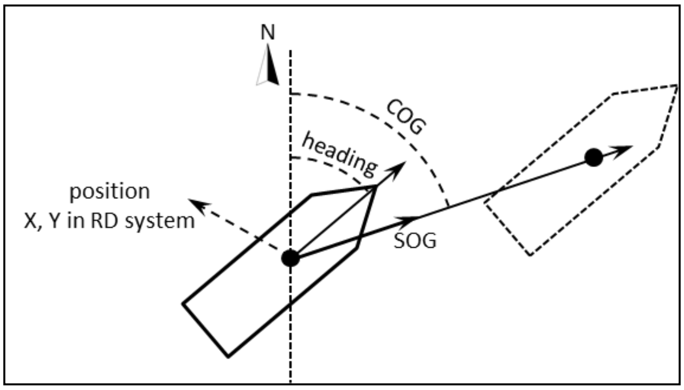

Figure 3.2. Illustration of behavior attributes in AIS data (RD system is the geographical coordinate system in the Netherlands).The ship with a solid outline is the current position, while the ship with a dotted outline is the position at next time step. The position of the ship is represented as the center in the figure, but the exact position for each ship depends on the location of transmitter installed on board.

3.2.2 Meteorological and hydrological data

Since the ship behavior is highly influenced by the external environmental conditions (Shu et al., 2017), meteorological and hydrological data are collected to describe the external conditions of ship behavior.

The meteorological condition refers to wind and visibility. Both are measured during the same period as for which the AIS data have been collected (2014). The location of the measuring stations are presented in Figure 3.1. The measured wind velocity data are stored at an interval of 5 minutes, while the visibility is presented every minute. In non-extreme weather conditions, there is no sudden change of wind within 5 minutes. Thus, the data are reliable and sufficiently accurate in presenting the external conditions. Since there are no obstructions in the study area, the wind and visibility are deemed to be the same for the whole area.

The hydrological condition refers to the current, in particular, the current velocity. Unlike wind and visibility, the measured current velocity at a specific measuring station is not representative for the whole area, due to the propagation of flow and the velocity variation over the water-depth. Thus, the data of current velocity are calculated by the port authority using the SIMONA model (Vollebregt et al., 2003) using the measured water level from eight stations around the port as input. The modeled velocity has been validated by comparing to the measured velocity at one station in the area. The collected data describe the current velocity in 41×7 orthogonal curvilinear grids with a resolution of about 85 meters. The current velocity in each grid cell is presented by 10 layers with the same depth averaged by the water depth of the grid at an interval of 15 minutes. For most of the ships, the length is larger than 85 meters, so the grid resolution is sufficiently accurate. The data represent the current situation along the voyage of ships.

3.3 Research methodology

The goal of this research consists of two parts, being distinguishing behavior clusters and classifying ships. Since the data mining in this research involves multi data sources, data preparation is necessary. The flow diagram in Figure 3.3 illustrates the three steps of the research methodology, which are further explained in this section.

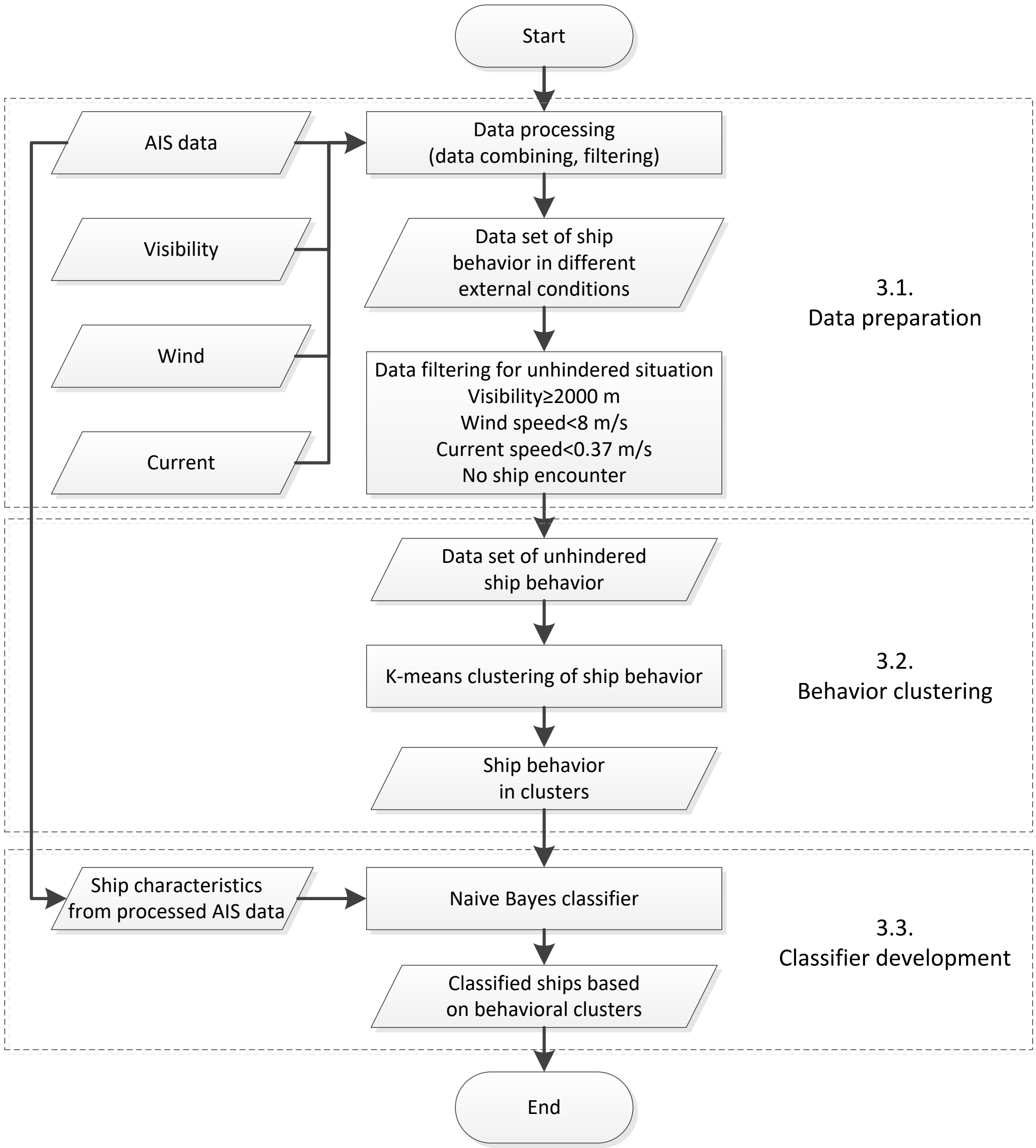

Figure 3.3. Flow diagram of the ship classification based on ship behavior clustering.

3.3.1 Data preparation

Since ship behavior is influenced by the external conditions (Shu et al., 2017), the clustering of ship behavior is assumed to be based on the unhindered situation. This way, the impacts of external factors are eliminated, which could reveal the behavior patterns mainly due to the ship characteristics. In the unhindered situation, the bridge team is assumed to behave with good seamanship, which is mostly based on the ship characteristics and maneuverability. The clustered ships are also expected to behave similarly when they are in some specific hindered situation. Therefore, multiple data sources are integrated.

In the data processing of this research, the raw AIS data are integrated with the data of visibility, wind, and current based on the time and ship position in each AIS message. To eliminate the impacts of environmental factors, thresholds are used to filter out the unhindered situation. The thresholds have been previously analyzed in the impact analysis of external factors using the same data set (Zhou et al., 2017). An unhindered situation is characterized by visibility ≥ 2000 m, wind speed < 8 m/s, and current speed < 0.37 m/s. Besides, in order to exclude the impact of ship encounters, the processed data set has filtered the trajectories of ships with any encounter with another ship in the study area. The three main types of ship encounter identified in the International Regulations for Preventing Collisions at Sea (COLREGs) are taken into account: head-on, overtaking, and crossing. The encounters of overtaking and crossing can be easily distinguished by the speed and position changes. The head-on situation at sea is defined when one ship is coming towards the other one roughly within 6 degrees on either side of the heading. For the bi-directional waterway in port area, any two ships sailing in opposite directions will be deemed as head-on situation, since the inland waterway is narrow. When the two ships sail close to each other, they may change their course to avoid collision risk. Even without the collision risk, both ships will sail as near to the outer limit of the waterway on her starboard side as is safe and practicable, according to the rule of narrow channels in COLREGs. Thus, when two ships pass by each other, such encounter will influence the behavior of both ships. The head-on situation is identified and filtered, when one ship encountering the other from the opposite direction in the study area. So far, the data set of ship behavior in the unhindered situation is generated.

The AIS messages are transmitted at different time intervals due to the different speeds of ships. In the collected AIS data, the duration of the time interval is between 6 seconds and 15 seconds. A set of cross-sections has been developed parallel to the Y'-axis in order to analyze the behavior pattern of all ships when passing the same cross-section. The distance between cross-sections is equal and is determined by calculating the proceeded distance of ships between two adjacent AIS messages. The distance should guarantee that there is at least one AIS message in between two adjacent cross-sections for most of the ships in order to reduce the inaccuracy introduced by interpolation. This results in a distance between cross-sections of 65 meters, with 35 cross-sections in total. The data of ship behavior attributes are linearly interpolated by the last message before and the first message after the cross-section. Considering the ships cannot make sudden changes in behavior in port areas due to the maneuverability and large inertia, linear interpolation of ship behavior within short distance will not decrease the data accuracy or influence the results.

3.3.2 Behavior clustering

The AIS data in unhindered situations are used to form classes for each behavior attribute using clustering techniques. Clustering analysis is an unsupervised technique in data mining. The data set without any pre-classification can be grouped into multiple clusters, so that the objects within a cluster have high similarity with each other, but are distinctive to the objects in other clusters (Han et al., 2011). Clustering methods can be divided into two groups: hierarchical and partitioning techniques (Saxena et al., 2017). In the hierarchical clustering methods, clusters are revealed by iteratively dividing the groups using a top-down method or forming the groups by a bottom-up approach. The result of such methods usually leads to a dendrogram among the data objects. As the behavior of individual ships is assumed to be independent, the hierarchical clustering method is not appropriate for this research. Therefore, the partitioning method is adopted, with the aim to assign the data objects into clusters without hierarchical structure by optimizing some criterion function. The criterion is usually expressed by the dissimilarity between each data object and the corresponding cluster center. In the clustering of ship behavior, the behavior attributes are all scalable and each ship can only be assigned to one cluster. Thus, the centroid-based portioning technique, *k*-means algorithm, satisfies the requirements in this research.

The general procedure of *k*-means clustering includes: step 1, choosing initial cluster centers for a given number of clusters; step 2, assigning each data object to the cluster with least dissimilarity to the cluster center; step 3, updating the cluster center after all objects being assigned and repeat step 2 until there is no change in cluster center. The limitations of this method can be found through its procedure (Saxena et al., 2017): (i) strong reliance on the user to define the number of clusters in advance; (ii) high sensitivity to the initialization phase; (iii) high sensitivity to the outliers in the assigning process; (iv) high sensitivity to the definition of stopping criterion. In this research, the disadvantages are improved or overcame in the ship behavior clustering algorithm.

(i) decision on the number of clusters

Given the general ship behavior data set, the number of behavior clusters is unknown beforehand. Too few clusters will lead to an obscure recognition of behavior patterns, as some behavior patterns might be combined. Meanwhile, choosing too many clusters will lead to a lack of general representativeness of behavior patterns, and the clustering patterns are possibly indicated by statistical artificial differences.

To deal with the influence of the number of clusters, the *k*-means clustering method is performed using different numbers of clusters as input, starting with 2 clusters, and increasing the number of clusters until the ship behavior data in each cluster are significantly different with the data objects in other clusters over the whole area, which can be compared at all cross-sections. The statistical t-test is performed to compare the ship behavior patterns with a significance level of 95% (corresponding to a p-value of 0.05). This condition guarantees that the clustering results represent the ship behavior patterns in the whole study area. When the data in two clusters are not significantly different at some cross-sections, these two clusters cannot be deemed to have a different behavior pattern in the whole area.

(ii) the defined initialization phase

The common *k*-means clustering starts with an arbitrary choice of the centers of initial clusters. However, the random initialization would lead to different clustering results in different runs, where each run starts with different centers of initial clusters. In order to get a unique clustering result representing behavior patterns, the centers of initial clusters are defined to be distinct. As the ship behavior is assumed to be smooth without sudden changes due to its maneuverability, the initial centers can be calculated from the data objects. For any ship trajectory *n*, a general indicator of behavior attribute B_n is defined as the mean value of this behavior attribute on all cross-sections. Two of the cluster centers are the minimum and maximum B_n, respectively. The other cluster centers are the trajectories with the corresponding percentile value of B_n. For instance, when the number of clusters is 4, the initial cluster centers are the minimum, 33rd percentile, 67th percentile and maximum of B_n. This way, the initial centers are unique and distinct to each other.

(iii) the measure of overall dissimilarity between clusters

In the *k*-means algorithm, every data object will be assigned to a cluster and influence the cluster center, which makes the algorithm sensitive to the outliers. Outliers in ship behavior in AIS data are mostly caused by the occasional measurement error during one message transmission. The clustering based on differences of behavior when passing a specific cross-section is sensitive to such data outliers. Besides, the cluster of ship behavior should represent the general behavior pattern over an area. Thus, to express such overall dissimilarity of behavior and overcome the sensitivity to the outliers at some point, the measure of distance between a data object to the cluster center is defined considering the ship behavior on all cross-sections. For any ship trajectory *n*, the distance to the center of cluster *i* $D_{(n,i)}$ is defined as

$$D_{(n,i)} = \sum_{j=1}^{m} \left(B_{n(j)} - B_{c(i,j)} \right)^2 \tag{5.1}$$

where $B_{n(j)}$ denotes the behavior attribute of trajectory *n* on cross-section *j*, $B_{c(i,j)}$ denotes the center of cluster *i* for this behavior attribute on cross-section *j*, and *m* is the total number of cross-sections.

The difference is squared for each cross-section to avoid difference compensation and to weigh the difference (larger differences have a larger effect). Based on the calculation of distance to all cluster centers, each ship trajectory will be assigned to the cluster with the minimum distance to the corresponding center.

(iv) the data-based stopping criterion

After each iteration of assigning ships to clusters, the centers are updated by calculating the mean value of the behavior attributes on each cross-section in each cluster. The clustering stops when the centers do not longer change. In the application to practical problems, a specific stopping criterion needs to be defined, which is usually indicated by the number of iteration steps. However, in the clustering of ship behavior to recognize the behavior pattern in an area, such stopping criterion (no change of cluster centers or a definite number of iterations) lead to heavy computation load or incomplete clustering results. In this research, the stopping criteria are decided based on the significant figures of behavior data. When the maximum change of cluster centers is less than a threshold value, further clustering is no longer significant in practice. Then, the clustering repetition stops. In this research behavior, the threshold of position is set as 0.1 meter, while it is set to 0.01 knot for SOG.

When the clustering results satisfy the aforementioned stopping criteria, the formed clusters represent the general ship behavior patterns in the area. The clustering result for each ship trajectory is input as label for its behavior pattern in the process of ship classification, see the next section.

3.3.3 Classifier development

The clustering result reveals the behavior patterns and identifies clusters for each type of ship behavior. In this section, the proposed classifier(s) is identified to predict to which behavior cluster a ship belongs to, based on the ship characteristics. To discover the most appropriate criteria to classify ships using available data, four combinations of ship characteristics are selected to develop classifiers, and their performances need to be tested and compared. These combinations are: (1) ship length; (2) ship beam; (3) ratio between ship length and ship beam; (4) ship length and ship beam.

The data classification is a two-step process, consisting of a learning step to develop a classifier or a classification model and a classification step where the classification model is used to predict class labels for given data objects (Han et al., 2011). In the second step, the performance of the developed classifier can be tested. In this research, the holdout method with random subsampling is used to compare the performances of different classifiers. Two-third of the ship trajectories are allocated to the training set, while the remaining one-third of the trajectories are used in the test set. To avoid the impact of seasonality of port operation on maritime traffic, random subsampling is performed to the data per month over the year. This way, both training and test sets cover the whole year of collected data.

Five main categories of classification algorithms are distinguished (Kotsiantis et al., 2007): logic-based algorithms, perceptron-based techniques, statistical learning algorithms, instance-based learning, and Support Vector Machines. In this research, instead of a direct causal relationship between ship characteristics and ship behavior, there is a possibility for any ship to belong to any behavior pattern. It means that the class of a data object is predicted by the highest possibility to belong to a single class among all classes. Besides, it is expected that more than two classes of ship behavior will be distinguished. Thus, in this research, the statistical learning algorithm underlying a probability model is adopted. Among the statistical learning algorithms, the naive Bayesian classifier has been found to be comparable in the performance with other neural network classifiers, and it has a high accuracy and short computational time when applied to large data sets (Han et al., 2011). As the effects of ship characteristics on the prediction of behavior class are assumed to be independent, it also follows the basic assumption in Naive Bayesian classification. Thus, the Naive Bayesian classifier is appropriate for this research. In the following, the two steps of classification using a Naive Bayesian classifier are further elaborated upon.

Step 1: learning step to develop classifier

Let any ship $S_n \in S$ be represented by its characteristics, $\mathbf{X} = \{x_1, x_2, ..., x_m\}$. Suppose that there are *k* behavior clusters (the results from ship behavior clustering), $C_1, C_2, ..., C_k$. The classifier will assign S_n to class *i* with the highest posterior probability, which is the maximum posteriori probability (MAP) presented as

$$C_{MAP} = \arg\max_{S_n \in S} P(C_i | \mathbf{X}) \tag{5.2}$$

The posterior probability is calculated according to Bayes' theorem:

$$P(C_i | \mathbf{X}) = \frac{P(\mathbf{X} | C_i) P(C_i)}{P(\mathbf{X})} \tag{5.3}$$

Since $P(\mathbf{X})$ is the same for all classes, only $P(\mathbf{X}|C_i)P(C_i)$ needs to be calculated and maximized. The prior probabilities of all behavior classes $P(C_i)$ are known based on the clustering results for each behavior attribute. Thus, only the prior probability of different characteristics should be estimated. For numerical characteristics, there are two alternatives to estimate the prior probability:

(i) For each ship characteristic, if a continuous distribution can be fitted based on the collected data, the prior probability can be computed using the distribution function.

(ii) If there is no fitted distribution for the ship characteristics, the data need to be discretized into bins to generate the prior probability from the training data set. The techniques of discretization can be categorized as supervised or unsupervised (Witten et al., 2016). Since neither method always yields better results than the other, both discretization methods have been tested in this research.

(a) unsupervised discretization

Among the unsupervised discretization methods, the equal-width binning and equal-frequency binning are the basic ones, while the discretization based on clustering is more sophisticated (Joiţa, 2010). Since the number of intervals for each ship characteristic is unknown, the discretization by clustering analysis, such as *k*-means discretization, cannot be applied. As the purpose of discretization in this chapter is to calculate the prior probability, the equal-frequency interval binning is not appropriate. Thus, the equal-width binning is chosen as unsupervised discretization method.

In the equal-width interval binning, the data range $(a_1, a_2, ..., a_n)$ is divided into *k* intervals of an equal width determined by $(a_{\max} - a_{\min}) / k$. This way, the interval is determined by the data objects and the desired number of intervals. However, as stated before, the number of intervals in this research is unknown. Thus, the interval width for each ship characteristic is given in the discretization instead of the number. Since an empty bin of ship characteristics in the training set means the prior probability equal to 0, the ships with such characteristics cannot be properly classified. To avoid empty bin and consider the values of different ship characteristics, the interval for length is determined as 10 meters, 2 meters for beam, and 0.5 for the ratio between length and beam.

(b) supervised discretization

Compared to the unsupervised discretization methods, the supervised methods make use of the class labels when partitioning the characteristics. Several discretization methods exist, and the supervised discretization methods in classification have been tested and compared (Lavangnananda and Chattanachot, 2017). They show that the Chi2 algorithm yielded the best performance in most datasets compared to other supervised methods. In the classifiers with Naive Bayes, Chi2 also yielded the best performance. Thus, in this research, Chi2 is adopted, which is a bottom-up discretization method using the χ^2 value to determine the merging point (Liu and Setiono, 1995).

The discretization process starts with sorting the values of a characteristic. Then, the following steps are performed: (1) each value forms one interval; (2) the χ^2 value for every pair of adjacent intervals are calculated according to equation 4; (3) the pair of adjacent intervals with the lowest χ^2 value are merged into one interval. Since the main behavior class in adjacent intervals of ship characteristics might be different, the merging only considering the χ^2 value may change the distribution of behavior classes within the interval. To avoid such unexpected variation, one more criterion for merging is required, being that the pair of adjacent intervals should be consistent in the main behavior class.

$$\chi^2 = \sum_{i=1}^{2}\sum_{j=1}^{k}\frac{\left(A_{ij} - E_{ij}\right)^2}{E_{ij}} \tag{5.4}$$

where:

k is the number of classes;

A_{ij} is the number of data objects in the i^{th} interval, j^{th} class;

E_{ij} is the expected frequency of A_{ij}, $E_{ij} = R_i * C_j / N$;

R_i is the number of data objects in the i^{th} interval, $R_i = \sum_{j=1}^{k} A_{ij}$;

C_j is the number of data objects in the j^{th} class, $C_j = \sum_{i=1}^{2} A_{ij}$;

N is the total number of data objects, $N = \sum_{i=1}^{2} R_i = \sum_{j=1}^{k} C_j$.

Instead of setting a threshold of χ^2, Chi2 introduces the inconsistency rate. For the data objects with the same value of a characteristic, the inconsistency count is the total number of objects minus the largest number of objects with the same class label. The inconsistency rate is the sum of the inconsistency count divided by the total number of the objects in the interval. For example, there are n data objects with the same value of a characteristic, c_1 objects belong to class 1, c_2 objects to class 2, and c_3 objects to class 3, where $c_1 + c_2 + c_3 = n$. If c_1 is the largest among the three classes, the inconsistency count is $n - c_1$. In the original Chi2 algorithm, the merging process stops when the inconsistency rate exceeds a certain value δ. However, an appropriate value of δ can only be given after some tests on the data set. The same value of δ for all intervals also ignores the different portion of inconsistent objects in different intervals. Thus, the value of δ is set as a dynamic criterion, which is the lowest initial inconsistency rate among the involved initial intervals. For instance, if the i^{th} interval is merged from the 4^{th}, 5^{th}, and 6^{th} initial intervals, the value of δ for the i^{th} interval is the minimum of the inconsistency rate among the three intervals at the initial step without any merging. This is still to avoid the change of the behavior class distribution after merging the intervals.

Since the supervised discretization considers the class labels, the discretization for the same ship characteristics for different ship behavior might be different. Thus, in the research, the discretization would perform 6 times, which are for 2 ship behavior attributes with 3 ship characteristics.

Step 2: classification step to measure performance

The performance of a classifier can be evaluated by comparing the predicted class labels by the classifier and the actual class labels by behavior clustering (Sokolova and Lapalme, 2009). The confusion matrix in this research is defined in a one-versus-others method based on the classical matrix for binary classification, as listed in Table 3.1.

Table 3.1. Confusion matrix for class *i* in ship classification.

Actual ship behavior class	Predicted as class *i*	Predicted as other classes
Class *i*	true positive (TP_i)	false negative (FN_i)
Other classes	false positive (FP_i)	true negative (TN_i)

Considering the characteristics of different performance measures for classification (Sokolova and Lapalme, 2009), three evaluation metrics are selected for different purposes: (1) Average Accuracy to represent the average per-class effectiveness of the classifier; (2) $\mathrm{F_1score}$, which is the harmonic mean of precision (a measure of exactness) and recall (a measure of completeness) with equal weights, to represent the effectiveness of the classifier to identify positive class; (3) Area Under the Curve (AUC), which is also referred as balanced accuracy, to represent the classifier's ability to avoid false classification. Usually, the AUC of a classifier should be in the interval [0.5,1]. When the AUC is equal to 0.5, it means random guessing in binary classification. When the AUC equals to 1, the prediction of the classifier perfectly matches the actual labels.

$$\text{Average Accuracy} = \left(\sum_{i=1}^{k} \frac{\text{TP}_i + \text{TN}_i}{\text{TP}_i + \text{TN}_i + \text{FP}_i + \text{FN}_i} \right) / k \tag{5.5}$$

$$\text{Average Precision} = \left(\sum_{i=1}^{k} \frac{\text{TP}_i}{\text{TP}_i + \text{FP}_i} \right) / k \tag{5.6}$$

$$\text{Average Recall} = \left(\sum_{i=1}^{k} \frac{\text{TP}_i}{\text{TP}_i + \text{FN}_i} \right) / k \tag{5.7}$$

$$\text{F}_1\text{score} = \frac{2 \cdot \text{Precision} \cdot \text{Recall}}{\text{Precision} + \text{Recall}} \tag{5.8}$$

$$\text{AUC} = \frac{1}{2} \left(\sum_{i=1}^{k} \frac{\text{TP}_i}{\text{TP}_i + \text{FN}_i} / k + \sum_{i=1}^{k} \frac{\text{TN}_i}{\text{TN}_i + \text{FP}_i} / k \right) \tag{5.9}$$

The performance test is to investigate the developed classifiers from two aspects: (1) to compare the classification based on two discretization methods; (2) to discover the most appropriate criterion(-a) to classify ships regarding the ship behavior.

In the next section, the methodology introduced in this chapter will be applied to the data set introduced in section 3.2.

3.4 Results and analyses

For the application of the proposed methodology, the behavior of both inbound and outbound ships in the study area have been analyzed. Since the sailing direction (approach to or departure from a port) might influence the ship behavior, the data of inbound and outbound ships are handled as two independent data sets in the research. In this section, the behavior clustering results are discussed (section 3.4.1) and the performances of classifiers based on different ship characteristics are compared (section 3.4.2).

3.4.1 Ship behavior clustering and statistical test results

The behavior clustering results of ship path and SOG are discussed in this section. The results of inbound ships are presented with detailed explanations, while the results of outbound ships are briefly provided, as they only deviate slightly from the results of the inbound ships.

According to the methodology proposed in section 3.3.2, the ship behavior attributes are clustered into 2 to 10 clusters. The statistical *t*-test is performed to the behavior data of all clusters on all cross-sections, as presented in Table 3.2.

Table 3.2. Number of cross-sections with significantly different behavior in all clusters of inbound ships.

No. of clusters	2	3	4	5	6	7	8	9	10
Path	35	35	35	35	35	33	32	29	28
SOG	35	35	35	35	34	33	32	30	29

* The total number of cross-sections is 35. The gray shading indicates the formed clusters are significantly different on some cross-sections, not over the whole area.

For the ship path, the clusters are significantly different from each other on all cross-sections, when the number of clusters is less than 7. With a further increase of the number of clusters, the clusters are not significantly different on all cross-sections anymore. Thus, the number of path clusters of inbound ships is determined as 6, for which the different behavior patterns (indicated as clusters) over the whole area can be recognized. The ship paths for each cluster are shown in Figure 3.4. Since the mole locating at the south of the study area is slightly bent with an irregular outline, the shape is extracted from the map and indicated as an irregular black bar at the bottom of each plot. The solid line shows the center value of each cluster, while the dashed line shows the 95% confidence interval of the ship path of each cluster on each cross-section. The lines do not refer to the behavior of a single ship, but the behaviors of all ships within that cluster. The vessel behavior of clusters varies within the range. Thus, an overlap of the range can be observed between clusters, which refers to the ships with the behaviors on the edges of the clusters. For the individual ships from two clusters may have similar behaviors. However, the defined function of distance to the cluster center (in section 3.3.2) can mathematically guarantee that every ship will be clustered to the group with least dissimilarity over the whole area. When comparing the cluster centers of all clusters, the ship paths are generally different over the whole area, with the ship path of cluster #1 closest to the starboard bank while the ship path of cluster #6 is farthest away from the starboard bank. The range and distribution of paths in clusters are also different, when looking at the ship path at 95% confidence interval. Along the sailing direction of inbound ships (from the left to the right of the figure), the ship paths in all clusters move farther away from the X'-axis. The reason is that the waterway becomes narrower outside the right boundary of the study area as shown in Figure 3.1. Thus, the ships sail farther away from the starboard bank to enter the neighboring waterway smoothly. Similarly, the clustering results for outbound ships consist of 4 clusters of path.

The comparisons of ship path centers between clusters of inbound and outbound ships are presented in Figure 3.5. The ship path centers for outbound clusters (see Figure 3.5(b)) are obviously different with each other over the study area. However, for the inbound ships, the path centers of cluster #3 and cluster #4 cross in the middle area. The ships in cluster #3 sail closer to the starboard bank when entering the study area from the sea compared to the ships in cluster #4, while farther away from the bank when leaving the study area. When investigating the composition of ships in these two clusters, approximately half of ships in both clusters have medium length (100-170 meters) and medium beam (16-26 meters). Of the remaining ships in cluster #3, more ships have small lengths and beams than large ones. The percentage of ships with small and large length and beam in cluster #4 are around the same. As the majority of ships in these two clusters are similar in ship characteristics and the sailing situation is unhindered, the behavior difference in path is possibly due to the maneuvering preferences of officers onboard when sailing in a narrowing waterway. Especially for the ships with medium size, the space for sailing in the waterway is more flexible than smaller ships (which need to sail closer to the starboard bank due to the navigation rules in narrow channels) or larger ships (which need to sail farther to the starboard bank due to the bigger draught). Some officers prefer to change their position more to the center in advance in case of unexpected situation in the neighboring narrower waterway, which is presented as cluster #3. The other officers prefer to keep themselves as close to the starboard bank as possible according to the advice of navigation rules, shown as cluster #4. Thus, not only the different behavior patterns over the whole area can be recognized by the proposed clustering method, the behavior change patterns are also identified in different clusters.

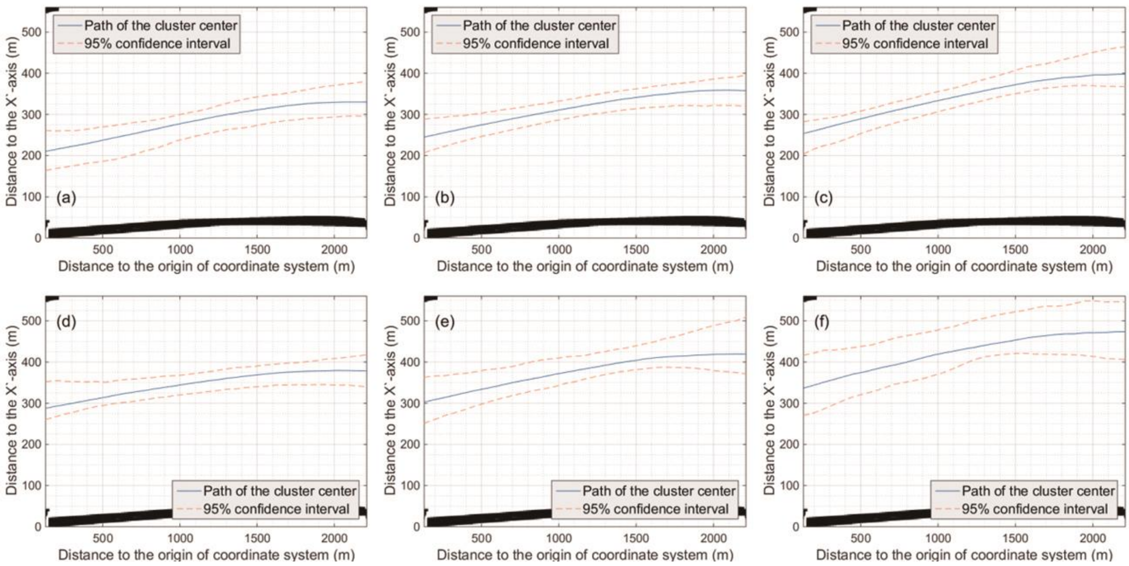

Figure 3.4. Clustered inbound ship paths: (a) cluster #1; (b) cluster #2; (c) cluster #3; (d) cluster #4; (e) cluster #5; (f) cluster #6 (The distance to the X'-axis as a function of the distance to the origin of the coordinate system with the sailing direction from the left to the right of the figure). The black bar at the bottom of each plot indicates the mole, Splitsingsdam, as shown in Figure 3.1.

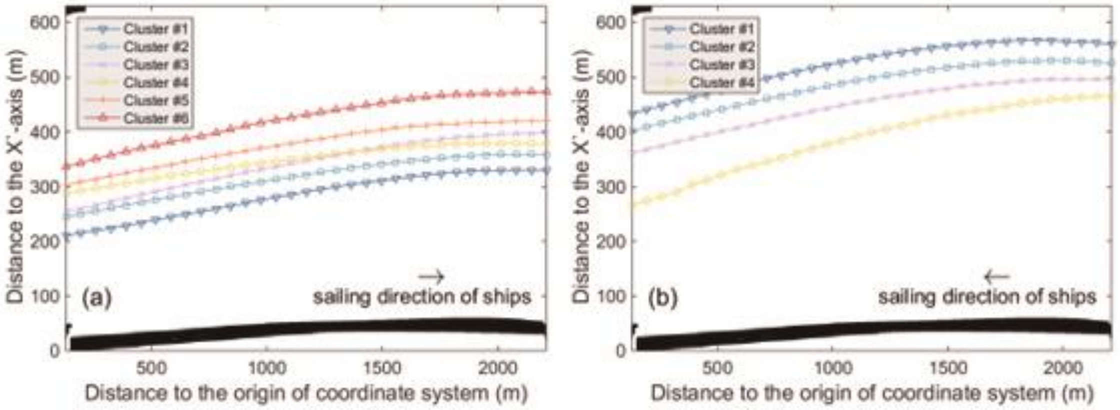

Figure 3.5. Comparison of ship path in clusters: (a) inbound ships; (b) outbound ships. The black bar at the bottom of each plot indicates the mole, Splitsingsdam, as shown in Figure 3.1.

The method to decide the number of clusters for SOG is the same as the method used for ship path, see Table 3.2. The five clusters of SOG for inbound ships are presented in Figure 3.6. The ships in SOG cluster #1 sail with the lowest speed, while the SOG for cluster #5 is highest. For the ships in cluster #3, #4, and #5, the range of the 95% confidence interval is larger at the boundaries than in the middle of the area. The ships with high speed tend to have more variation of speed when entering a waterway, while behaving similarly when there is no change in the sailing environment. The behavior patterns of SOG are significantly different in all clusters over the whole study area for both inbound and outbound ships, as shown in Figure 3.7. Most of the ships keep a stable speed during the whole voyage in the area (cluster #1, #2, #3 for inbound ships, cluster #1, #2, #3, #4 for outbound ships). However, for the ships with high speed, the closer to the neighboring narrow waterway (the right of the figure), the lower speed they sail (cluster #4, #5 for inbound ships, cluster #5, #6 for outbound ships). A lower speed in the narrow waterway reduces the impact of ship wave on other ships and guarantees sufficient time for maneuvering in case of unexpected situations.

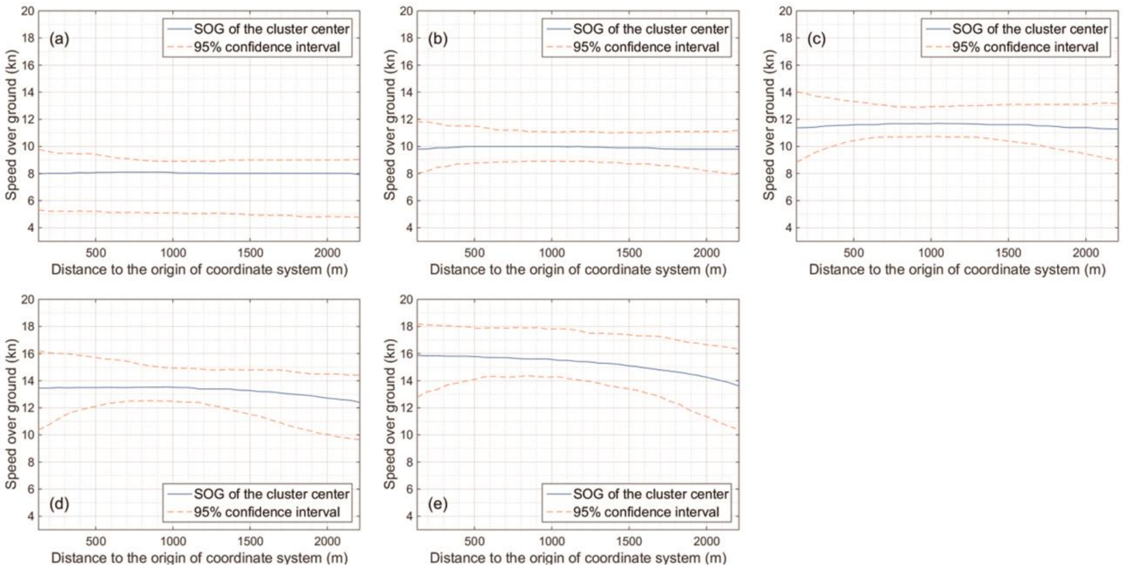

Figure 3.6. Clustered inbound ship SOG: (a) cluster #1; (b) cluster #2; (c) cluster #3; (d) cluster #4; (e) cluster #5 (The ship SOG as a function of the distance to the origin of the coordinate system with the sailing direction from the left to the right of the figure)

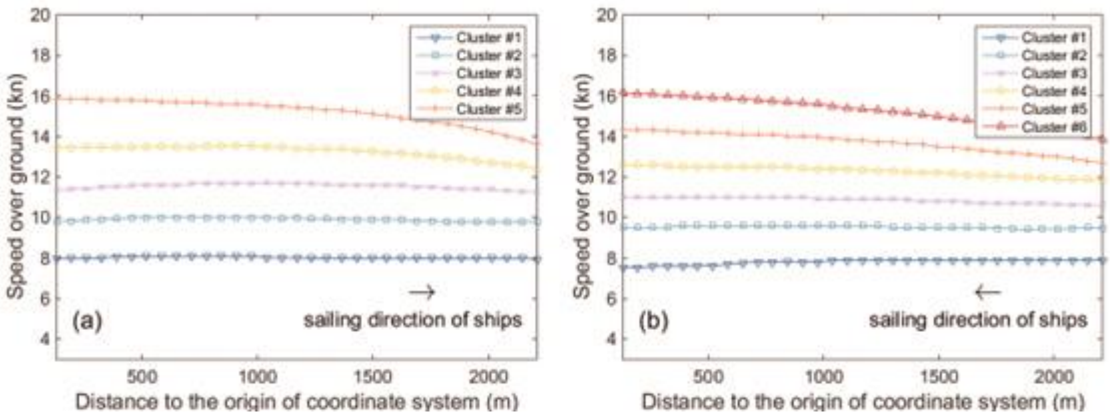

Figure 3.7. Comparison of ship SOG in clusters: (a) inbound ships; (b) outbound ships.

To further interpret the clustering results with respect to the correlation between ship path and SOG (the integral ship behavior), the number of ships in each path and SOG cluster for both inbound and outbound directions are shown in Figure 3.8. Based on the number of ships in clusters for path and SOG, some patterns of the integral behavior can also be revealed for both inbound and outbound ships. Generally, ships sailing with low speed (SOG #1) mostly sail close to the starboard bank (Path #1). With an increase of speed, ships sail farther from the starboard bank. However, the ships with the highest SOG (cluster #5 of inbound ships and cluster #6 of outbound ship) keep a proper distance to both sides of the bank, instead of sailing farthest to the starboard bank. It is possibly in consideration for sufficient maneuvering space for ship encounter or other special circumstances.

When comparing the behavior pattern for inbound and outbound ships, the speed range for both are similar, but the distribution of speed for the ships sailing farthest away from the starboard bank is different. For the inbound ships (path cluster #6), most of them sail with a high speed as in SOG cluster #4 and #5. Meanwhile, the speed for outbound ships in path cluster #4 is evenly distributed. When investigating for both directions the composition of ships sailing farthest to starboard bank, most of them are large-size ships. In narrow waterway, large ships need a relatively high speed to maintain the rudder effectiveness, even it may consume more fuel. For inbound ships, they need to keep a relatively high speed (SOG cluster #4 and #5) for maneuvering in the neighboring narrow waterway. However, for outbound ships, they can sail at their desired speed maintaining the basic maneuverability without consuming much fuel.

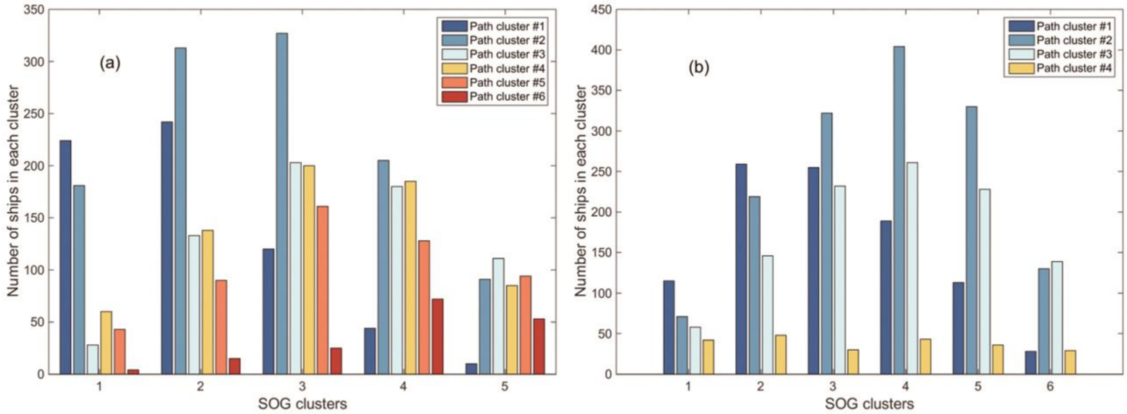

Figure 3.8. The number of ships in different path and SOG clusters: (a) inbound ships; (b) outbound ships.

3.4.2 Ship classification and performance measures results

As stated in the methodology of ship classification (section 3.3.3), the first step is to estimate the prior probability of different ship characteristics. Since the characteristics of length, beam and the ratio between length and beam are all ratio variables, the ship data are analyzed using Arena Input Analyzer to fit common statistical distributions, including normal, lognormal, gamma, Erlang, beta, Weibull, uniform and exponential distributions (Takus and Profozich, 1997). The results show that the lognormal distribution is the most likely distribution for the beam and the ratio between length and beam of inbound ships and all three characteristics for outbound ships, while the gamma distribution best describes the length of inbound ships. Based on the fitting results, the Kolmogorov-Smirnov test (K-S test) is performed to the data and the most likely distribution. The null hypothesis is that the data are drawn from the corresponding distribution. However, the null hypotheses are rejected for all characteristics of inbound and outbound ships with the p-value of 0.05. Thus, the most likely distribution cannot represent the real situation. Therefore, the second solution to estimate the prior probabilities for each characteristic is adopted consisting of computing the observations in the data set using supervised and unsupervised discretization methods, respectively. The number of intervals for different ship characteristics resulting from these two discretization methods is shown in Table 3.3. The supervised discretization method Chi2 results in different intervals of ship characteristics when considering the classes of behavior attributes.

Table 3.3. Number of intervals for different ship characteristics by two discretization methods.

Ship characteristics	Unsupervised discretization (EWB)	Supervised discretization (Chi2)			
		Inbound ships		Outbound ships	
		Path	SOG	Path	SOG
Length	18	23	6	21	26
Beam	14	3	6	4	4
Length/Beam	12	6	8	17	9

To test the classifiers, 50 runs of classification are performed with the holdout method using the collected data. The values of three evaluation metrics in 50 classification runs for each classifier follow a normal distribution, which has been statistically tested. The mean value of evaluation metrics of the classifiers for inbound and outbound ships are shown in Table 3.4.

Table 3.4. Mean value of evaluation metrics for the ship classification in 50 runs.

Data set of ships	Behavior attributes	Ship characteristics	Classification based on unsupervised discretization (EWB)			Classification based on supervised discretization (Chi2)		
			Average Accuracy	F_1 *score*	AUC	Average Accuracy	F_1 *score*	AUC
Inbound ships	Path	Length	0.7830	0.6233	0.7077	0.7943*	0.6781*	0.7435
		Beam	0.7838*	0.6256*	0.7198	0.7805	0.6567	0.7354
		Length/Beam	0.7734	0.6188	0.6899	0.7741	0.6602	0.7069
		Length & Beam	0.7837	0.6256*	0.7265*	0.7901	0.6687	0.7487*
	SOG	Length	0.7411	0.5881	0.6829	0.7391	0.6244	0.7025
		Beam	0.7465*	0.5898	0.6941	0.7462*	0.6296*	0.7031
		Length/Beam	0.7304	0.5791	0.6658	0.7286	0.6126	0.6808
		Length & Beam	0.7450	0.5900*	0.7013*	0.7412	0.6140	0.7182*
Outbound ships	Path	Length	0.7266	0.6443	0.6801	0.7333	0.6771	0.7028
		Beam	0.7344*	0.6506*	0.6927*	0.7328	0.6774	0.7019
		Length/Beam	0.7036	0.5886	0.6373	0.7087	0.6358	0.6589
		Length & Beam	0.7295	0.6486	0.6916	0.7346*	0.6802*	0.7065*
	SOG	Length	0.7756	0.6149	0.7159	0.8001*	0.6868*	0.7602
		Beam	0.7820	0.6209	0.7230	0.7788	0.6545	0.7311
		Length/Beam	0.7635	0.5984	0.6988	0.7686	0.6418	0.7200
		Length & Beam	0.7865*	0.6277*	0.7318*	0.7988	0.6797	0.7621*

* In the classification for each behavior attribute in each data set of ships (e.g., for the path of inbound ships), the highest values of each evaluation metrics in the developed classifiers are marked with a star(*), respectively. The gray shading indicates the classifiers outperforming others in all three evaluation metrics.

For all of the developed classifiers, the AUC values are larger than 0.5, which suggests the classifiers perform better than a random class assignment. The classifiers with gray shading in Table 3.4 are the ones with an overall good performance in classifying ships to the corresponding behavior classes. For the classifiers marked with two stars, the differences of the remaining evaluation metrics to the highest value are all less than 0.01. The performance of such classifier is also deemed as comparable and adoptable in practice.

To compare the classification based on two discretization methods, the classifiers based on Chi2 outperform the ones with EWB. The reason is that the behavior classes of ships have been considered during the Chi2 discretization. Thus, the estimate of prior probabilities based on such discretized intervals will lead to a better performance in classification. Especially when looking at F_1score and AUC which indicate the ability to identify the correct classes, the classifiers based on Chi2 discretization are better than the other algorithm in all cases. Thus, the Chi2 algorithm is recommended to perform discretization of ship characteristics, though the complexity of such classification increases than the one with EWB.

To discover the most appropriate criterion(-a) of ships characteristics, the performances of classifiers based on different characteristics in both discretization methods are analyzed. When investigating the classification based on a single criterion, the classifiers based on beam outperform the others, considering the evaluation metrics and the number of intervals in Chi2 discretization. In the classification based on EWB discretization, the classifier based on beam also outperforms the other classifiers with a single criterion. Comparing the performances of all classifiers, the ones based on length & beam perform well with two or three stars in three cases (path in inbound ships, SOG in inbound ships, SOG in outbound ships) in the classification with EWB discretization. In the classification with Chi2 discretization, the classifiers based on length & beam are marked with the highest AUC value in all cases. The AUC value represents the classifier’s ability to avoid false classification. Considering the other two evaluation metrics, the performances of classifier based on length & beam are also comparable to the ones with highest value. It could also be expected that with more ship characteristics for classification, the performance is better, since the ship can be characterized from different aspects.

The classification for inbound and outbound ships are developed and tested independently. If to choose a classifier for both inbound and outbound ships in practice for the study area, the one with Chi2 discretization based on length & beam is recommended.

3.5 Conclusions

This chapter presents a methodology for clustering ship behavior in an area and classifying ships into these clusters based on the static ship characteristics. The ship behavior clustering methodology is based on the *k*-means theory and modified to overcome its drawbacks in subjective decision on number of clusters and sensitivity to initialization and stopping criteria. The proposed algorithm is stable in clustering results without subjective decisions in the initialization phase. The ship classifier is developed according to the principle of Naive Bayesian classification. Instead of assuming a distribution to estimate the prior probability, two discretization methods (unsupervised Equal Width Binning and supervised Chi2) are tested to calculate the probability. The most appropriate classifier can be indicated by the evaluation metrics.

The methodology has been independently applied to two subsets: inbound ships and outbound ships in the study area in the port of Rotterdam. The clustering result can recognize both the fully different behavior patterns over the whole research area and the different behavior change patterns for some clusters of ships. The integral ship behavior pattern can also be revealed. With the holdout method, the developed classifier (based on training data set) has been used to classify ships (in testing data set) to the corresponding behavior cluster. The evaluation results of classification show that the Chi2 algorithm tends to perform better than EWB. The classifications based on length & beam outperform the ones based on a single criterion. The results reveal the underlying relation between ship characteristics and behavior patterns.

Both the port authority and the researchers could benefit from the proposed methodology and the identified clusters. For the port authority, the ship behavior clustering results reveal the ship behavior patterns and the ship behavior change patterns in a specific area, which helps the port operation and traffic management. The developed classifiers can be used to predict the behavior patterns of ships. For nautical researchers, this chapter provides an integrated method of behavior pattern recognition based on AIS data and the corresponding ship classification. The results could also help to simulate the behavior of different ships in a systematic way. For data mining researchers, the method of deciding the number of clusters in *k*-means clustering can be applied to other problems. The results of classification based on two discretization methods indicate the applicability and effectiveness in the domain of maritime traffic.

Future research can be to include more ship characteristics in the classification. With a more comprehensive data set of ship particulars (e.g., GT, DWT, actual draught), the classifier performances can be compared to choose the criterion best indicating ship behavior patterns. In a later stage, the results will be applied in traffic model development to simulate such ship behavior. Given the detailed recognition of ship behavior patterns, the simulation results will be closer to the reality.

4. Impact of Navigational Infrastructures on Ship Speed

Due to the limited course alteration space in most waterways, ships have to carefully control their speed considering their inertia and maneuverability in case of an encounter with another ship or other unexpected circumstances. Especially when the waterway layout becomes more complex with more navigational infrastructures and changing currents and winds, the underlying external impacts on ship speed are still unknown. This chapter studies the external impacts of varying current conditions and navigational infrastructure on ship speed by an empirical analysis in a complex waterway with width change and an interconnecting area of two waterways.

By looking into the tidal pattern and flow field in the research area, the varying current conditions have been found to not impose additional impacts on ship speed compared to straight waterways. Applying the developed classifier in chapter 3, the corresponding speed patterns of the clusters can be obtained. Low-speed and high-speed clusters of ships present different speed change patterns. Considering the distribution of the navigational infrastructures in the waterway, four phases can be identified with generic characteristics. The speed pattern phases can be marked by local Aids to Navigation as landmark references into four segments. By waterway segmentation according to the observed ship speed phases, the impact of navigational infrastructures on ship speed is generalized.

This chapter is currently under review for journal publication:
Zhou, Y., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. Empirical analysis on impact of navigational infrastructure on ship speed in a complex waterway layout. *Physica A: Statistical Mechanics and its Applications*.

4.1 Introduction

As one of the most important freight transportation modes, waterborne transport has been the backstone of international trade and global economy. Even under the impacts of the COVID-19 pandemic, over 80 percent of the volume of international trade in goods is carried by sea in 2021, with an increase of 4.3 percent to the shock in the year 2020 (United Nations Conference on Trade and Development, 2021). The increase of both number of ships and ship size in hub ports has drawn a lot of concern for the navigation safety in ports and waterways. The impacts of external navigational factors probably lead to more serious consequences than in open waters, which may result in substantial loss or damage of life and property. To guarantee the ship safety and improve the port capacity, effective ship traffic management in port is always needed. Unlike sufficient maneuvering space in open waters, the ship maneuverability is restricted in port areas. Due to the limited width in most waterways and the large ship inertia, ships have to carefully control their speed on the basis of their harbor speed. In case of encounter with another ship or other unexpected circumstances, a too low speed may limit the maneuverability, while a too high speed requires a longer reaction distance. Therefore, a full understanding of any underlying external navigational impact on ship behavior, especially ship speed, in real-life situations will benefit the effective ship traffic management in the seaports and inland waterways.

The impacts on ship speed in confined waterways have been studied a lot. As generalized by the studies on the analysis or modeling of ship speed in inland waterways, the influencing factors include intrinsic ship factors, waterway parameters, meteorological and hydrological conditions, local speed control regulations, etc. (Bąk and Zalewski, 2021; Du et al., 2017; Fan et al., 2021; Kim et al., 2014; Zhou et al., 2019b) However, when the waterway layout becomes complex, besides the impacts of identified factors, the relationship between speed change and waterway layout is unknown. Unlike the full dependency on e-Navigation at open sea, the visual objects assist the officers onboard to sail in ports and inland waterways, such as banks and aids to navigation (AtoN). Obviously, such objects physically indicate the boundary of navigable water area. At the same time, the AtoN facilities also provide navigational reference landmarks for the officers onboard, e.g., to adjust sailing direction and longitudinal position. The local authorities normally use such marks to define the applicable segments of special navigation rules as well. In this chapter, the navigational infrastructure is defined as all components for a safe and efficient water transportation system, including but not limited to waterway, jetty, bridge, river training structure, lock-and-dam facility and the supporting aids to navigation set by the local authority.

The aim of this chapter is *to investigate the potential external impacts of navigational infrastructures on ship speed in a complex waterway layout by an empirical analysis*. The ship speed refers to the observed speed over ground from collected Automatic Identification System (AIS) data. Based on this aim, the following research questions are answered in this chapter:

- Research question 1: How do meteorological and hydrological factors influence the ship speed in more complex waterway layouts?
- Research question 2: What are the generic characteristics of ship speed change patterns among different ships in the situations without encounters with other ships?
- Research question 3: How do navigational infrastructures influence the ship speed in ports and narrow waterways?

In this chapter, section 4.2 reviews the literatures in the influencing factors of ship speed in confined waterways. Section 4.3 introduces the research area and the collected data, followed by the problem elaboration and the research approach in section 4.4. The analysis results are presented in section 4.5, where each section is dedicated to a specific research question. Section 4.6 concludes the chapter with discussion and recommendations for further research.

4.2 Literature review

The ship speed in confined waterways is analyzed from two viewpoints, namely the macroscopic traffic flow and the individual ship behavior. From the perspective of ship traffic flow, the ship speed in narrow waterway is investigated through statistical analysis to obtain the average speed or the speed distribution of different sizes or types of ships (Nowy et al., 2021; Qi et al., 2017b; Zhang et al., 2022). Besides the intrinsic ship differences, the impacts of meteorological and hydrological conditions are included as a random disturbance following a fitted function (Piccoli, 2014; Qi et al., 2017a). The local traffic rules regarding speed are represented by speed limit for a specific waterway segment or specific ships (Aarsæther, 2011; Piccoli, 2014; Rayo, 2013; Xu et al., 2015). Since these studies focus on the characteristics of the traffic flow, the influencing factors of individual ship speed are not investigated in detail.

The studies from the viewpoint of individual ship behavior, especially the research into ship maneuverability, provide a broad scope of the factors influencing the ship speed in confined waterways. Firstly, the ship's own factors, e.g., type, length, beam, or tonnage, intrinsically distinguish the ship speed. The behavior patterns differ among cargo ship, tanker, passenger ship, fishing ship and others (Kraus et al., 2018; Zhang et al., 2019). Mostly, compared to smaller ships, large ships tend to sail at a relatively slow speed in ports and waterways (Shu et al., 2013; Xiao et al., 2015; Zhou et al., 2019a). Regarding the external factors, the impacts of waterway dimensions on ship speed are analyzed due to the individual ship maneuvering differences given the widths of waterways (Bąk and Zalewski, 2021; Du et al., 2020, 2017). Mostly, these studies require the essential particulars of individual ship maneuverability. With such information, the impacts of meteorological and hydrological factors are also analyzed considering the hydrodynamic processes (Beschnidt and Gilles, 2005; Du et al., 2017; Kim et al., 2014; Leguit, 1999; Saha et al., 2017; Sariöz and Narli, 2003). When the detailed maneuvering characteristics of individual ships are not available in most ports and waterways, the generic meteorological and hydrological impacts have also been qualitatively and quantitatively investigated (Nieh et al., 2019; Shu et al., 2017; Zhou et al., 2020). In respect of the local speed control regulations, the permitted speed in specific waterway is considered as constraints, which is similar as the studies of ship traffic flow (Fan et al., 2021; Wang et al., 2020).

From the literature review, in a given waterway of certain width, the external impacts on ship speed have been deeply investigated. However, when the waterway layout becomes more complex with more navigational infrastructures, e.g., waterways with changing width or the AtoN facilities, the underlying external impacts on ship speed are still unknown. Considering the visual navigation by the officers onboard in ports and inland waterways, the impacts of such navigational infrastructures need to be investigated from the navigational practice perspective. Therefore, this chapter analyzes the potential impacts on ship speed in a complex waterway layout through an empirical analysis, in which the sailing behavior of officers onboard is also implicitly included.

4.3 Research area and data description

In this section, the research area is introduced in detail in section 4.3.1. The data for empirical analysis (AIS data) are described in section 4.3.2 and meteorological and hydrological data in section 4.3.3. The data are collected from the port authority of Rotterdam, covering the year 2014.

4.3.1 Research area

The research area is located at the entrance of the port of Rotterdam, the Netherlands, as shown in Figure 4.1. The data are collected of all ships quipped with AIS sailing in the dashed rectangle. Previous studies on the unhindered ship behavior and the wind and current impacts are conducted in the straight stretch, the Nieuwe Waterweg (Zhou et al., 2020, 2019a), which is slightly bent with physical banks on both sides. However, to analyze the ship behavior in a more complex waterway, a longer stretch with richer navigational infrastructures is required. Thus, the trajectories of ships sailing from the North Sea (northwest corner of the research area) to the Nieuwe Waterweg (the north waterway on the east boundary of the research area) are selected, and the trajectories of ships sailing in the opposite sailing direction as well. The selected waterway stretch is curved with a total direction change of about 20 degrees, and its total length is about 10.2 km. In this stretch, the waterway width varies, which is used to reveal the impact of waterway width change on ship speed. The traffic in the Maasgeul channel (see top left of dashed rectangle in Figure 4.1) splits into the Nieuwe Waterweg and the Calandkanaal, which are physically separated by a slightly bent mole, named the Splitsingsdam. For the convenience of ferries and small cargo ships sailing between the Nieuwe Waterweg to the Maasvlakte and the Europoort, there is an interconnecting area in the middle of the Nieuwe Waterweg for shortcut turning. Due to the resulting physical waterway layout, the (current) flow field in this area will be complex.

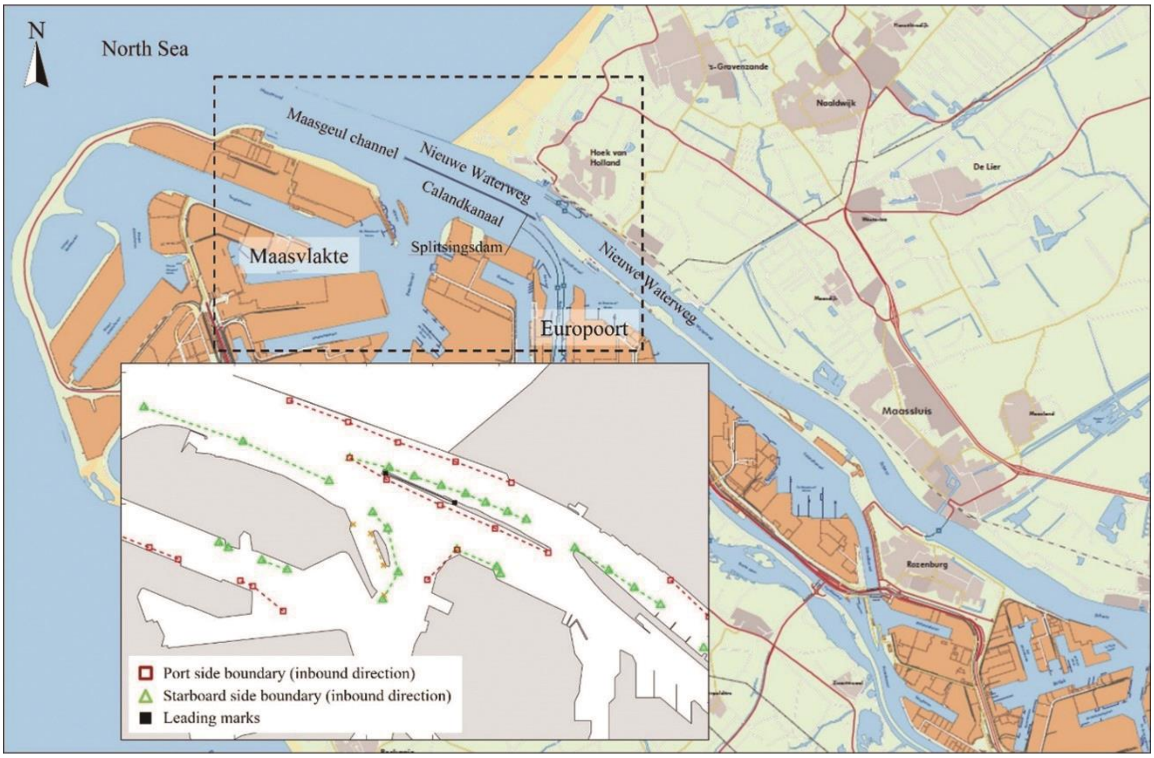

Figure 4.1. Research area with the distribution of Aids to Navigation.

Along the inbound sailing direction (from North Sea to Nieuwe Waterweg), red buoys mark the port side boundary of the navigable waters (shown as unfilled red square in Figure 4.1), while green buoys mark the starboard side (shown as unfilled green triangle in Figure 4.1) (International Association of Marine Aids to Navigation and Lighthouse Authorities, 2014). The more complex the waterway layout is, the more buoys are set. In the Nieuwe Waterweg, the green buoys are denser to mark the slightly curved waterway boundary. However, around the interconnecting area, no buoy is set on the concave bank, which is to avoid collisions in case of adverse external conditions (Colchester, 1993). On the Splitsingsdam, the front and rear leading marks indicate the centerline of the Maasgeul for inbound ships (shown as filled black square in Figure 4.1).

4.3.2 AIS data

In this research, the AIS data of the year 2014 are collected to describe the ship behavior, including speed and position along the waterway. Considering the seasonal differences of environmental conditions and port operations, the collected data covering a full year is sufficient to investigate the generic ship behavior characteristics under external impacts.

AIS is an automated tracking system onboard ships, which also automatically transmits the information to other nearby ships and the local authorities. In 2000, the International Maritime Organization (IMO) issued an amendment adopting a new requirement regarding the introduction of the AIS system in the International Convention for the Safety of Life at Sea (International Maritime Organization, 1972). By the end of 2004, the AIS system was mandatory for all ships of more than 300 Gross Tonnage (GT) engaged on international voyages, cargo ships of more than 500 GT engaged in national voyages and all passenger ships irrespective of size. In the Netherlands, according to the resolution by Central Commission for the Navigation of the Rhine (2013), both commercial and recreational inland ships and sailing vessels longer than 20 meters are mandatory to use AIS since December 1st, 2014. Since the year 2014 is a transition period, the number of inland ships providing AIS data is limited. In the research area, all seagoing ships have installed AIS equipment and used it all the time as required by the local port authority, which account for the majority of the collected data.

According to the guidelines by International Maritime Organization (2003), three categories of information are recorded in AIS data: (1) static information (Maritime Mobile Service Identity number, IMO number, ship name, radio call sign, ship type, overall length, beam, etc.); (2) dynamic information (UTC time, ship position, speed over ground (SOG), course over ground (COG), heading, navigational status, etc.); and (3) voyage-related information (draught, destination, etc.). In this research focusing on ship behavior, only the first two categories of data are used.

The static information is entered into the AIS system by the equipment provider when the equipment is initially installed and updated after a major change of the ship structure. According to previous studies, the information inconsistency problem of vessel type occurs in most of the ships, while the information of overall length and beam appears to be mostly reliable. The beam can be used to distinguish the ship size for ship classification and to represent the wind and current impacts differences among different sizes of ships (Zhou et al., 2020, 2019a).

The dynamic information is automatically updated based on the sensor data. In this chapter, the ship speed change pattern along the stretch is investigated, which is labelled SOG in the collected AIS data. Along the trajectories in the research area as shown in Figure 4.2, the ship position moves monotonically on the x-axis direction of the Dutch geographical coordinate system, the Rijksdriehoeksmeting (RD system). It can also be observed that all ships sail within the boundaries marked by the buoys. To intuitively link the ship behavior pattern to the relative position in the waterway stretch and the corresponding navigational infrastructures, the x-position of ships in AIS data is directly adopted to represent the sailing process. As indicated by the International Telecommunication Union (2014), the reporting interval depends on the ship's speed and course alteration. For most trajectories in the collected dataset, the time interval is 6 seconds, or at least transmitting the messages at an interval of 10 seconds when the ships sail at a low speed.

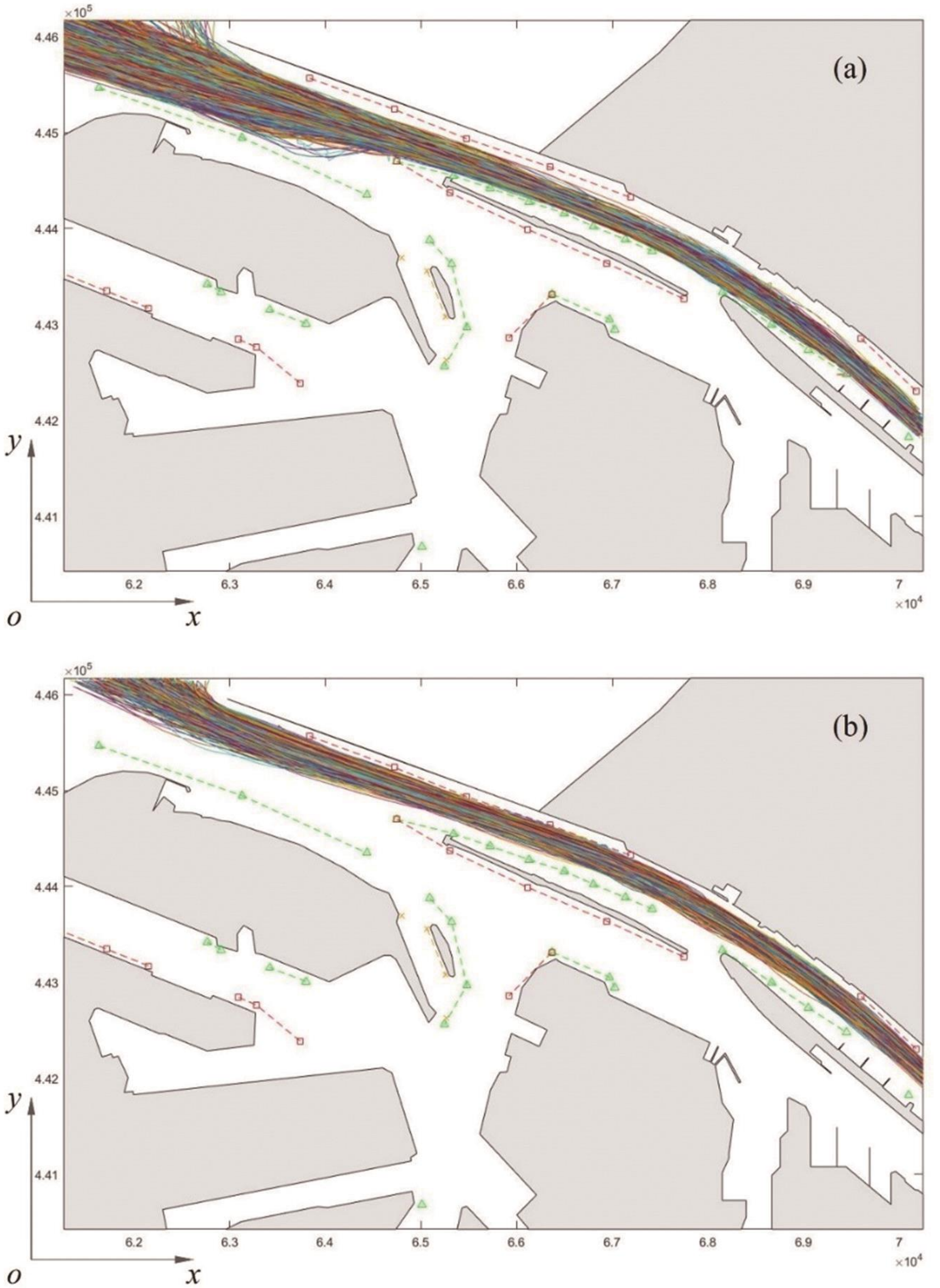

Figure 4.2. Overview of trajectories without any encounter of other ships in AIS data (The o-xy coordinate system is RD system.): (a) inbound 4051 trajectories by 738,667 messages; (b) outbound 4746 trajectories by 683,071 messages.

4.3.3 Meteorological and hydrological data

The meteorological conditions refer to the conditions for wind and visibility. Both are measured at different stations in the research area (see the black cross showing the wind measuring station and the black circle for the visibility measuring station in Figure 4.3). The wind velocity is measured at an interval of 5 minutes, while the visibility is measured every minute. In non-extreme weather conditions, there is no sudden change of wind within 5 minutes. Thus, the measuring frequency of the data is sufficient in presenting the external conditions. The wind and visibility are assumed to be homogeneous for the whole area. The impact of wind on ship behavior (including ship speed) in the straight segment of Nieuwe Waterweg has been quantitatively investigated (Zhou et al., 2020). It can be assumed that the impact would be the same through the extended stretch analyzed in this chapter. Thus, the impact of wind on ship speed will not be further elaborated.

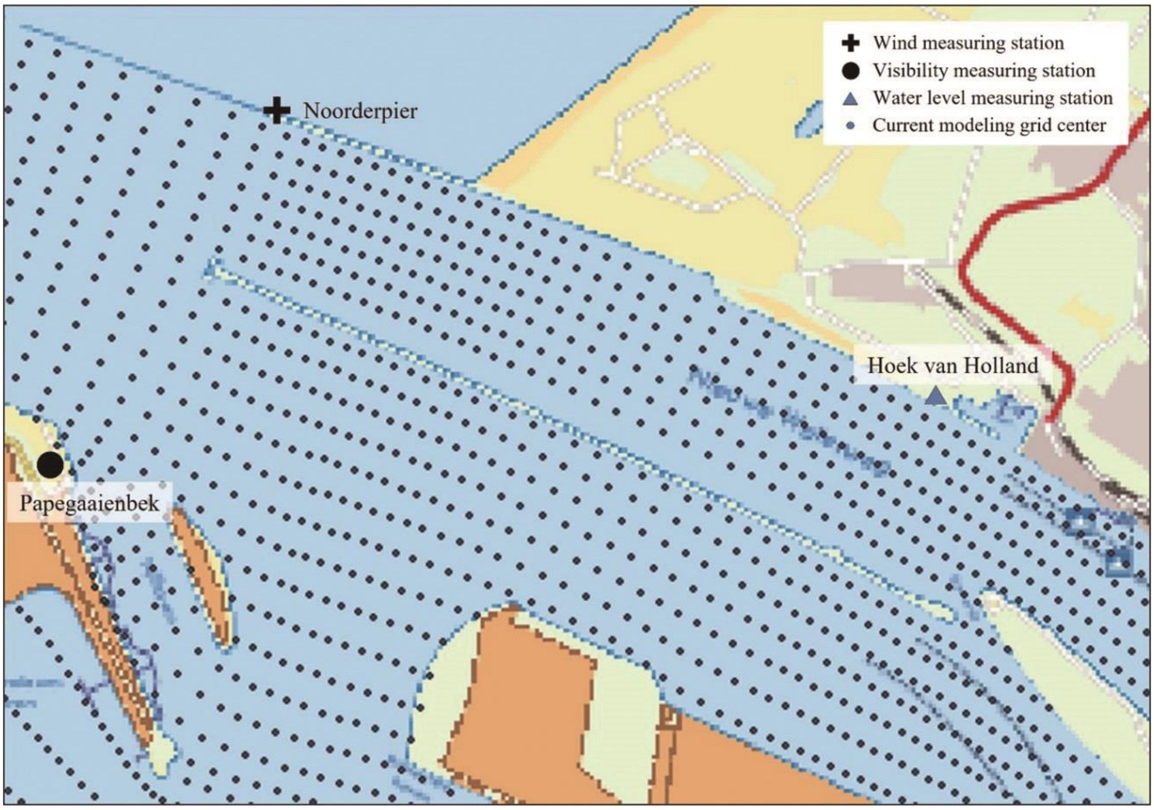

Figure 4.3. Meteorological and hydrological data measuring stations in the research area (the black cross for wind measuring station, the black circle for visibility measuring station, and the blue triangle for water level measuring station) and the hydrological data modeling grid map (shown as the blue dots).

The detailed hydrological conditions are represented by the velocity of the current in the waterway. The ship behavior is influenced via the hydrodynamic forces and moments working on the ship's hull. Unlike wind and visibility, the current velocity at a specific station is not representative for the whole area, due to the propagation of flow and the velocity variation over the water-depth. Thus, the current velocity field is calculated by the port authority using the SIMONA model (Vollebregt et al., 2003). The measured water level from eight stations around the port are the input of this model, in which one station is in the research area naming Hoek van Holland shown as the blue triangle in Figure 4.3. Since the Nieuwe Waterweg is a tidal reach connecting sea and inland waterways, the water level at this station can represent the tidal pattern in this waterway. The modeled velocity has been validated by comparing it to the measured velocity at this station as well. The collected data describe the current velocity in orthogonal curvilinear grids with a resolution of about 85 meters (see the blue dots in Figure 4.3). The current velocity in each grid cell is presented by 10 layers with the same depth averaged by the water depth of the grid at an interval of 15 minutes. For most of the ships, the length is larger than 85 meters, so the grid resolution is sufficiently accurate. During each movement of the ships, the current velocity is instantly updated in the data set. The current velocity varies among grids and over water depth. According to the previous analysis on the current impact, the surface current velocity is identified as the indicator to represent the current condition (Zhou et al., 2017). In this chapter, the research area is with more complex waterway layout, the flow field is also expected to be complicated, especially in the area linking the Maasgeul channel to the Nieuwe Waterweg and the interconnecting area between the Nieuwe Waterweg and the Calandkanaal. Thus, the possible additional impact of current on ship speed needs to be investigated.

4.4 Problem elaboration and research approach

When investigating ship behavior in the extended waterway stretch in situations without encounters, some unexpected speed change phenomena are observed for some ships in the interconnecting area (see Figure 4.4).

Looking at the speed and its change through the whole voyage in general, three features of ship speed are observed. (1) For both sailing directions, the ship speed fluctuates through the voyage. (2) For both sailing directions, besides the above-mentioned speed fluctuation, the ships present a substantial deceleration followed by an instant acceleration around the interconnecting area, which is marked by dashed rectangles in Figure 4.4. Comparing the x position range of the dashed rectangles and the local map (see Figure 4.2), the deceleration-and-acceleration behavior occurs around the interconnecting area. (3) Comparing the values at both ends in Figure 4.4(c) and (d), most of the inbound ships leave the research area with a lower speed than the entry speed, and the opposite holds for the outbound ships. However, there are still some ships presenting the speed change tendency on the contrary to the majority.

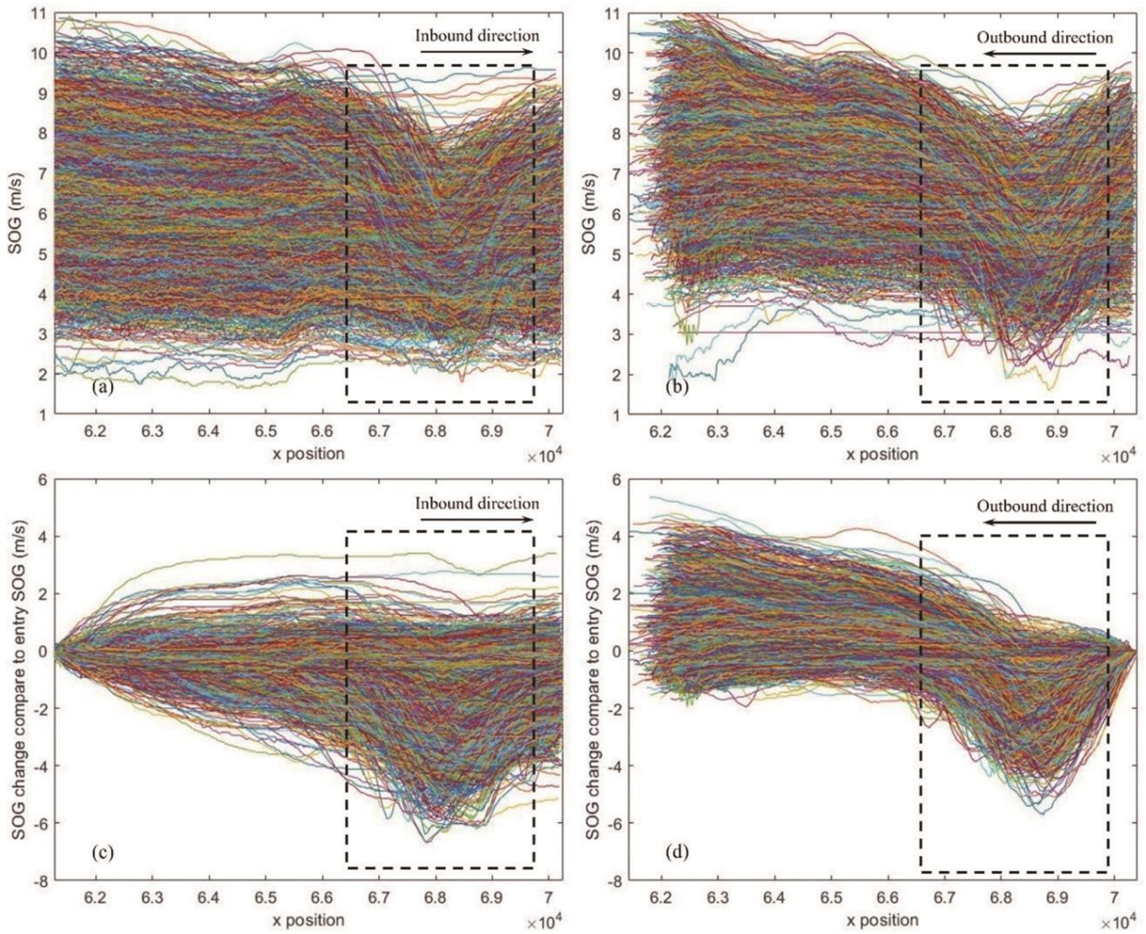

Figure 4.4. SOG and its change over x position of ships during the voyage in the research area: (a) SOG of inbound ships; (b) SOG of outbound ships; (c) SOG change of inbound ships; (d) SOG change of outbound ships. (The dashed rectangles in the figures mark the phenomenon of a deceleration followed by an instant acceleration for some ships.)

It is common that the behavior of ships varies due to their different maneuverability and the different habits of officers onboard. However, when there is a common tendency observed in the majority of ships in the area, there is probably some underlying reasons. To investigate the speed change pattern and the potential influencing factors, three research questions have been proposed in section 4.1. To answer them, different statistical or analytical methods are adopted. The overview of the research approach is presented in Figure 4.5.

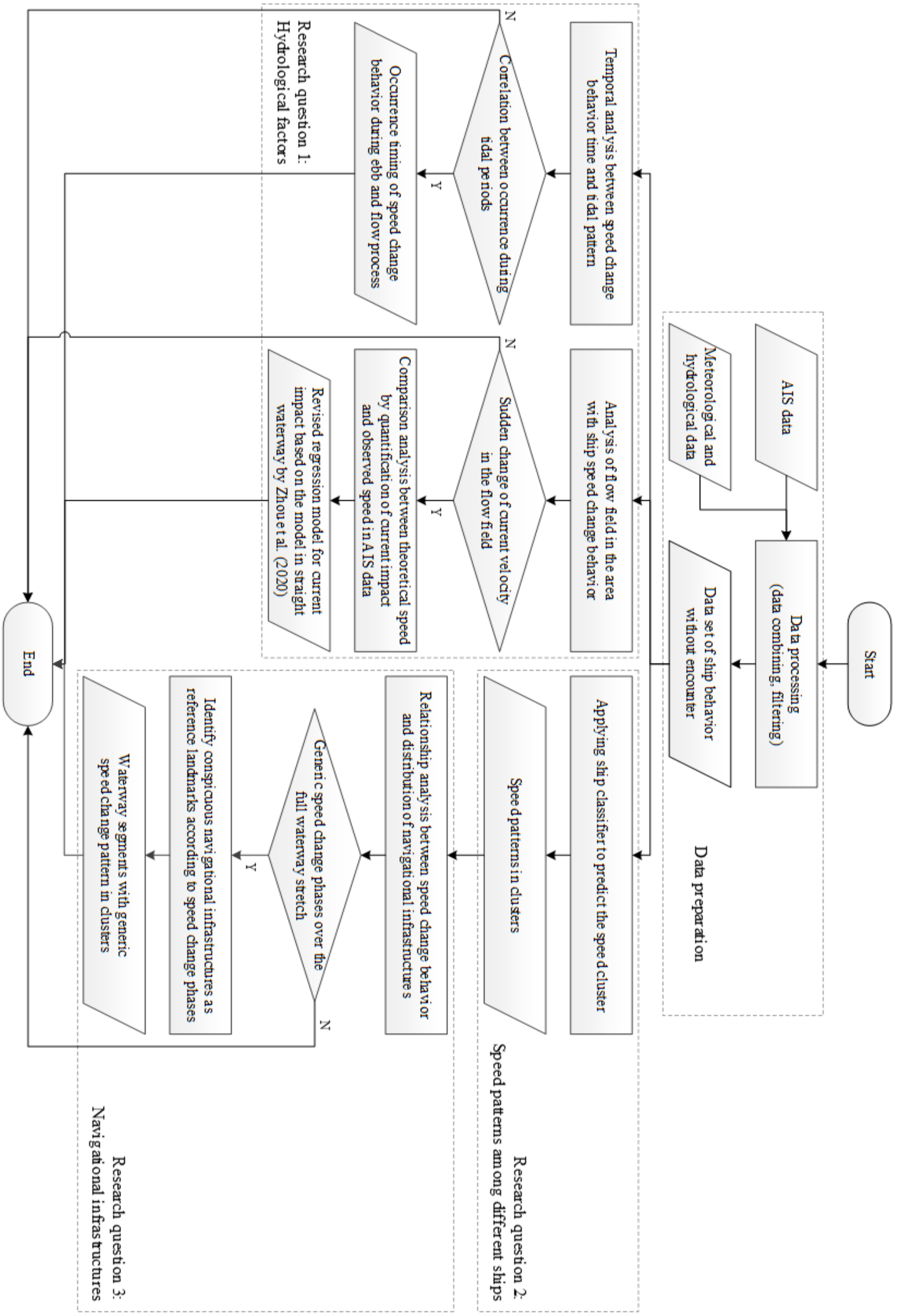

Figure 4.5. Flow diagram of the research approach.

Research question 1: How do meteorological and hydrological factors influence the ship speed in more complex waterway layouts?

According to the previous study, the fluctuations observed in the speed change feature (1) could be the resulting behavior under the identified wind and current impacts, together with other undefined impacts (Zhou et al., 2020). It is common that the officers onboard adjust the speed according to the combination of all external factors in the waterway, including the meteorological factors of wind and visibility, and the hydrological factors of current flow.

However, as stated in section 4.3.3, the wind is assumed to be homogeneous in the whole research area. The impact of wind should be consistent through the full voyage. The sudden substantial speed change in feature (2) is impossible to be caused by wind forces. Thus, in the same area, even with the extended and more complex waterway stretch, the impact of wind on ship speed will not be further investigated.

Regarding the possible impact of current, given the current velocity, the impact mechanism has been analyzed in our previous paper (chapter 5) (Zhou et al., 2020). Unlike the consistent wind conditions, the flow field is expected to be more complicated in the extended stretch in this chapter, especially in the interconnecting area at the east end of the Splitsingsdam. Besides, since the research area is a tidal reach, it is also possible that the speed change pattern correlates to the ebb and flood pattern of the tide. Therefore, a two steps analysis should be performed. Firstly, the relationship between the timing of the speed change behavior in a day and the tidal pattern is analyzed. If such a relationship can be shown, the hydrological impact would refer to the tidal pattern. It means, during specific phases of the ebb and flood period, the officers onboard accordingly control the ship speed. Secondly, the flow field in the interconnecting area where the substantial deceleration-and-acceleration behavior occurs needs to be checked during the full ebb and flood cycle. If there is no substantial change in the current flow field, it means the sudden speed change in feature (2) is not caused by the current factor. Other undefined factors, such as the navigational infrastructure, would be the cause of such behavior. However, if there exist obvious changes in the current velocity, either speed or direction, the observed ship speed in the area will be compared to the theoretical speed calculated by the quantification of wind and current impact. There could be two possible results: (1) The observed speed fits the theoretical value, which implies that the speed change pattern is mainly caused by the local complicated flow field; (2) If the two sets of speed do not fit, it means the previously revealed wind and current impact mechanism does not work for the situation with complicated hydrodynamic processes in complex waterway layout. Regression analysis will be performed to revise the previous model for current impact.

Research question 2: What are the generic characteristics of ship speed change patterns among different ships in the situations without encounters with other ships?

In our previous studies on unhindered ship behavior, the ship size always plays an important role in the behavior differentiation observed in AIS data (Zhou et al., 2015).

However, due to the behavior variations by human factors of ships navigation, especially through a complex waterway layout, the behavior of ships with the same size may probably be different. The direct comparison method to define the threshold of ship size distinguishing speed change patterns is hardly feasible.

During the previous analysis on ship classification based on ship behavior, the ship speed in the straight waterway stretch in the research area in unhindered situation, i.e., without wind and current impacts, is clustered by a systematic *k*-means clustering method (Zhou et al., 2019a). The ships in each cluster present similar speed and change pattern when sailing in the area. Generically, the clusters of ships can be identified from low-speed cluster to high-speed cluster. The number of clusters is objectively determined by the developed behavior clustering algorithm. The proposed classifier successfully classifies the ships to the corresponding behavior clusters, which works for ship speed. Since the research area in this chapter is extended on the basis of the studied straight waterway stretch, the classifier can be directly applied. Thus, for the ships in the collected data, the speed clusters can be predicted based on the ship size factor, i.e., ship beam. After the ships are categorized into clusters, the generic characteristics of speed change patterns for each speed cluster in the extended waterway stretch could be compared and analyzed.

Research question 3: How do navigational infrastructures influence the ship speed in ports and narrow waterways?

Currently, there is no research focusing on the impact of navigational infrastructures on ship speed in ports and waterways. In the existing models simulating ship behavior, the impact of physical or virtual waterway boundaries on ship behavior is simplified as a push force to keep the ships away from the boundaries. Thus, only the course and/or the lateral position in the waterway is influenced. Regarding the ship speed control in navigation practices, there could be local rules to limit the speed or provide instructions in some waterway stretches. Or considering the local waterway layout, the officers onboard take actions in accordance with the requirement of good seamanship. By checking the local rules in the port of Rotterdam in the year, no specific rule is issued for the observed speed control (Port of Rotterdam, 2014). Thus, the sudden speed change of deceleration followed by an instant acceleration (the above-mentioned feature (2)) is probably the common behavior of the officers onboard based on their local sailing experiences.

It is obvious that, compared to the straight waterway, the surrounding navigational infrastructures become more complicated in the extended waterway stretch. Considering that the officers onboard usually use the visible landmark to recognize the area with specific requirement of behavior, the speed change pattern over the full waterway stretch will be linked to the distribution of navigational infrastructures. If some conspicuous infrastructures mark the speed change pattern, the whole waterway stretch could be divided into segments underlying the sailing behavior. The segmentation should also consider the possible impacts from local current flow conditions (in Research question 1) and the potential differences between clusters of ships (in Research question 2). The qualitative analytical way to investigate the ship behavior presented by AIS data provides evidence for the implicit local maneuvering behavior because of good seamanship.

4.5 Results and analyses

The analysis results to answer the proposed three research questions are elaborated with practical interpretations in the following subsections, respectively.

4.5.1 Tidal pattern and flow field

The research area connects sea and inland waterways, which is a tidal reach (see Figure 4.1). For seaports, there exists ship behavior following the tidal rhythm, e.g., deep-draught ship riding the tide. Thus, regarding the impacts of hydrological factors, the correlation between the occurrence of deceleration-and-acceleration behavior and the tidal rhythm is firstly analyzed.

At the station of Hoek van Holland (see Figure 4.1), there are 2 high waters and 2 low waters with different amplitudes in a period of 24 hours. A special phenomenon manifests itself, which has a double low tide with the second low water being lower than the first., which can be observed in the water level change at the station. To investigate the typical tidal period, two extreme situations are selected, being the week with lowest and highest water level of the year, respectively. The conditions of flow field and current velocity are expected to be more complicated than the daily average ebb and flood processes. The water level variation in the one-week tidal period is shown in Figure 4.6 (lowest water level week) and Figure 4.7 (highest water level week), together with the number of trajectories with deceleration-and-acceleration action. It is worth noting that the highest water level is caused by storm surge at North Sea.

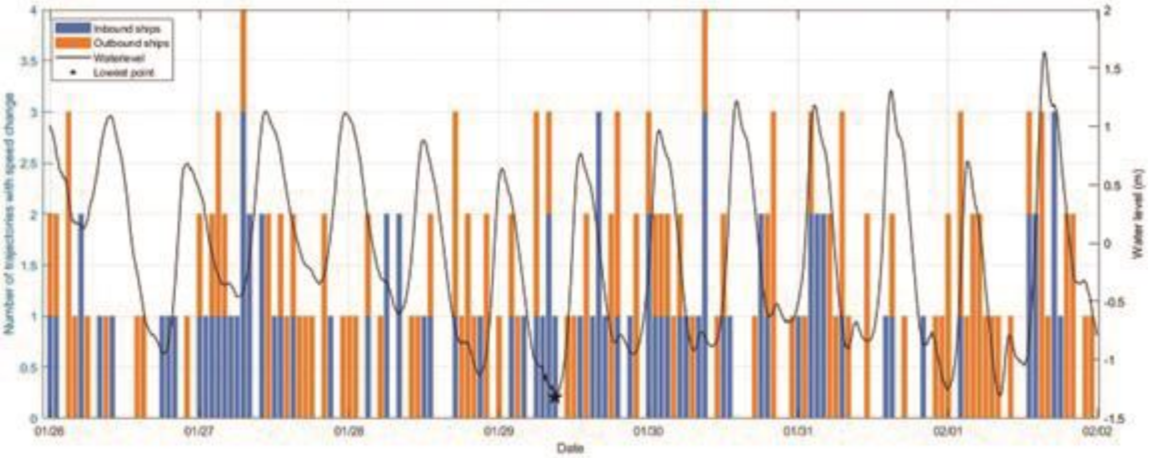

Figure 4.6. One-week tidal period with lowest water level in the year and the number of trajectories with speed change pattern in the same period.

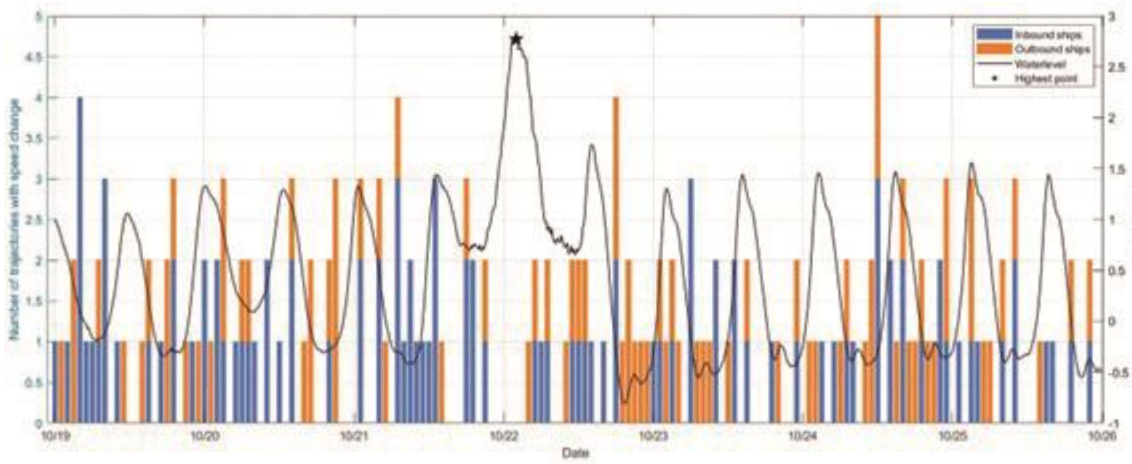

Figure 4.7. One-week tidal period with highest water level in the year and the number of trajectories with speed change pattern in the same period.

In both figures, there are periods without ships with speed change pattern in the research area. One reason is that this chapter focuses on the ship behavior without encounter with other ships. Thus, the trajectories with encounter are filtered from the data set for analysis during data processing. The other reason is that some ships indeed sail through the area without substantial speed change as can be seen in Figure 4.4. Looking at the occurrence of ship speed change behavior, there is no correlation with the phases of ebb and flood period. The behavior happens no matter the water level is during the processes of rise/fall, or the water level is at high/low waters. Thus, the tidal rhythm does not correlate to the occurrence of the ship's deceleration-and-acceleration behavior.

In a waterway with banks on both sides, the current direction normally follows the bank layout. For a tidal reach, the flow field changes between ebb and flood phases may cause sudden complicated current velocity changes, including both current speed and direction. For a detailed look into the current conditions, the area with obvious physical layout distinction is selected in the extended research area, where a substantial current velocity change probably occurs. The interconnecting area lies to the east of the Splitsingsdam, connecting the Nieuwe Waterweg to the Maasvlakte and the Europoort (see dashed rectangle in Figure 4.1). The flow field in the area is checked during one full ebb and flood cycle, which is about 12 hours. Similar to identify the typical tide period, the flow field in the tidal period with the lowest and highest water level in the year is plotted in Figure 4.8 and Figure 4.9, respectively.

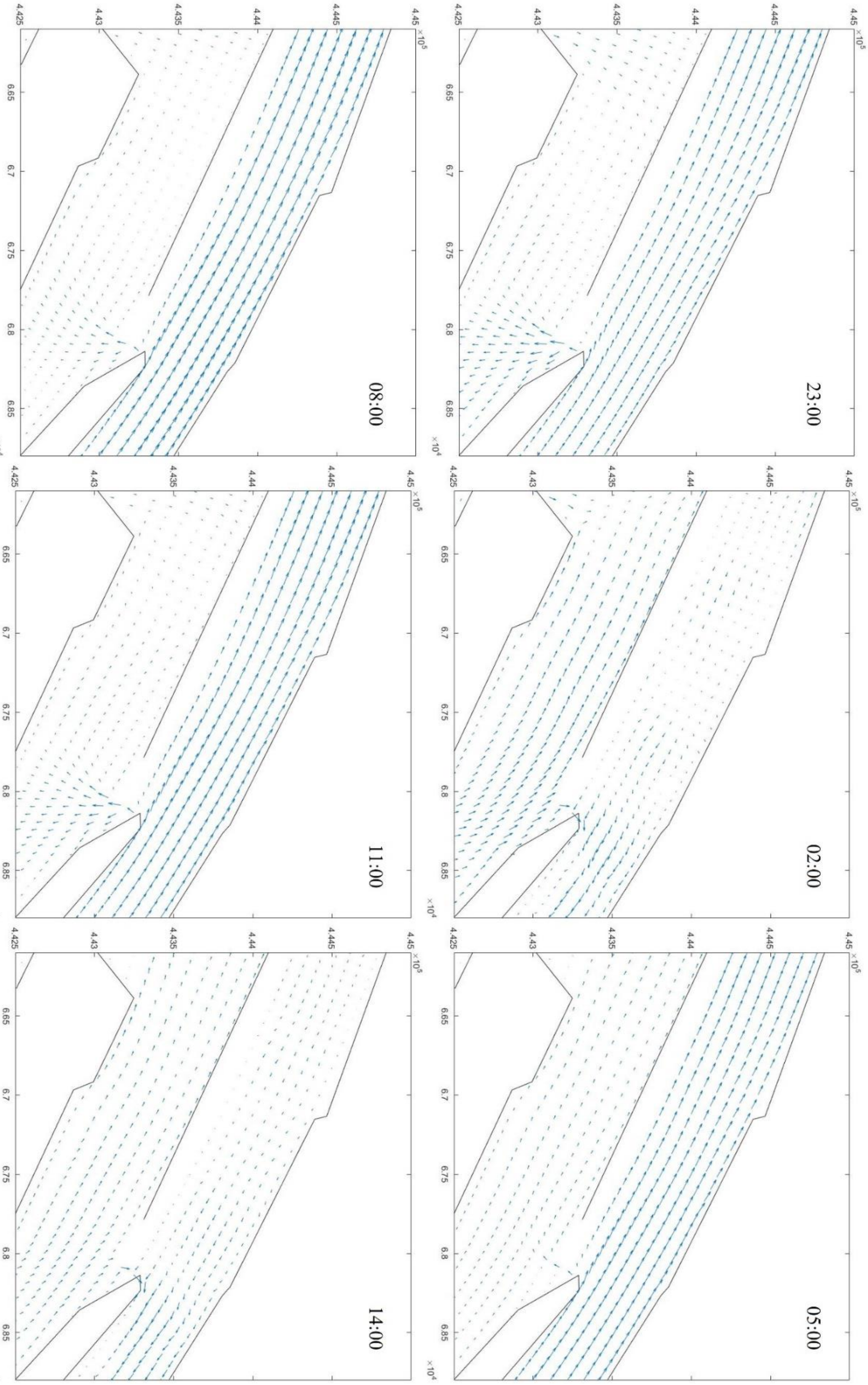

Figure 4.8. Flow field in the tidal period with the lowest water level in the year in the interconnecting area.

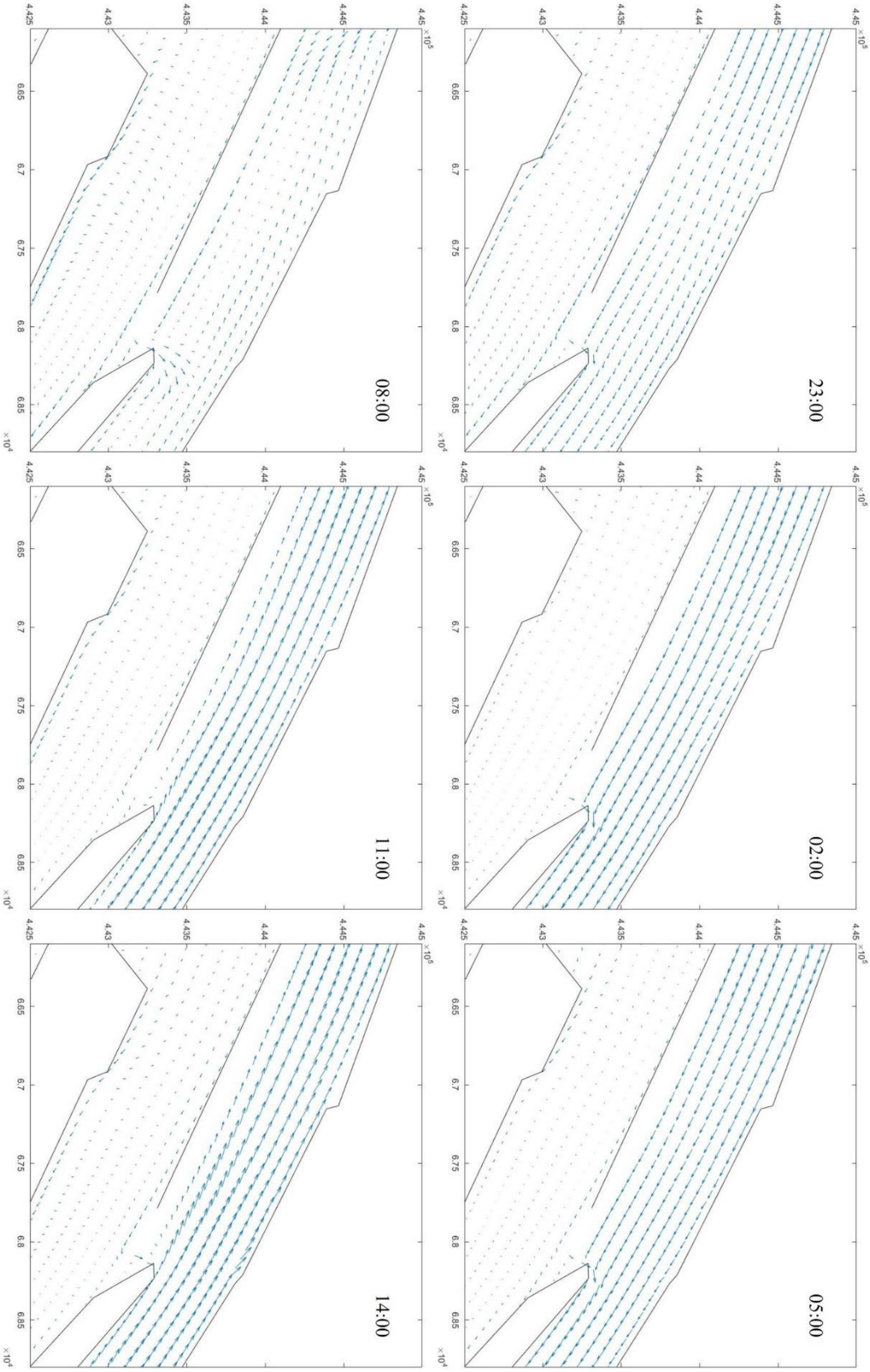

Figure 4.9. Flow field in the tidal period with the highest water level in the year in the interconnecting area.

It can be observed that the current speed indeed changes during the ebb and flood process. But, when the flow is strong, the current directions keep consistent along the whole waterway Nieuwe Waterweg, without sudden change in the interconnecting area. Only when the tide turns between flood and ebb, the flow field becomes complex with varying flow directions (02:00 and 14:00 at lowest water level in Figure 4.8, and 08:00 at highest water level in Figure 4.9). However, during such periods, the current speed is rather small, which imposes weak forces on ships. According to the quantified impact mechanism of current on ship speed, the influence is small, which will not cause the substantial deceleration-and-acceleration behavior as presented by AIS data.

Compared to the empirical and experimental findings in the straight tidal waterways in different ports (Kim et al., 2014; Zhou et al., 2020), the current conditions become more complex in the waterway stretch with width change and intersections. However, the speed control behavior still follows the identified mechanisms considering the current velocity as in the simple waterway layout. The tidal patterns and the varying current conditions do not impose additional impacts on ship speed.

4.5.2 Generic characteristics of speed patterns in ship clusters

Our previous study developed a ship classifier based on the clusters of ship behavior (speed or path) in the straight waterway stretch, the Nieuwe Waterweg (Zhou et al., 2019a). The waterway stretch in this chapter is extended on both ends of the previous research area. Thus, the classifier can be applied in this research to predict the unhindered speed cluster based on the ship size, which is five clusters for inbound ships and six clusters for outbound ships. According to the methodology of classification, in the SOG clusters, cluster #1 include the ships sailing at the lowest speed, while cluster #5 for inbound ships and cluster #6 for outbound ships refer to the high-speed ships. Using ship beam as the classification criterion, the speed profiles of inbound and outbound ships in clusters are shown in Figure 4.10 and Figure 4.11, respectively.

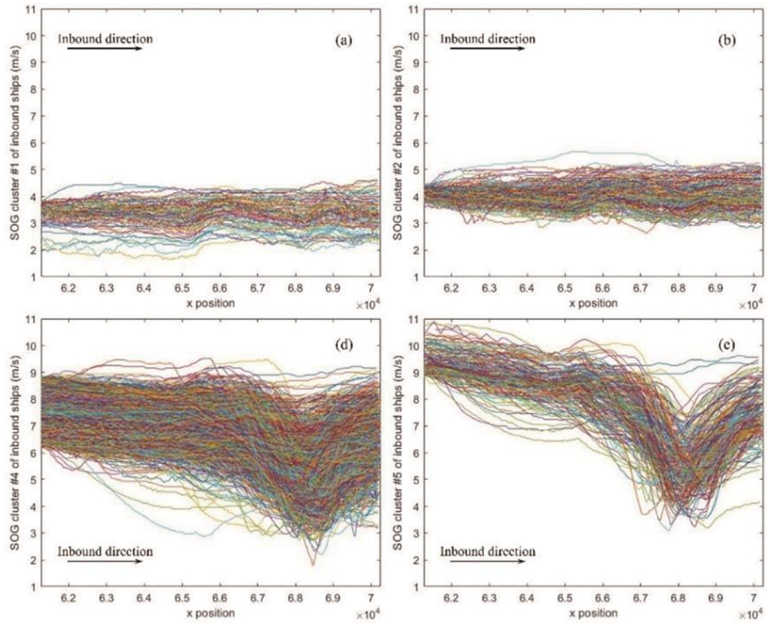

Figure 4.10. SOG of inbound ships in clusters predicted by the proposed classifier by (Zhou et al., 2019a): (a) to (e) refers to cluster #1 to #5, respectively.

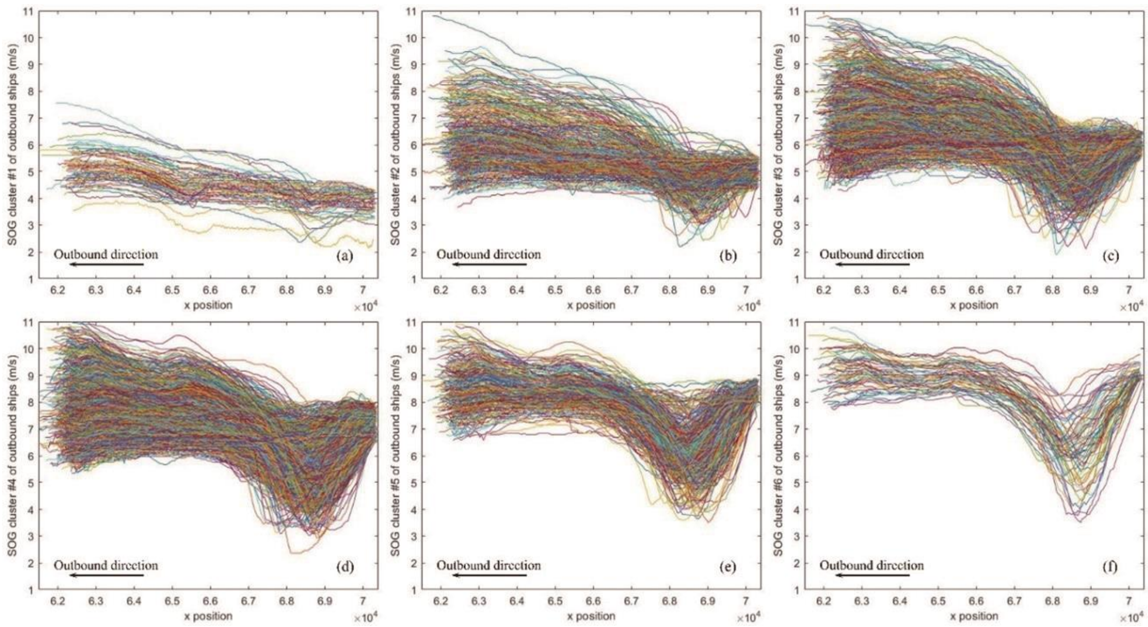

Figure 4.11. SOG of outbound ships in clusters predicted by the proposed classifier by (Zhou et al., 2019a): (a) to (f) refers to cluster #1 to #6, respectively.

Generally, the sailing speed increases from the first cluster to the last one. However, since the entry speed varies among the ships within each cluster, the magnitude of speed change pattern can hardly be analyzed from the value of speed directly. Besides, for high-speed ships and low-speed ships, the maneuvering capability and energy consumption effort to achieve same speed change, for instance 2 m/s, are different. Therefore, to intuitively compare the speed change patterns among clusters, the speed change magnitude in proportion to the entry speed of ships in percentage is calculated. The corresponding speed change patterns of the clusters are presented in Figure 4.12 (inbound ships) and Figure 4.13

(outbound ships). The black dots plot the median value of the speed change percentage along the waterway stretch indicated by x position, while the gray dots mark the range of the cluster at 95% confidence interval.

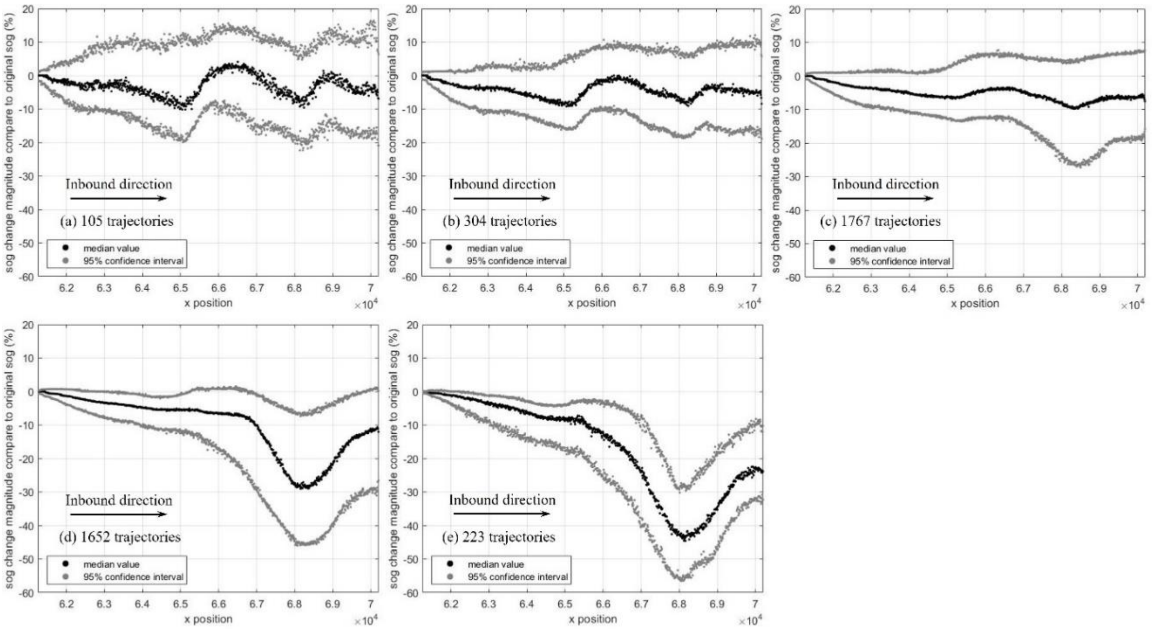

Figure 4.12. SOG change magnitude compared to the entry SOG of inbound ships in clusters by (Zhou et al., 2019a): (a) to (e) refers to cluster #1 to #5, respectively.

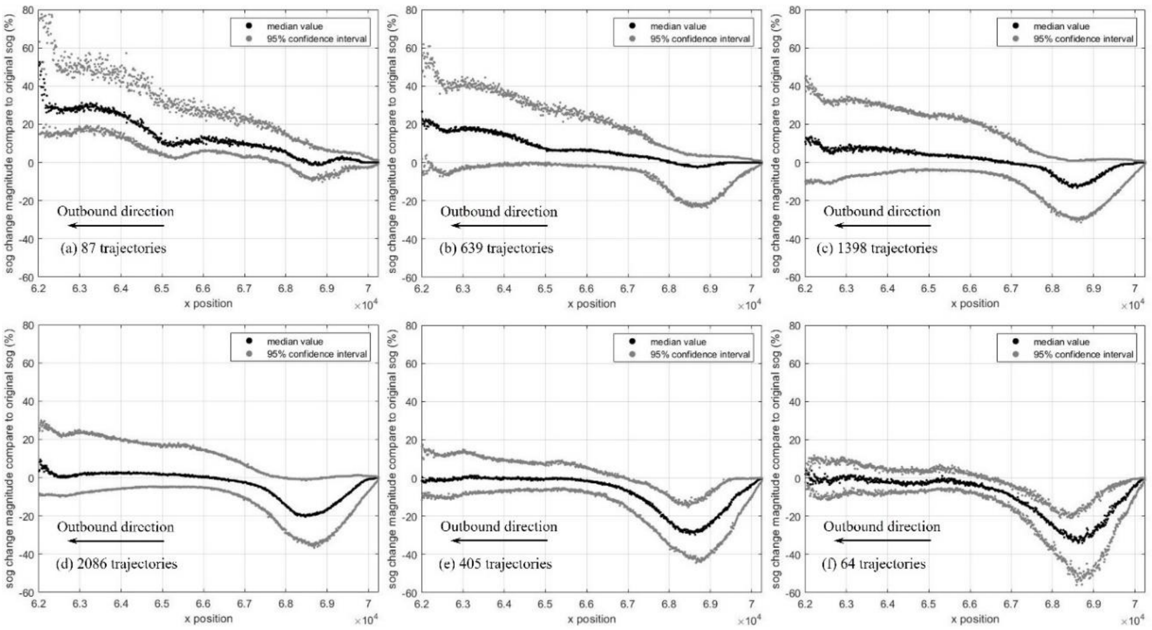

Figure 4.13. SOG change magnitude compared to the entry SOG of outbound ships in clusters by (Zhou et al., 2019a): (a) to (f) refers to cluster #1 to #6, respectively.

Due to the limited number of trajectories in cluster #1 of inbound ships and cluster #1, #6 of outbound ships, the descriptive values (median value and 95% confidence interval) are not as smooth as the other clusters. The generic characteristics of ship speed change patterns among different ships can be explained for inbound and outbound directions as follows.

For the first three clusters of inbound ships, it can be observed that there are two deceleration-and-acceleration changes along the waterway. For the first speed change, the ships in cluster #1 present more fluctuation and larger magnitude than the ships in cluster #2, and cluster #3 shows the least magnitude. For the second change, the opposite phenomenon is observed. The ships in cluster #3 decelerate to a larger extent, and the total speed change comparing the leaving speed to the entry speed is also larger. However, for cluster #4 and #5, the first acceleration can hardly be observed, the ships gradually decelerate after entering the research area. While around the same area of the second speed change of the first three clusters, the ships of the last two clusters take only one substantial deceleration-and-acceleration action. The higher the entry speed, the larger the speed change magnitude, and the larger total speed change magnitude as well. The magnitude is obviously larger than the first three clusters. The findings show that the officers onboard ships with different sailing speed will take different maneuvering actions in the same water area. Though the magnitude of speed change varies among clusters, the area where occurs the deceleration-and-acceleration action can be identified. Especially for the second one, nearly all ships take such substantial action, which can be found in the dashed rectangles in Figure 4.4 in section 4.4. The flow field and current velocity in the area need to be checked, to investigate whether the local current forces impose specific impacts on ship speed.

4.5.3 Navigational infrastructures

As stated in Rule 6 (Safe Speed) in the International Regulations for Preventing Collisions at Sea (COLREGs), every ship shall at all times sail at a safe speed so that the ship can take effective actions to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions (International Maritime Organization, 1972). It implies that the ship speed should always be controlled according to her stopping maneuverability. In Rule 9 (Narrow Channels), a ship nearing a bend or an area of a narrow waterway where other ships may be obscured by an intervening obstruction shall navigate with particular alertness and caution. There is no detailed instruction of behavior in narrow waterway provided in COLREGs. However, it can also be expected that when the surrounding navigational infrastructures become complex, the officers onboard will take additional actions out of good seamanship for the purpose of navigation safety. To investigate the relationship in between, the median speed change patterns in clusters are compared on top of the distribution of the navigational infrastructures in the research area (see Figure 4.14).

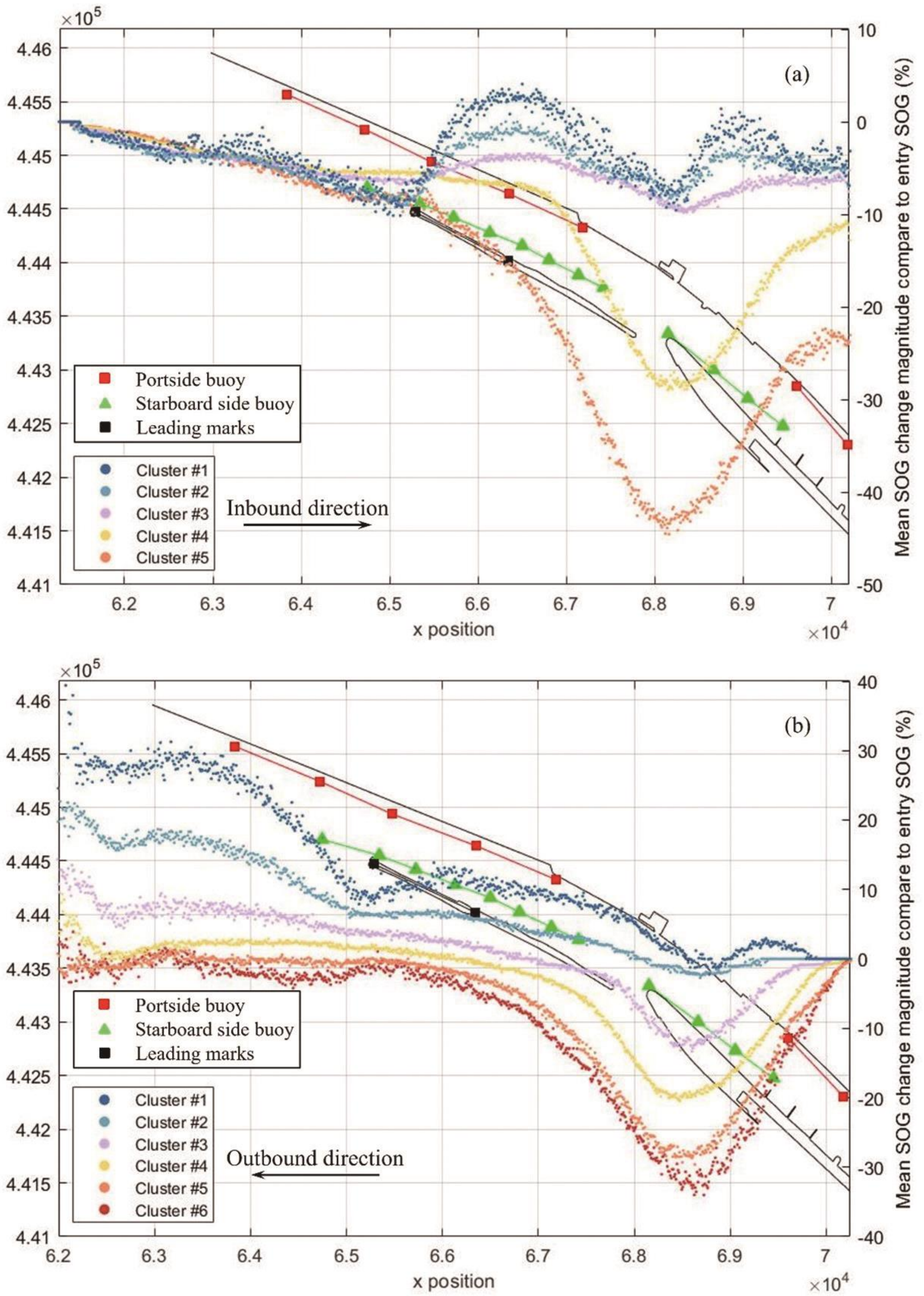

Figure 4.14. Median SOG change patterns in clusters (right axis) on top of the distribution of navigational infrastructures: (a) inbound ships; (b) outbound ships.

Due to the differences among the maneuvering habits and local sailing experiences of officers onboard and the maneuverability of ships, the exact timing to initiate the deceleration or acceleration action and the magnitude of such action vary, which is difficult to be quantified. However, it can be observed from Figure 4.14 that their behavior shows similar relationship to the distribution of navigational infrastructures.

For inbound ships, (1) before they enter the Nieuwe Waterweg by the Splitsingdam, the ships mostly sail with gradual deceleration possibly due to the approach to the destination, which was revealed in previous studies. (2) After entering the Nieuwe Waterweg, the low-speed clusters of ships (Cluster #1 to #3) would accelerate to maintain their maneuverability in a narrowed waterway, where the bank effects usually become stronger than in the wider waterways. However, for the high-speed clusters of ships (Cluster #4 and #5), they maintain the gradual deceleration as before without acceleration. The possible reason is also to weaken the bank effects caused via the ship-generated waves, which become stronger when the ship speed is high (Du et al., 2020). (3) When the ships sail about the middle of the Splitsingdam, the deceleration action happens to all clusters of ships. The higher the speed, the larger the deceleration. Since the interconnecting area is ahead, the officers onboard shall keep necessary precautions in case of any encounter of another turning or crossing ship or other emergency in the area. As the ship inertia is big, a high speed requires a longer reaction distance in case of emergency. Thus, the behavior magnitude differs among ships with different entry speed. (4) After passing the interconnecting area, the ships accelerate to continue their normal voyage in the following inland waterway. Again, possibly due to the approach to their destination, the sailing speed when leaving the area is slightly lower than the entry speed.

For outbound ships, (1) due to the limitation of the research area, the starting point to decelerate could be outside the east boundary of the area, which cannot be exactly defined. (2) Before entering the interconnecting area, the ships already prepare a low speed for the necessary precautions in case of any encounter in the area, which is similar to inbound ships. (3) Afterwards, the ships accelerate to proceed their voyage. Different from the inbound direction, the overall speed tendency of outbound ships is to accelerate to sail at sea. When the ships sail from the narrower Nieuwe Waterweg to the wider Maasgeul channel, the bank effects also become weaker, which do not require specific speed control. (4) The low-speed clusters of outbound ships (Cluster #1 and #2) present a larger acceleration rate compared to the behavior in the Nieuwe Waterweg.

For ships in both sailing directions, four phases of speed control behavior can be generalized. Considering the waterway stretch is fully equipped with AtoNs (aids to navigation), some conspicuous AtoNs can be adopted for waterway segmentation in accordance with the phases found in the speed change patterns. Using visible landmarks to recognize the area with specific requirement of behavior also follows the common practice of seamen in the maritime domain. Therefore, the waterway is split into four segments marked by three AtoNs as references (see Figure 4.15), being *the front leading mark*, *the rear leading mark*, and *the first green buoy at the edge of the interconnecting area*. In the Nieuwe Waterweg, there are several buoys set along with the Splitsingdam. Since the selected reference mark is expected to be noticeable for officers onboard during visual navigation, the leading marks are adopted instead of buoys in this segment. Compared to the floating buoys on water surface, the leading marks are fixed structure with a certain height, which are easier to be observed from the viewpoint of officers onboard. After the interconnecting area, the first buoy is sufficiently visible for officers onboard. Though for outbound ships, the deceleration-to-acceleration change occurs between the first and second buoy, it is still the first buoy adopted to mark the segment.

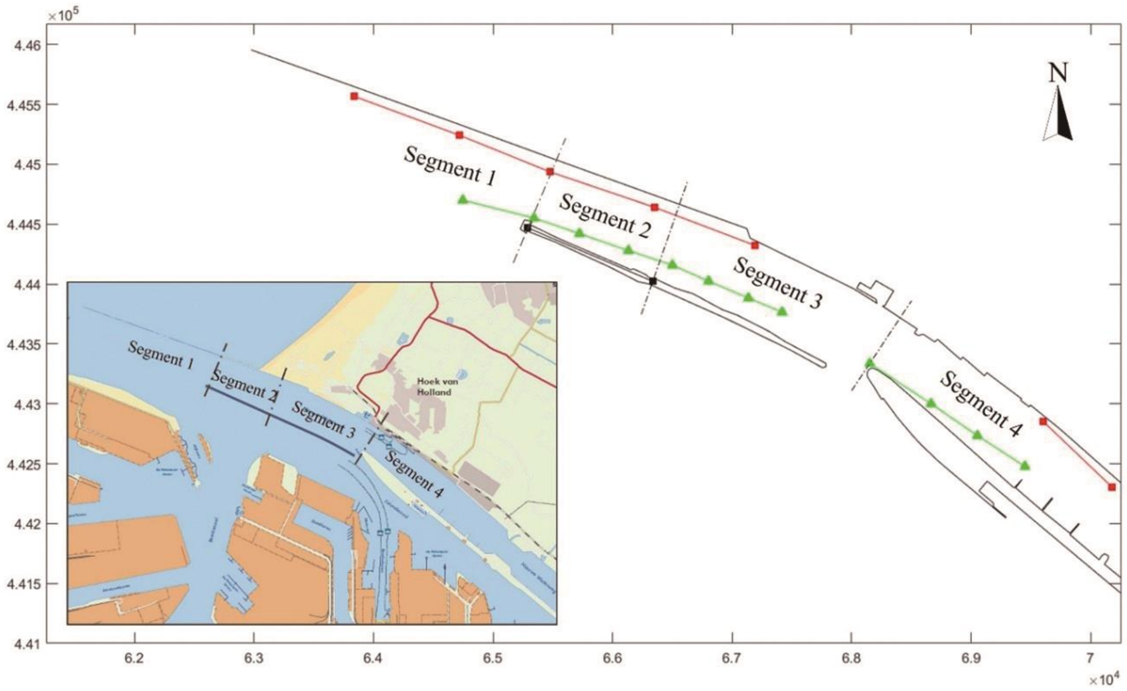

Figure 4.15. Waterway segments marked by AtoN in the research area.

From the empirical analysis results of the AIS data, the impacts of navigational infrastructures on ship speed in a complex waterway layout are generalized by waterway segmentation according to the ship speed control phases. Considering the fact that the officers rely on visual navigation in ports and inland waterways, the implicit impacts of visual objects are revealed by empirical evidence. However, due to the variation of ship maneuverability and the different maneuvering habits of officers onboard, the exact speed change pattern under the influence of the navigational infrastructures is difficult to be quantified like the wind and current impacts. The findings in speed clusters still hold for further behavior analysis and simulation.

4.6 Conclusions

This chapter investigates external impacts on ship speed in ports and waterways with fully equipped navigational infrastructures by an empirical analysis using AIS data. Generic characteristics of ship speed change patterns are revealed, and the impacts of varying current velocities and the presence of navigational infrastructures are analyzed.

Firstly, *the potential impacts of varying current conditions* are qualitatively analyzed from two aspects, being the tidal pattern and the current velocity. Regarding *the tidal pattern*, no correlation is found between the tidal rhythm and the occurrence of speed control behavior observed in AIS data. Looking into the flow field during the two typical ebb and flood cycles, *the current velocity* (both speed and direction) indeed changes during the process in the waterway stretch with width change and intersections. However, neither will cause the observed speed control behavior, according to the quantification of current impact on ship speed in our previous study. Therefore, the varying current conditions do not impose additional impact on ship speed compared to straight waterways.

Secondly, in a more complex waterway layout (the research area extended on both ends of the straight waterway stretch in our previous study), *the corresponding speed cluster of ships* in the extended research area can be predicted by applying the previously proposed ship classifier. Though the magnitude of speed change varies among the clusters of both inbound and outbound ships, generic characteristics of speed change patterns can be revealed. Four inbound ships, the low-speed clusters of ships sail with more fluctuations of speed and perform two deceleration-and-acceleration actions during the whole voyage. However, for the high-speed clusters, only one substantial deceleration-and-acceleration action is observed, where the latter one of the low-speed clusters occurs. Around the same area, nearly all outbound ships take the similar action as well. Thus, the findings imply there exists implicit *relationship between the local conditions and the ships speed change pattern*.

Lastly, the impacts of *navigational infrastructures* on ship speed in the waterway are generalized by waterway segmentation according to the ship speed control phases. Based on the ship speed change patterns in clusters, the deceleration-and-acceleration actions can be obviously observed in four phases, though the magnitude of speed change is different among clusters. The overall inbound deceleration comparing entering and leaving speed is due to the approaching of destination, while the opposite phenomenon for the outbound ships. The first acceleration of the low-speed inbound clusters is probably to maintain their maneuverability in case of the potential stronger bank effects in narrower waterway. The other deceleration-and-acceleration behavior happens to nearly all ships, irrespective of the sailing directions. Such action is taken to prepare a safe speed to keep necessary precautions in the interconnecting area ahead, which complies with the good seamanship. Considering the distribution of navigational infrastructures along the waterway stretch, three AtoNs are adopted as reference marks for waterway segmentation into four segments in accordance with the four phases of speed change pattern, being the front and rear leading marks and the first green buoy at the edge of the interconnecting area. The speed change patterns of ship clusters can be qualitatively identified. However, due to the variation of ship maneuverability and the different maneuvering habits of officers onboard, the exact speed change timing and magnitude is difficult to be quantified. Therefore, *the impacts of navigational infrastructures on ship speed* are described by the statistical characteristics of ship behavior in clusters based on the waterway segmentation.

In this chapter, the impact of navigational infrastructures on ship speed in a complex waterway layout is analyzed for the first time. Based on the prediction of ship behavior clusters by previously proposed classifier, the speed change patterns for ship clusters are investigated. With the revealed impacts of navigational infrastructures on ship speed, the ship sailing behavior can be further investigated to identify other undefined influences, e.g., different encounter situations, etc. The findings from unhindered ship behavior to the impacts of various external factors are essential to simulate the realistic ship behavior under different conditions.

5. Impacts of Wind and Current on Ship Behavior

In ports and waterways, the impacts of external navigational factors may lead to serious incidents due to limited space for ship maneuvering. In order to estimate ship behavior under external impacts without detailed ship maneuvering information, the impacts of wind and current on the observed dynamic ship behavior (speed over ground and leeway and drift angle) in ports and waterways have been investigated by analyzing Automatic Identification System data (showing ship paths over time) and the meteorological and hydrological data in this chapter.

The relation between unhindered speed variation and ship size is revealed. The regression analysis results on ships with similar size indicate the differences between wind and current impacts. Especially for small ships, the current impact on speed over ground outweighs the wind, while the wind influences the leeway and drift angle more than the current. Based on the quantified impact variation over ship size, the proposed impact mechanism explains the variance of speed over ground and leeway and drift angle.

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5.1 Introduction

Seaborne transport has been an important means of international freight transport, which accounted for over 80 percent of the global trade by volume and more than 70 percent by value until 2017 and grew by another 4 percent in 2018 (United Nations Conference on Trade and Development, 2018). According to this forecasting of UNCTAD, the maritime trade is projected to expand at an annual growth rate of 3.8 percent between 2018 and 2023. Due to the large amount of cargo carried by individual ships and the high frequency of ships visiting the hub ports, nautical traffic safety in ports has been an important and sensitive issue for nautical traffic management and port authorities. Unlike the large space for ship maneuvering at sea, the maneuverability is restricted under different external conditions, such as strong wind and current, in ports and inland waterways. In such areas, the impacts of external navigational factors may lead to more serious consequences, such as grounding or collision with vast loss of life and property and damage to the environment and local infrastructure. Thus, the understanding of external navigational impacts on ship behavior in real-life situations will benefit the effective management of nautical traffic considering the external conditions in the seaports and inland waterways.

To analyze and simulate the maritime traffic considering individual ship behavior in an area, various models have been developed, which are compared by Zhou et al. (2019a) from the ship behavior modeling perspective. However, external conditions, such as wind and current, have seldom been considered in the models, even though it has been proven that the external factors do influence the ship behavior (Kepaptsoglou et al., 2015; Shu et al., 2017; Zhou et al., 2017). In the numerical models to simulate individual ship behavior considering the specific maneuverability, the effects of wind, tidal current and waves on moving ships are significant due to the hydrodynamic forces and moments working on the ship's hull (Chen et al., 2015; Soda et al., 2012). Using the detailed data of individual ship maneuverability, the wind, wave and current forces are estimated, which provides an accurate prediction of the ship behavior under the external conditions. In the nautical traffic models considering external environmental factors, two methods have been adopted to indicate such impacts. The simplified method is to introduce random variables (Qi et al., 2017a; Qu and Meng, 2012) or generic rules (Almaz et al., 2006; Camci et al., 2009; Merrick et al., 2003). It shows a generic random variation of ship movement under external impacts, which is feasible when describing the traffic flows at an aggregated level. However, the corresponding mechanism of such impacts is not included when investigating the behavior of individual ships. On the contrary, the other method is to consider the maneuverability of each individual ship under specific wind and current conditions to model the corresponding behavior (Beschnidt and Gilles, 2005; Leguit, 1999; Sarıöz et al., 2002). This method specifies the hydrodynamic processes and requires maneuvering particulars for specific ships for model calibration, which cannot be used for simulation of generic nautical traffic in an area. Therefore, in the field of nautical traffic modeling considering individual ship behavior, the research gap is that neither method can be applied to model the wind and current impacts for different ships in an area where the maneuverability particulars of individual ships are unavailable.

In order to investigate ship behavior, Automatic Identification System (AIS) data have proven to be a valuable source (Yang et al., 2019). To analyze macroscopic navigation patterns or the nautical traffic characteristics in an area, AIS data are widely used due to its detailed record of behavior for almost all passing ships (Altan and Otay, 2017; Gao et al., 2017; Gunnar Aarsæther and Moan, 2009; Silveira et al., 2013). To analyze the safety distance during collision avoidance considering ship drift, the external forces can be considered by the difference between heading and course in AIS data (Altan, 2019). Since AIS equipment has been mandatory for most of the ships, the data can be obtained by all port authorities, which can be utilized to analyze the behavior in a port or other area. In this research, AIS data is collected to describe the ship behavior under different external conditions (including wind, current and visibility). Thus, the meteorological and hydrological data are also collected. By comparing the average behavior in hindered and unhindered behavior, the impacts of external factors including wind, current, visibility and encounters are found (Shu et al., 2017). Combining AIS data with meteorological and hydrological data, the impacts of wind and current on ship behavior have been qualitatively analyzed and presented (Zhou et al., 2017). It shows that both ship speed and lateral position in a waterway are affected by wind and current, where the wind and current directions are categorized into four directions, being from the bow, the stern, the port side and the starboard side. The impacts found are different for ships of different sizes. However, the qualitative analysis results cannot be used to estimate the behavior of different ships under different wind and current conditions in an area.

The aim of this chapter is to quantitatively analyze and estimate the impacts of external conditions (wind and current) on ship behavior in ports and waterways, where the actual hydrodynamic forces cannot be calculated due to the unavailability of individual ship particulars. To focus on the wind and current, the impacts of visibility and ship encounter are eliminated by filtering the external navigational conditions. Based on the previous qualitative analysis results and the theory in dead reckoning to estimate ship position, a generic modeling paradigm of wind and current impacts on ship behavior is introduced. Using the AIS data and the meteorological and hydrological data in the same period, a regression analysis is performed to quantify the external navigational impacts on ship behavior (expressed by speed over ground, leeway and drift angle) as a function of the ship's own size and the wind and current conditions. The originality of this research is to reveal the mathematical formulations of ship behavior under the wind and current impacts without detailed ship particulars. These mathematical formulations can thus be used in a microscopic nautical traffic model to include the impacts of external conditions. It also provides the port authority with an insight into relations between ship behavior and external factors.

Based on this aim, the following research questions are proposed:

- Research question 1: What is the mathematical relation between the variation in speed over ground and ship size in unhindered situation?
- Research question 2: What is the mathematical formulation of ship behavior under the wind and current impacts considering ship size differences without individual ship maneuvering particulars?

In this chapter, the research area and the collected data set are introduced in section 5.2. Section 5.3 explains the behavior variables and the proposed research approach. The analysis results for wind and current impacts are presented in sections 5.4. Section 5.5 concludes the chapter with discussion and recommendations for further research.

5.2 Study area and data description

In this section, the study area is introduced in section 5.2.1, followed by the description of the data, including AIS data in section 5.2.2 and meteorological and hydrological data in section 5.2.3. These data have been collected for the whole year of 2014 by the port authority of Rotterdam. The AIS data reveal the ship behavior in the study area. Regarding external conditions, the meteorological data describe the condition of visibility and wind, and the hydrological condition is represented by current velocity.

5.2.1 Study area

The study area is a nearly straight waterway, Nieuwe Waterweg, located at the entrance of the port of Rotterdam, the Netherlands, as shown in Figure 5.1. The reason for choosing an almost straight waterway for external impacts analysis is to eliminate the impact of a specific waterway layout on ship behavior. In a curved waterway, besides the impact of more complex current conditions due to the curve, the bridge team on board also needs to hold the ship position to follow the direction of the waterway. It leads to a large variation of ship behavior due to the maneuvering habits of individual officers when passing a curve. Thus, the impacts of wind and current are hardly separated from the resulting trajectories in a curved waterway, and a straight waterway is preferable to focus on such impacts. However, the study area is not exactly straight with parallel banks on both sides. The impacts of such slight bending waterway layout may still exist in the analysis results, but are considered to be negligible. The total direction changes of the waterway stretch in the study area is about 2 degrees. The length of the study area is 2300 m, and its width is about 650 m. The changes the bridge team has to make to follow the waterway layout are therefore assumed to be negligible, and all changes visible in the trajectory are attributed to the external conditions. The traffic in the Maasgeul channel (see Figure 5.1) splits into Nieuwe Waterweg and Calandkanaal, which are physically separated by a slightly bent mole, named the Splitsingsdam.

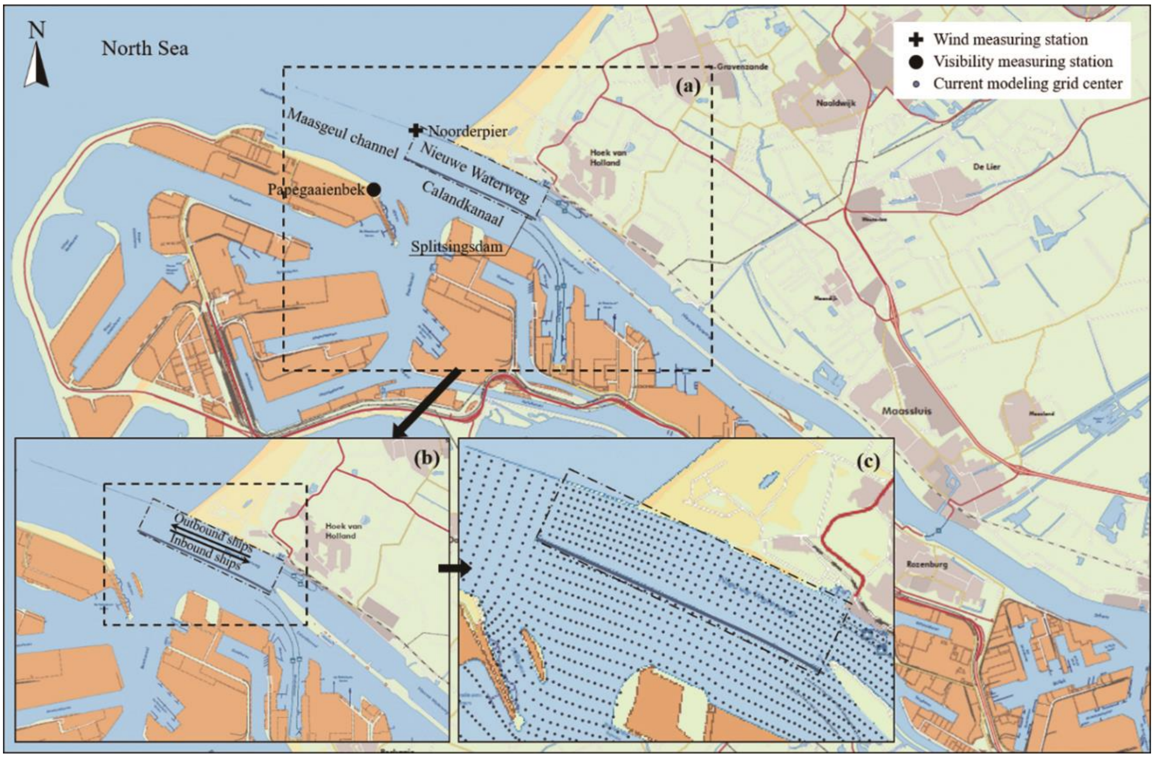

Figure 5.1. (a) Location of the study area in the port of Rotterdam with the meteorological data measuring stations; (b) Zoom-in view of the study area with the sailing direction of the ships; (c) Zoom-in view of the hydrological data modeling grid map in the study area.

5.2.2 AIS data

In this research, AIS data is used to describe the ship behavior under different external conditions. The Automatic Identification System is an automated tracking system onboard ships to automatically transmit information about the ship to other ships and coastal authorities. In 2000, the International Maritime Organization (IMO) issued an amendment adopting a new requirement regarding the introduction of AIS system in the International Convention for the Safety of Life at Sea (International Maritime Organization, 1974). By the end of 2004, the AIS system was mandatory for all ships of 300 Gross Tonnage (GT) and more engaged on international voyages, cargo ships of 500 GT and more not engaged in international voyages and all passenger ships irrespective of size. Inland ships, both commercial and recreational, and sailing vessels longer than 20 meters are mandatory to use AIS since December 1st 2014 according to the resolution by Central Commission for the Navigation of the Rhine (2013). The resolution applies to most of the inland vessels in the Netherlands. In the study area, all seagoing ships including the ships below the GT limit of IMO regulation have installed AIS equipment and used it all the time as required by the local port authority. Since the year 2014 is a transition period, the majority of the collected AIS data of 2014 in the study area are seagoing ships. The collected AIS data in the study area contain 415,121 messages (inbound 4300 ship trajectories by 215,926 messages, outbound 4732 ship trajectories by 199,195 messages). However, the exact number of missed inland ship trajectories in AIS data can hardly be estimated. There could be some inland ships without AIS equipment sailing in the area without record in the data, which may affect the analyzed ship behavior. The focus of this analysis remains to be seagoing ships recorded in the collected AIS data. One of the possible reasons that the data set contains less AIS messages for outbound ships, while there are more outbound ships is the different reporting interval of ships at different speed. Part of the outbound ships will take a left turn directing to Calandkanaal, and the speed will be low with longer reporting intervals and thus less AIS messages compared to other ships.

According to the guidelines by International Maritime Organization (2003), the AIS data contain three types of information: (1) static information (Maritime Mobile Service Identity number, IMO number, ship name, radio call sign, ship type, overall length, beam, etc.); (2) dynamic information (UTC time, ship position, speed over ground (SOG), course over ground (COG), heading, navigational status, etc.); and (3) voyage-related information (draught, destination, etc.).

The collected data set in text file has been processed from the original messages by an institute authorized by the local port authority. The data processing includes the data formatting and the combination of AIS data, radar data and the ship information in the system of IVS (Informatie Verwerkend Systeem in Dutch, Information Processing System in English). The document of data processing between the institute and the port of Rotterdam is not released in public. Thus, no reference can be cited due to confidentiality agreement. The format of the collected data after the official processing are listed in Table 5.1.

Table 5.1. Fields and format of the collected AIS data set processed by the authorized institute.

Field	Format/Unit	Range	Remarks
UTC-time	string with format ‘dd-mm-yyyy hh:mm:ss’	-	
sensor type	-	Radar only, AIS only, Combined	
AIS IMO number	string	arbitrary number of digits	Sensor type ≠ ‘R’
AIS MMSI number	string with 9 digits	000000000~999999999	Sensor type ≠ ‘R’
AIS vessel type	string	arbitrary number of printable characters	Sensor type ≠ ‘R’
AIS length	decimeter	0~10000	Sensor type ≠ ‘R’
AIS beam	decimeter	0~10000	Sensor type ≠ ‘R’
AIS x-position	meter (Rijksdriehoek)	-14000~113999	Sensor type ≠ ‘R’
AIS y-position	meter (Rijksdriehoek)	381000~508999	Sensor type ≠ ‘R’
AIS COG	degree	0~359	Sensor type ≠ ‘R’
AIS SOG	centimeter/second	-2500~2500	Sensor type ≠ ‘R’
AIS heading	degree	0~359	Sensor type ≠ ‘R’
AIS draught	decimeter	0~1000	Sensor type ≠ ‘R’
AIS nav. status	string	arbitrary number of printable characters	Sensor type ≠ ‘R’
track number	-	1-10000	marked by local authority
length in IVS	decimeter	1-10000	fully identified in IVS
beam in IVS	decimeter	1-10000	fully identified in IVS
draught in IVS	decimeter	1-1000	fully identified in IVS
x-position	meter (Rijksdriehoek)	-14000~113999	
y-position	meter (Rijksdriehoek)	381000~508999	
speed	centimeter/second	-2500~2500	
heading	degree	0~359	

The static information is entered into the AIS system by the equipment provider when the equipment is initially installed or after a major change of the ship structure. According to the study on AIS data reliability by Harati-Mokhtari et al. (2007), MMSI number, ship name and call sign are fully correct for all ships. To ensure the reliability of the ship identity information, for the collected data set, the MMSI number and the IMO number of the ships have been checked with the identification in the system of IVS. Besides, when a ship enters the port, a temporary track number for the voyage is marked by the local authority. Together with this track number, the trajectories are uniquely identified in the data set. However, the information inconsistency problem of vessel type occurs in most of the ships, while the information of length and beam is mostly reliable.

The dynamic information is automatically updated based on the sensor data. In the collected data set, the x-position, y-position and heading values from the sources of Radar and AIS are checked, while COG only derives from AIS data. According to the technical recommendations by International Telecommunication Union (2014), the precision of COG is 0.1 degree, while 1 degree for heading. However, as can be seen from Table 5.1, the precision of both COG and heading is 1 degree in the data set. In this research, for each message, the value of heading is deemed reliable when the data are consistent from the two sources, while the value COG is adopted when the other dynamic information are all consistent. As indicated by the International Telecommunication Union (2014), the reporting interval depends on the ship speed and course alteration. For the ships in the study area with small course changes, the time interval is 6 seconds when speed is larger than 14 knots (7.2 m/s), and 10 seconds for ships at speed lower than the value. The dynamic trajectories of inbound and outbound ships in the study area are illustrated in Figure 5.2. Besides the layout sketch, the buoys in the area are also marked. It can be observed that all ships sail within the boundaries marked by the buoys.

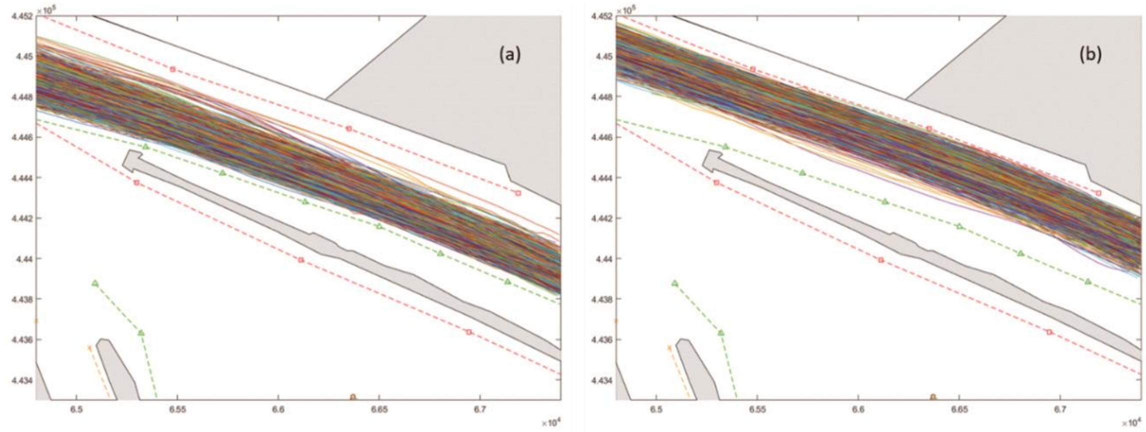

Figure 5.2. (a) AIS trajectories of inbound ships; (b) AIS trajectories of outbound ships.

The voyage-related information should be manually updated to the real-time situation by the officers on board. The actual draught may indicate the loading condition of the ship, which affects the ship's maneuverability. However, in the collected data set, errors are found in the draught information. The draught of most ships in the data set is not updated on each voyage. For some ships, the value of draught equals the molded draught in the registration. Other ships are recorded with a draught of 0 meters or an unreasonable small value in the data set. Bailey et al. (2008) also show that 31% of the investigated messages have obvious errors in draught information. It implies that the data of ship draught are not reliable, thus these are not included in the analyses of this chapter. Reliable ship draught data would have indicated the water depth that a ship is involved in. Since the current direction and speed can be different over the water depth in tidal waterway, the impact of current actually working on ship's hull can be analyzed with the draught information.

5.2.3 Meteorological and hydrological data

To analyze the impacts of wind and current on ship behavior, the wind and current conditions during the sailing of the ships are needed, i.e., the velocity of both wind and current. Thus, the meteorological and hydrological data in the study area are collected.

The meteorological condition refers to wind and visibility. Both are measured at different stations in the study area (see Figure 5.1). The wind velocity is measured at an interval of 5 minutes, while the visibility is measured every minute. In non-extreme weather conditions, there is no sudden change of wind within 5 minutes. Thus, the measuring frequency of the data is sufficient in presenting the external conditions. The wind and visibility can be deemed to be homogeneous for the whole area. In the study area, there are some artificial dunes and the storage tanks for LNG on the south side of the waterway, but without any high-rise buildings on land. Considering the scale and distance to the waterway, it is assumed that there is no impact on the wind and visibility in the area. Thus, the measuring data at a single station represents the wind and visibility conditions in the whole area. The wind direction probability in the study area is visualized by the wind rose diagram in Figure 5.3. It can be observed that the wind direction is changing over the year, which is seldom parallel to the direction of the waterway (WNW/ESE). It means for ships sailing in the study area, besides the wind from the bow or stern direction, there is lateral forces on the ship hull by the crosswind for most of the time, which causes leeway in the observed ship behavior. The complexity of wind conditions is sufficient in the area to analyze the wind impact on ship behavior.

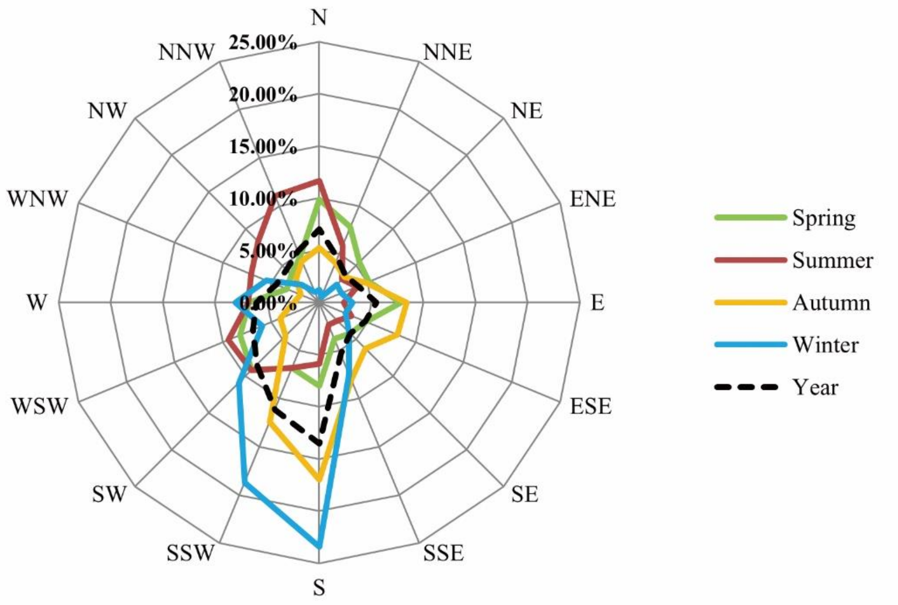

Figure 5.3. Wind rose diagram of the study area.

According to the collected data, the time with visibility distance less than 1000 m holds 0.52% of the year, while the frequency of visibility less than 2000 m is 4.87%. When the visibility is less than 2000 m, specific restriction measures are applied by the local port authority (Port of Rotterdam, 2014), e.g. entry restriction, specific traffic guidance by Vessel Traffic Service center, etc. Thus, the number of ship trajectories in restricted visibility is limited, and the reflected ship behavior involves the effects of local restrictions. We have removed the trajectories of the ships sailing in restricted visibility, as this chapter focuses on the impacts of wind and current. The data of visibility will be used to filter the sailing situation under restricted visibility, i.e. to exclude the impact of visibility on ship behavior (speed) as revealed by other researchers (Shu et al., 2017).

The hydrological condition is represented by the velocity of the current in the waterway. The ship behavior is influenced via the hydrodynamic forces and moments working on the ship's hull under different current conditions. Unlike wind and visibility, the measured current velocity at a specific measuring station is not representative for the whole area, due to the propagation of flow and the velocity variation over the water-depth. Thus, the current velocity field is calculated by the port authority using the SIMONA model (Vollebregt et al., 2003) using the measured water level from eight stations around the port as input. The modeled velocity has been validated by comparing it to the measured velocity at one station in the area. The collected data describe the current velocity in 41×7 orthogonal curvilinear grids with a resolution of about 85 meters (see Figure 5.1). The current velocity in each grid cell is presented by 10 layers with the same depth averaged by the water depth of the grid at an interval of 15 minutes. For most of the ships, the length is larger than 85 meters, so the grid resolution is sufficiently accurate. During each movement of the ships, the current velocity is instantly updated. The current velocity varies among grids and over water depth. The studied waterway links the inland waterway and the sea with natural physical boundaries on both sides (see Figure 5.1), which is a tidal reach. Through the ebb and flood of the tides, the current directions in all grids at different water-depth do not always follow the sailing direction of the ships or the direction of the waterway.

5.3 Research approach

This research uses AIS data to statistically investigate the impact of wind and current on ship behavior via a regression analysis approach. In this section, the behavior variables in the AIS data and the wind and current directions are illustrated in the coordinate system. With an introduction of the underlying assumptions of the research, the data analysis method is explained in steps, including the data preparation and the approach to answer the two research questions proposed in section 5.1.

5.3.1 Behavior variables and their coordinate system

The coordinate system to present dynamic ship motion is shown in Figure 5.4. It consists of the space-fixed coordinate system $o_0 - x_0 y_0$ and the moving ship-fixed coordinate system $o - xy$. Compared to the geographical coordinate system, the x direction points to the true North. The ship heading ψ is defined as the angle between x and x_0 axes.

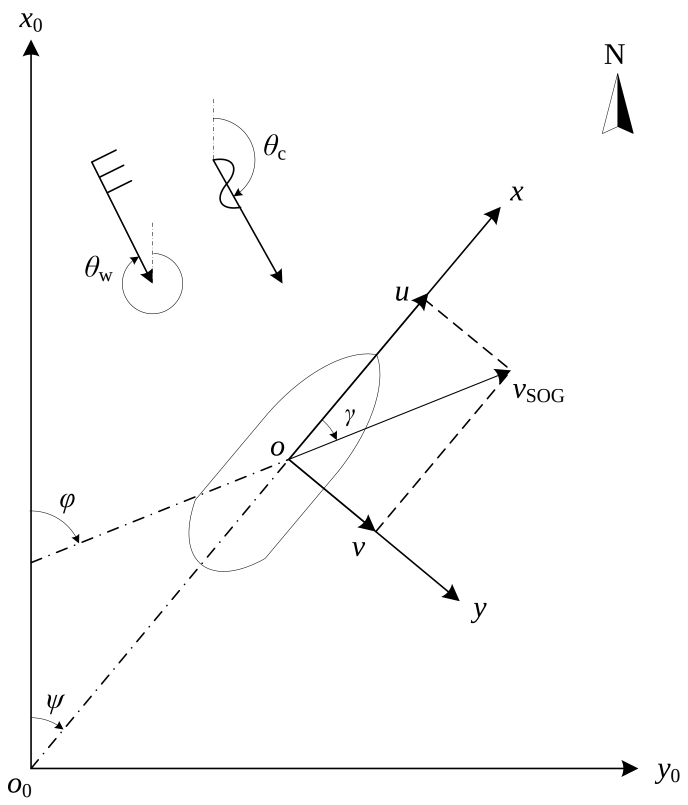

Figure 5.4. Illustration of ship behavior variables and wind and current directions in the coordinate systems (v_{SOG} : speed over ground; φ : course over ground; ψ : heading; γ : leeway and drift angle; u : longitudinal speed; v : lateral speed; θ_w : wind direction in degrees as indicated by the arrow; θ_c : current direction in degrees as indicated by the arrow).

The behavior variables discussed in this chapter are the resulting behavior of all factors (see Figure 5.4), rather than the ship maneuvering variables which are not known (e.g., rudder angle, and engine rate). Among the presented behavior variables, v_{SOG} , ψ and φ are directly collected from AIS data. The difference between ψ and φ is defined as γ , which is the leeway and drift angle indicating the angular deviation due to the external impacts. When the ship moves into the heading direction (i.e., $\varphi = \psi$), γ equals to zero, which can happen in two situations. One situation is that the external conditions do not affect the ship behavior at all. The other situation is that the different external impacts on ship behavior compensate each other, so the sum of directional impacts is zero. This way, the combination of v_{SOG} and γ can present the dynamic motion of a ship during sailing. Similarly, to directly represent the ship motion in longitudinal and lateral directions, the velocity components of v_{SOG} in x and y directions, namely u and v , can be calculated. These two variables in the ship-fixed coordinate system $o-xy$ directly describe the ship motion of surge and sway. During the data analysis, two sets of behavior variables (v_{SOG} , γ and u, v) have been tested. Both sets basically describe the same phenomenon of the ship motion, in which one is described in the space-fixed coordinate system, and the other in the ship-fixed coordinate system. The results are similar, and part of the corresponding results shown in Appendix. Thus, in this chapter, only the results for v_{SOG} and γ , which are derived directly from AIS data, are explained in detail.

Besides the ship behavior variables, the directions of wind and current are illustrated in the coordinate system. According to common practice, the direction of wind θ_w describes which direction the wind is from, while the direction of current θ_c indicates the direction into which the water flows. The visibility is indicated by the visibility distance without specific direction indicated.

5.3.2 Assumptions and generic expression of the wind and current impact

In this chapter, the following assumptions are applied to simplify the process.

- Besides the wind and current impacts analyzed in detail in this chapter, the ship maneuvering in confined waterways and the human factors of the bridge team will affect the ship behavior variables described in Figure 5.4. However, the impacts of human factors are not investigated in this research.

- It is assumed that the waterway layout and sailing direction (approach to or departure from a port) affect the ship behavior. The ships slightly change course to follow the waterway, and the inbound ships decelerate when approaching to the terminal. Thus, the behavior of inbound and outbound ships is separately investigated. However, these two factors are not quantitatively analyzed in this chapter due to a lack of data on individual terminals of departure and destination.

- In unhindered situations, ships of similar size are assumed to maintain similar behavior considering the inertia of ships. The bridge teams onboard ships of similar size are assumed to take similar maneuvering decisions. Under the impacts of wind and current, the resulting behavior of such ships is assumed to be similar. Thus, ship size is the only internal factor to distinguish ships in this chapter, irrespective of the maneuverability differences among individual ships.

- Without an encounter with other ships, the behavior of a ship in good visibility is assumed to be affected by the external factors of wind, current. The bridge teams are expected to take action based on the information of ship size, wind, and current, in line with good seamanship.

When considering the impacts of wind and current on ship speed, the linear combination form has been widely accepted for ship behavior modeling when considering ship as an integral rigid body and using the maneuvering particulars of individual ships (Beschnidt and Gilles, 2005; Yasukawa and Yoshimura, 2015). In their models considering such impacts, the mass or the weights regarding the under- and above- water parts of the hull for individual ships are needed to estimate the wind and current forces on the hull. The method of dead reckoning to estimate ship position is used to calculate the difference between heading and COG as the addition of leeway angle caused by wind and drift angle caused by current (Ni et al., 2010). Combining the above assumptions, a generic expression of speed over ground and leeway and drift angle under the impacts of wind and current can be formed as follows, while the detailed elaboration of each impact is given in section 5.3.3.3.

$$v_{SOG} = f_{SOG,\, size}\left(s_s\right) + f_{SOG,\, wind}\left(v_w, \theta_w, \varphi, s_s\right) + f_{SOG,\, current}\left(v_c, \theta_c, \varphi, s_s\right) + \varepsilon_{SOG} \tag{7.1}$$

$$\gamma = f_{\alpha,\, wind}\left(v_w, \theta_w, v_{SOG}, \psi, s_s\right) + f_{\beta,\, current}\left(v_c, \theta_c, v_{SOG}, \psi, s_s\right) + \varepsilon_{\gamma} \tag{7.2}$$

where s_s denotes the size of a ship, the functions $f_{\text{behavior variable, factor}}$ explain the detailed impact mechanisms of each factor, γ is the sum of the leeway angle α and the drift angle β . ε_{SOG} and ε_{γ} are included in the equations to represent the behavior variation of individual ship due to the bridge team onboard. The bank effects on ship behavior or the proactive deceleration/acceleration when approaching/departing the terminals, are not considered either.

5.3.3 Data analysis method

The flow diagram in Figure 5.5 illustrates the steps of the research approach, which are further explained in this section. The collected data are first processed to generate the data sets of ship behavior analyzed in this chapter. Then, two phases of data analysis are developed to answer the research questions proposed in section 5.1, respectively. The data set of unhindered behavior is used to explain the speed variation of ships due to the size differences. Based on this result, the impacts of wind and current are investigated using the whole data set of ship behavior.

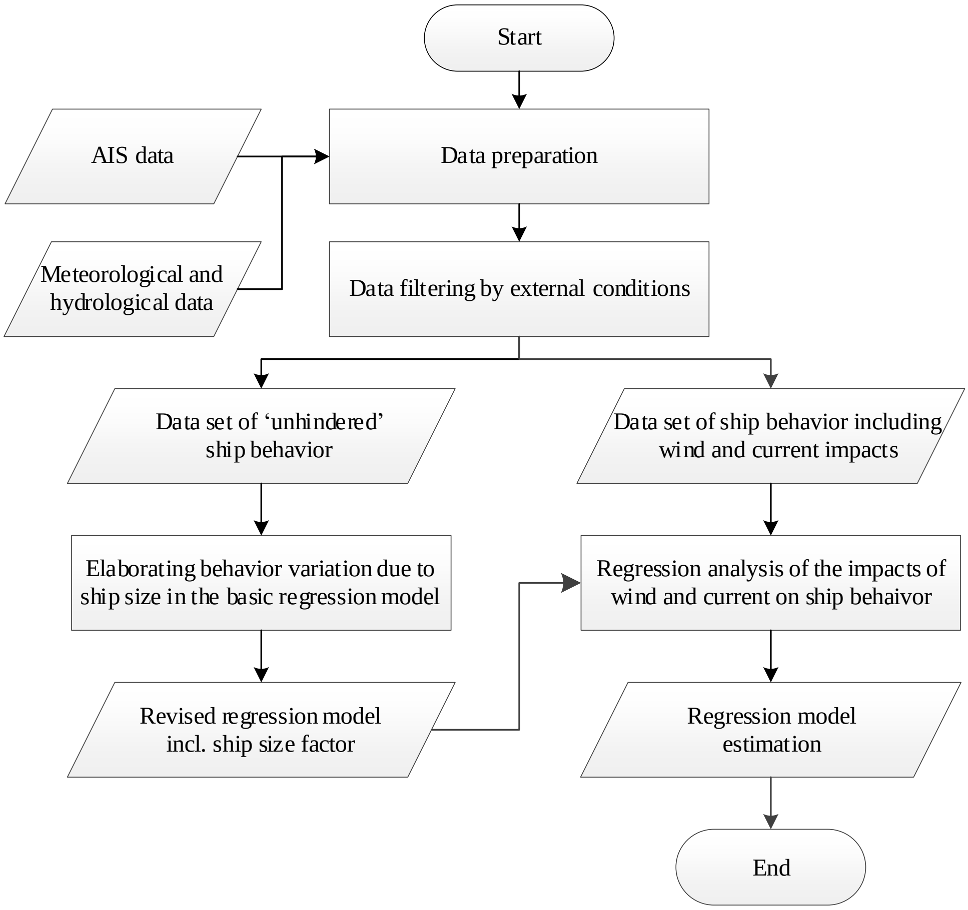

Figure 5.5. Flow diagram of data preparation and data analysis.

5.3.3.1 Data preparation

Since the port authority of Rotterdam only stores the mandatory fields in AIS data, the ship size characterization is limited to length, beam, and draught. However, the information on draught is not reliable since too many errors are found. Thus, in this chapter, only length and beam are adopted as the proxy for ship size.

During the data processing (the first step of the data preparation), the raw AIS data are filtered. This so-called data cleaning is performed using two steps. Firstly, the messages with sensor type marked as radar only are filtered, since there is no AIS information for these ships. The second step is to filter the messages with inconsistent information from Radar and AIS. During this step, the values of dynamic information are checked. The clean AIS data are linked with the meteorological and hydrological data based on the time and ship position in each AIS message. The drift angle γ is calculated for each AIS message. the resulting data set contains ship behavior in all external conditions.

As stated in section 5.1, to focus on the impacts of wind and current, the impacts of visibility and ship encounter should be eliminated. In line with the preliminary analysis result, visibility $\geq$ 2000 m is defined as good visibility to avoid the impact of restricted visibility on ship behavior (Zhou et al., 2017). In order to exclude the impact of ship encounters, the processed data set has filtered the trajectories of ships with any encounter with another ship in the study area. The three types of encounters identified in the International Regulations for Preventing Collisions at Sea (COLREGs) are considered, namely head-on, overtaking, and crossing situations. If more than two ships are involved, the situation is deemed as a combination of several two-ships encounters of the above-mentioned types. The crossing situation can be easily distinguished by the relative position between ships, while the overtaking situation is characterized by the speed differences and position changes in between over time. A head-on situation at sea is defined when one ship is coming towards the other one roughly within 6 degrees on either side of the heading. Considering the length and width of the waterway in the study area, the head-on situation is identified and filtered, when one ship encountering the other from the opposite direction in the study area. So far, the resulting data set includes all ship behavior in good visibility and without any encounter of another ship. The wind and current conditions are not used to filter any ship behavior data.

To further elaborate the behavior variation due to ship size, a data set in the unhindered situation is prepared. The thresholds have been previously analyzed, which characterize the situation by visibility ≥ 2000 m, wind speed < 8 m/s (15.55 knots), and current speed < 0.37 m/s (0.72 knots) (Zhou et al., 2017). However, it should be noticed that the weak impacts of wind and current still exist in such a situation. Thus, when analyzing the impacts of wind and current, the whole data set including both hindered and unhindered situations will be used.

Since the waterway is not exactly straight with parallel banks on both sides, the impacts of the slightly bending waterway layout may affect the ship behavior, as stated in the assumptions. Besides, the sailing direction may influence the speed of a ship in the unhindered situation. Thus, the data set of inbound and outbound ships in the study area is separated and analyzed independently. By comparing the analysis results of these two data sets, it can prove whether the impacts of these two factors can be qualitatively proved.

5.3.3.2 Variation of unhindered speed due to ship size

In respect of the unhindered ship behavior, the speed variations among ships of different sizes have been observed (Shu et al., 2013; Zhou et al., 2019a, 2015). However, the direct relationship between ship size and SOG is still not revealed, which is represented by $f_{SOG,\,size}\left(s_s\right)$ in the generic expression of the impact mechanism. It is expected to find an isolate function to appropriately describe such a relationship using the data set of ship behavior in the unhindered situation. Thus, during the quantitative analysis of the wind and current impacts on ships of different sizes, the unhindered SOG of such different ships can be first estimated. The detailed steps to analyze speed variation due to ship size are present in Figure 5.6.

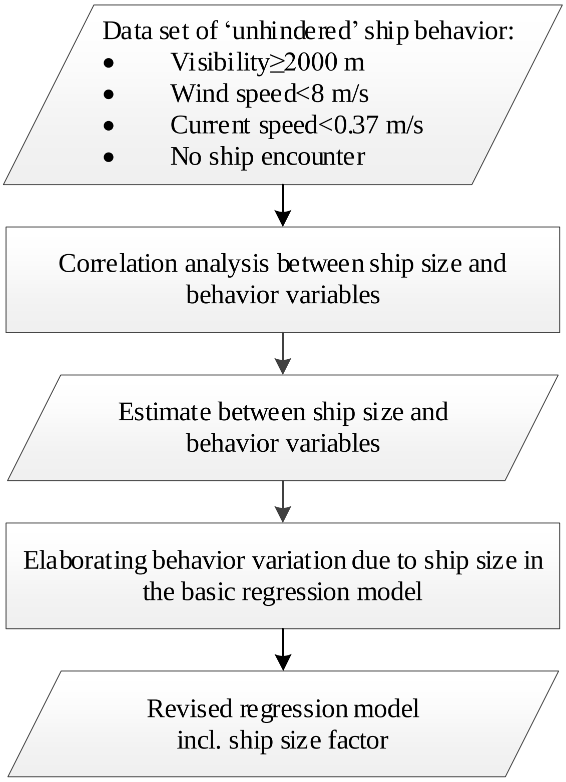

Figure 5.6. Steps to analyze speed variation due to ship size.

Firstly, a correlation analysis between unhindered SOG and ship size (length and beam) is performed. It is to indicate the strength of correlation relationship in between and identify which size criterion better characterizes the ship behavior variation.

Using the selected ship size criterion, the function to estimate the relationship with ship behavior is tested with monotonic elementary function types, which is considering the findings of behavior variation over ship size by Shu et al. (2013). The function type yielding the highest estimate result is adopted to describe the variation of unhindered ship behavior due to ship size. In case of the speed variation that is not monotonic as found in the preliminary analysis (Zhou et al., 2017), a piecewise function will be adopted for ships divided by the size threshold where the variation pattern changes.

The variation of SOG in the unhindered situation due to ship size can be described by $f_{SOG,\,size}(s_s)$ in Equation using the determined function form. In the following section analyzing the wind and current impact, the variation due to ship size will also be considered.

5.3.3.3 Impacts of wind and current

To quantify the impacts of wind and current on different ships, three steps, in general, will be taken as shown in Figure 5.7. Firstly, the functions to describe the mechanism of wind and current impacts in Equation (5.1) and (5.2) need to be determined, which specifies the form of regression models. Secondly, the regression analysis will be performed using the subsets of ship behavior with a similar ship size. The estimated results of all subsets will indicate whether the wind and current impacts vary among different sizes of ships. Finally, the overall functions to describe the wind and current impacts considering the variation pattern over ship size will be specified with coefficients estimated directly using the whole data set of ship behavior. In the following, each step will be elaborated upon.

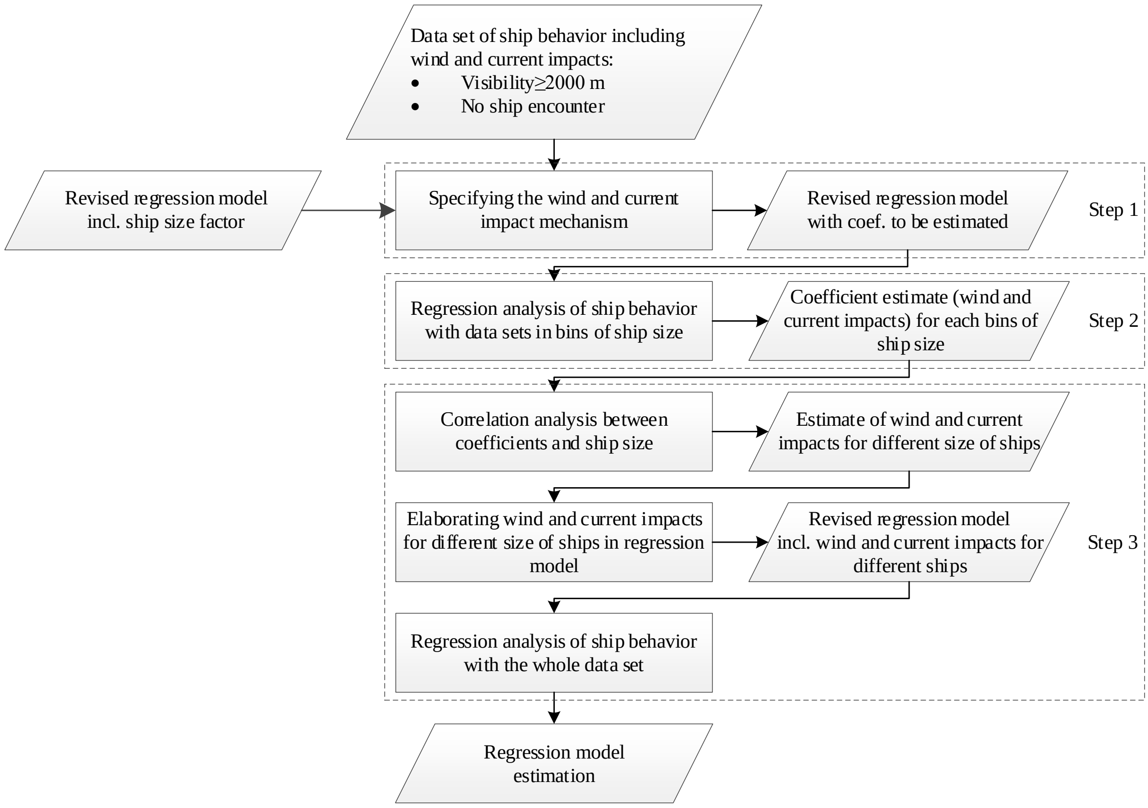

Figure 5.7. Steps to estimate the wind and current impacts.

Step 1: specifying the wind and current impact mechanism

As explained in the generic expression of the impact mechanism, the impacts of wind and current are assumed to be linear. This assumption could be tested by the calculation of hydrodynamic forces and moments working on the ship's hull. However, as the detailed ship particulars of each individual ship cannot be collected from AIS data, the wind and current impact mechanism are expressed using the generic ship size information and the wind and current velocity, as shown in Equation (5.3) and (5.4). Comparing to the estimate using specific information, such generic ship particulars may lead to a less accurate estimate result. But the method can be applied to estimate the ship behavior in a port, where the specific particulars for all visiting ships are unknown.

$$v_{SOG} = c_{SOG,s} \cdot f_{SOG,s}(s_s) + c_{SOG,w} \cdot f_{SOG,w}(s_s) \cdot \left(-v_w \cos(\varphi - \theta_w)\right) + c_{SOG,c} \cdot f_{SOG,c}(s_s) \cdot \left(v_c \cos(\theta_c - \varphi)\right) + c_{SOG} \tag{7.3}$$

$$\gamma = c_{\alpha,w} \cdot f_{\alpha,w}(s_s) \cdot \left(\frac{v_w}{v_{SOG}}\right)^2 \sin(\psi - \theta_w) + c_{\beta,c} \cdot f_{\beta,c}(s_s) \cdot \arcsin\left(\frac{v_c}{v_{SOG}} \sin(\theta_c - \psi)\right) + c_\gamma \tag{7.4}$$

where $f_{SOG,\,s}\left(s_s\right)$ denotes the variation of unhindered speed due to ship size, v_w, v_c and θ_w, θ_c describe the speed and direction of wind and current, the functions $f_{\text{behavior variable, factor}}\left(s_s\right)$ explain the variation of external impacts for different size of ships, the coefficients $c_{\text{behavior variable, factor}}$ will be estimated by the regression analysis. Since not all factors affecting ship behavior have been analyzed in the model, a constant c_{SOG} and c_γ has been added to each model to represent the impacts due to other unexplained factors.

The unhindered speed that a ship maintains when no effects of wind and current, is assumed to be affected by the ship size, which is analyzed in section 5.3.3.2. Regarding the external impact on ship's SOG, it is represented by the projection of wind/current velocity on the direction of v_{SOG} in Equation (5.3). The direction of velocity vector has been considered in the projection calculation.

Based on the theory of dead reckoning to estimate the ship position, the drift angle γ is the sum of the leeway angle α due to the wind and the drift angle β for the current in Equation (5.4) (Bowditch, 2017). The leeway angle is calculated according to the empirical equation for water surface leeway analysis (Richardson, 1997). However, the coefficients are achieved by field experiments for specific physical objects, which can be only applied for specific circumstances. Thus, using AIS data combining the meteorological and hydrological data, the coefficients will be estimated by regression analysis. The obtained results can be applied to predict such impacts on the ship behavior in the area. The drift angle is calculated in the current triangle adopting the law of sines, using the angle between the current direction and heading, current speed, and SOG.

Step 2: estimating the impacts on ship behavior with similar size

In the previous analysis, the impacts on different sizes of ships are observed to be different as well (Zhou et al., 2017). But it is still unknown whether the cause of such differences is occasional fluctuation or due to the relationship with ship size. To answer this question, a quantified analysis is performed for ships in bins, which groups the ships with the same or similar size. The analysis results are compared to identify whether the impacts vary along with the change of ship size.

The whole data set is split into subsets of ship behavior according to the ship size. The variation of unhindered ship behavior due to ship size $f_{SOG,\,s}\left(s_s\right)$ has been revealed in section 5.3.3.1. The regression analysis will be performed based on Equation (5.5) and (5.6) for each subset of ship behavior data.

$$v_{SOG} = c_{SOG,\,s} \cdot f_{SOG,\,s}\left(s_s\right) + c_{SOG,\,w} \cdot \left(-v_w \cos\left(\varphi - \theta_w\right)\right) + c_{SOG,\,c} \cdot \left(v_c \cos\left(\theta_c - \varphi\right)\right) + c_{SOG} \tag{7.5}$$

$$\gamma = c_{\alpha,\,w} \cdot \left(\frac{v_w}{v_{SOG}}\right)^2 \sin(\psi - \theta_w) + c_{\beta,\,c} \cdot \arcsin\left(\frac{v_c}{v_{SOG}} \sin(\theta_c - \psi)\right) + c_\gamma \tag{7.6}$$

Compared to Equations (5.3) and (5.4), the functions to represent impact variation for different ships have been removed, since these models will be applied for ships with the same or similar size. *F*-test and *t*-test are used to determine the significance of the estimated models and the coefficients (a 0.05 significance level is adopted). The models are estimated using standardized scores (Z-scores) to obtain the standardized coefficients. The results of standardized coefficients of wind and current impacts can be compared within each subset. The comparison results present the weights of wind and current impacts on ship behavior for this size of ships.

Step 3: estimating the impacts on ship behavior for ships of different sizes

To identify whether the external impacts change along with the ship size or not, the correlation analysis is performed using the estimated coefficients of wind/current impacts with the average ship size of each bin. If the correlation is significant at the level of 0.01 (p-value), the impact of the external factor on the behavior variable is deemed as related to the ship size. If the correlation is not significant, it implies that the wind/current impact is not strongly correlated to the ship size. It can also be because that the local wind/current speed are quite small, or the ship size range is limited, the correlation in between cannot be revealed based on the data set. The function to estimate the relationship between external impact and ship size should be removed in Equations (5.3) and (5.4). For the impacts significantly correlated to ship size, the function type to describe the variation is determined by selecting the function yielding the highest estimate result.

With the estimated functions $f_{SOG,w}(s_s)$, $f_{SOG,c}(s_s)$, $f_{\alpha,w}(s_s)$, $f_{\beta,c}(s_s)$, the generic regression models of each behavior variable for all ships with different size are determined. The models will be estimated using the whole data set of ship behavior. The final estimated regression model explains the quantitative impacts of wind and current on ship behavior.

5.4 Results and discussions

Since the ship speed is influenced by the proactive maneuvering for approaching/departing a port (i.e., the inbound ships mostly decelerate, while the outbound ships accelerate) and the course is influenced by the waterway layout, the behavior of inbound and outbound ships is independently analyzed. During the process to determine the form of the regression model, the results are similar for both inbound and outbound ships. Only the results for inbound ships are presented and explained in detail. For the estimation of the final regression model, both results will be shown and the reasons for the differences are discussed.

5.4.1 Variation of speed due to ship size

In order to intuitively estimate the relationship between ship size and speed, the speed over ground v_{SOG} in the unhindered situation is visualized as a function of ship size in Figure 5.8. In the boxplot, the distribution of ship speed within each bin is shown. It can be found for the first several groups of small ships and the last couple of large ship groups, the difference between the 25 and 75 percentile is rather small or rather large. This is because the number of ships within such groups are small, which leads to a large variation of the observations due to individual behavior differences. However, by comparing the median value of the bins, the overall variation pattern can be observed. For small ships, the speed increases when the ship size grows to maintain the maneuverability in the narrow waterway. For large ships, the value gradually decreases to a certain stable state when the size becomes larger, since the large ships cannot sail too fast in case of emergent maneuvering with big inertia. Thus, to use a single function describe the variation pattern is not feasible. In the previous sensitivity analysis for qualitative analysis, the threshold to distinguish small or large ships is 150 meters for length and 23 meters for beam, which also holds for the pattern shown in Figure 5.8 (Zhou et al., 2017). It means the length or beam from AIS data can be used to categorize the ships as small or large ones. To further identify which of the ship size (length or beam) best describes the speed over ground, the correlation analysis between unhindered speed and ship size has been performed, as shown in Table 5.2.

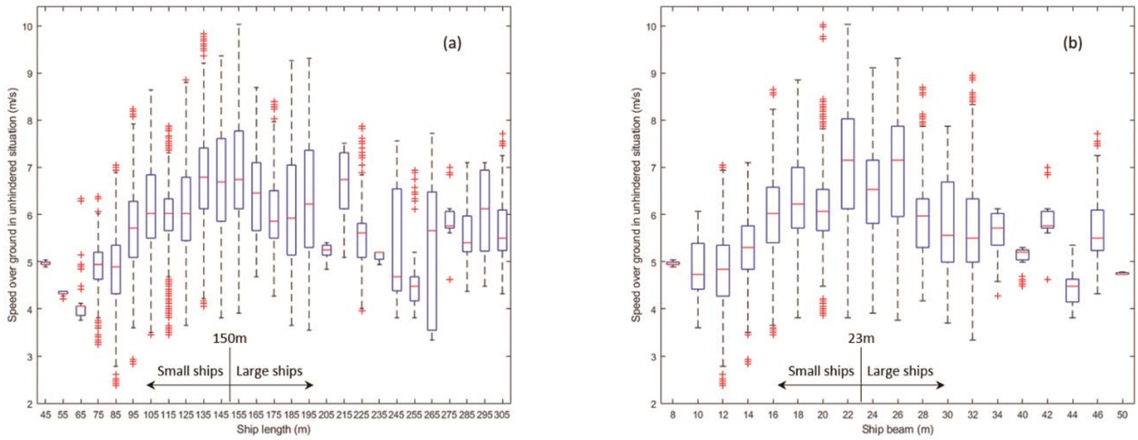

Figure 5.8. Boxplot of speed over ground v_{SOG} in the unhindered situation as a function of ship length (a) and beam (b). (The line in the middle of each bin indicates the median value. The 25 and 75 percentiles of the values form the lower and upper boundaries of the box. The crosses outside the bin represent the statistical outliers.)

Table 5.2. Correlation analysis between unhindered speed over ground and ship size.

Behavior variable	Small ships		Large ships	
	Length (< 150m)	Beam (< 23m)	Length (≥ 150m)	Beam (≥ 23m)
v_{SOG}	0.580	0.660	-0.234	-0.404

** All correlations are significant at the 0.01 level of p-value (2-tailed).

In the data set, the ship length ranges between 24 m and 333 m, while the beam varies between 8 m and 60 m. According to the correlation analysis results, the ship beam is expected to better describe the relationship between v_{SOG} and ship size than ship length. Thus, in the remaining part of this chapter, the beam is selected as the proxy for ship size during the quantitative analysis of wind and current impacts. To estimate the relationship between v_{SOG} and ship beam, four types of monotonic elementary functions have been tested for small and large ships, respectively. The estimated results are presented in Table 5.3. It should be noticed that the low R^2 value of the estimate result is due to ignoring other factors affecting ship behavior. Even in unhindered situations, there is still wind and current influencing ship behavior, and other unexplained factors as well.

Table 5.3. Comparison of estimated results through R^2 between unhindered speed over ground (v_{SOG}) and ship beam.

Type of function	Small ships (Beam < 23m)	Large ships (Beam ≥ 23m)
Linear: $v_{SOG} = c_{SOG,B} \cdot B + c_{SOG}$	0.435	0.163
Logarithmic: $v_{SOG} = c_{SOG,B} \cdot \log(B) + c_{SOG}$	0.437	0.167
Inverse: $v_{SOG} = c_{SOG,B} \cdot B^{-1} + c_{SOG}$	0.427	0.165
Exponential: $v_{SOG} = c_{SOG,B} \cdot \exp(B) + c_{SOG}$	0.423	0.170

* All results are significant at the 0.01 level of p-value.

Ideally, the function $f_{SOG,s}(s_s)$ to explain the relation between SOG and beam adopts the function type yielding the highest estimate result. However, it leads to different types of functions for small and large ships (logarithmic function for small ships and exponential function for large ships), which will result in different forms of the regression model for different ship sizes. The aim of this chapter is to find a generic model form for all ships. Comparing the overall performance of four function types to different ships, the result of logarithmic function ranks the best for small ships and the second-best for large ships. When estimating the behavior for large ships, the difference of R^2 to the best function type (exponential function) is 0.003, which is acceptable. Thus, the logarithmic function is adopted to describe the relationship between v_{SOG} and the ship beam. The function $f_{SOG,s}(s_s)$ is included as $\log(B)$ in Equation (5.3).

5.4.2 Quantification of wind and current impacts on ship behavior

In this section, the regression analysis results of wind and current impacts on subsets of ships with similar size are firstly explained. The results quantitatively compare the wind and current impacts on similar ships and prove whether the impacts vary with ship size. Then the analysis results considering the external impact variation among the different sizes of ships are presented.

5.4.2.1 Wind and current impacts on similar-sized ships

The whole data set of ship behavior is split into subsets with the same or similar ship beam. The bin size is mostly set as 1 meter, while for beams smaller than 10 meters or larger than 32 meters, the bin size is set as 5 meters to include sufficient data (more than 30 ships) in each subset.

The regression models in Equations (5.5) and (5.6) for v_{SOG} and γ are estimated for each subset of ship behavior with similar beams. Since the speed of wind is much larger than current in measured values, the estimated unstandardized coefficients are not directly comparable. However, the standardized coefficients are estimated from the standardized regression analysis where the variances of variables are 1. They explain which of wind and current impacts have a greater influence on ship behavior in this multiple regression model. These coefficients of wind and current for the two behavior variables in each subset are presented in Figure 5.9 and Figure 5.10. As an example, similar results for surge and sway speed (u and v) are shown in Appendix.

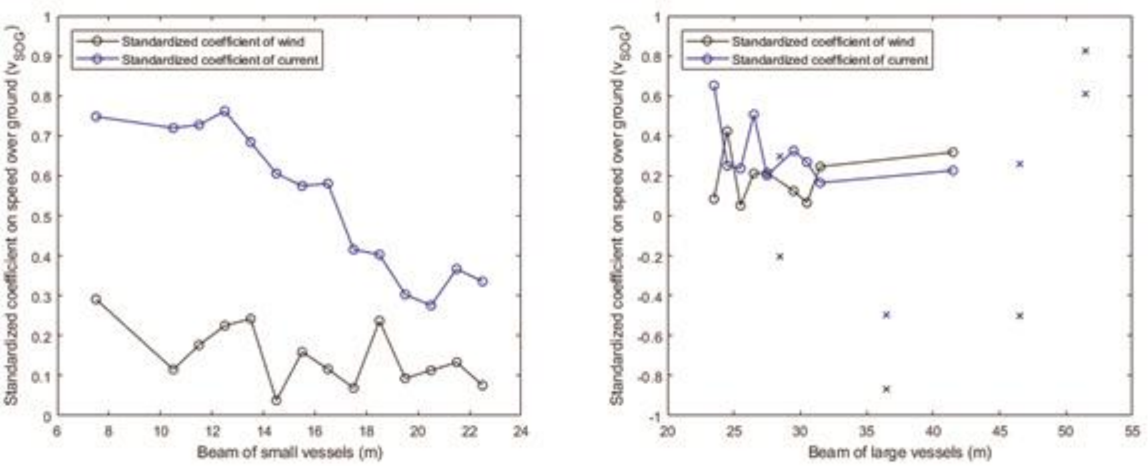

Figure 5.9. Standardized coefficients of wind and current impact on speed over ground $c_{SOG,\,w}$ (in black) and $c_{SOG,\,c}$ (in blue) as a function of ship beam (The subsets containing less than 30 trajectories are marked as crosses in the right figure).

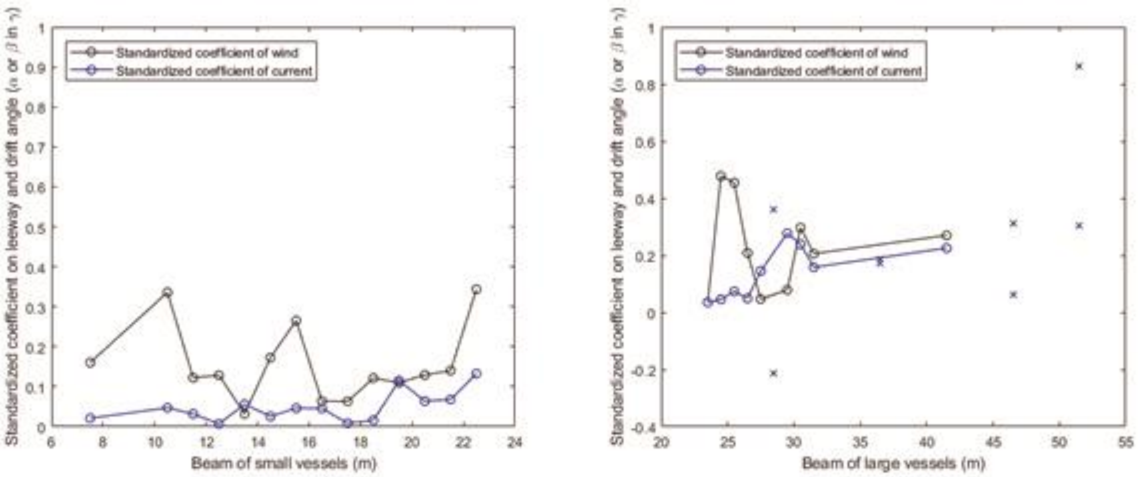

Figure 5.10. Standardized coefficients of wind and current impact on leeway angle α and drift angle β, $c_{\alpha,\,w}$ (in black) and $c_{\beta,\,c}$ (in blue) as a function of ship beam (The subsets containing less than 30 trajectories are marked as crosses in the right figure).

Two comparisons are taken to interpret the estimated standardized coefficients. When looking at the standardized coefficients for similar size within the same subset, the weights of wind and current impacts can be compared. For small ships, the impact of current on v_{SOG} is dominant, compared to the impact of wind. But for large ships, the impact differences are becoming smaller. The speed of a ship is mainly provided by the propeller, which is underwater and affected by the current. For large ships with high superstructures, the wind area is also large. The wind impact may outweigh the current, while the difference is small. However, for the impact on leeway and drift angle α and β , the impact of wind is mostly larger than current. It means, in the port area, when the officers onboard change heading to prepare leeway and drift angle, the wind direction would be the primary factor for their decision. For large ships, the wind and current impacts are comparable, probably due to the large draught underwater.

The other comparison is between the coefficients for different groups of ships, which indicates the variation of the external impacts among ships of different sizes. It can be observed that for small ships, both impacts of wind and current on SOG decrease when the ships get larger. For small ships, the smaller size usually comes with smaller inertia to maneuver in emergent circumstances. Thus, those ships do not consume extra fuel to compensate the influences of wind and current. But the larger ships in this group need to keep their speed either for basic maneuvering requirements or for emergent maneuvering. However, both impacts on the drift angle slightly increase with the increase of ship size, which is due to the larger wind and current forces on ship hull and propeller. For large ships, the variation of wind and current impacts are not always the same. When the ships get larger, the impact of wind on SOG gradually increases, but the impact on the leeway angle fluctuates with a decrease. Because for very large ships, the wind forces on superstructures are large. Once the maneuvering requirement can be fulfilled, the ships will not spend extra effort (consumption of more fuel) to compensate such impact on speed. But for leeway angle, such large ships need to avoid collision with banks under the wind forces. Thus, the resulting impact on behavior seems smaller. Meanwhile, for the impact of current, the opposite relationship is presented. The impact of current on SOG for larger ships is smaller, and the impact on the drift angle is larger. The reasons are the same as for the impact of current on the group of small ships.

The regression analysis test on ship behavior with similar size proves the external impact variation, which is in line with the preliminary qualitative analysis result and follows our expectation (Zhou et al., 2017). The detailed quantification of such variation along with the size change will be determined by statistical analysis in the following section.

5.4.2.2 Wind and current impacts considering ship size variation

To figure out the impact factors significantly varied among different sizes of ships, the relationship between the unstandardized coefficients for wind/current impact and ship beam are statistically tested by correlation analysis. The correlation coefficients are listed in Table 5.4. The p-value of 0.01 is taken as the threshold of significant correlation. The positive values indicate positive correlations in between, while the negative coefficient refers to the negative correlation.

Table 5.4. Correlation analysis between unstandardized wind/current impact coefficients for v_{SOG}, α, β and ship beam for inbound ships.

	$c_{SOG, w}$	$c_{SOG, c}$	$c_{\alpha, w}$	$c_{\beta, c}$
Small ships	-0.529	-0.934**	0.326	0.729**
Large ships	0.317	-0.819**	-0.184	0.377

**: Correlation is significant at the 0.01 level of p-value.

From the statistical test perspective, for all behavior variables of both small and large ships, the impact of wind varies without a strong correlation with ship size. Such variation can be caused by behavior differences among individual officers on board or other unexplained factors. This way, the corresponding functions in the regression model to indicate such correlation are removed from models in Equation (5.3) and (5.4), including $f_{SOG, w}(s_s)$, $f_{\alpha, w}(s_s)$. However, for the impacts of current, the coefficients are significantly correlated to the ship's size, except for the impact on the drift angle for large ships. Therefore, the functions presenting the relationship $f_{SOG, c}(s_s)$, $f_{\beta, c}(s_s)$ need to be elaborated to quantify such impact differences. For the three significant correlations, the same four types of monotonic elementary functions have been tested for each coefficient, as presented in Table 5.5.

Table 5.5. Comparison of estimate results R^2 for different functions between unstandardized wind/current coefficients and beam for inbound ships.

Type of function	Beam < 23m		Beam ≥ 23m
	$c_{SOG, c}$	$c_{\beta, c}$	$c_{SOG, c}$
Linear	0.873**	0.531**	0.672**
Logarithmic	0.858**	0.491**	0.684**
Inverse	0.792**	0.432*	0.688**
Exponential	0.845**	0.363*	0.685**

**: The result is significant at the 0.01 level of p-value. The function yielding the highest estimate result is marked as grey.
*: The result is significant at the 0.05 level of p-value.

The ideal situation is to adopt a generic function form for all ships, the same as the function to describe the variation of speed due to ship size. However, the correlation between the current impact on drift angle and the size of large ships is not significant, while the one for small ships is significant (see Table 5.4). It leads to different forms of functions for small and large ships. Thus, the functions best describing the relationship are adopted in the regression models to consider the impact variation due to ship size. The corresponding functions in Equation (5.3) and (5.4) are elaborated for small ships and large ships, respectively, as follows. In the linear functions, two coefficients need to be estimated.

For small ships (ship beam <23m),

$$f_{SOG,\,c,\,s}\left(s_s\right)=c_{SOG,\,c,\,s1}\cdot B+c_{SOG,\,c,\,s2} \tag{7.7}$$

$$f_{\beta,\,c,\,s}\left(s_s\right)=c_{\beta,\,c,\,s1}\cdot B+c_{\beta,\,c,\,s2} \tag{7.8}$$

For large ships (ship beam ⩾ 23m),

$$f_{SOG,\,c,\,l}\left(s_s\right)=c_{SOG,\,c,\,l}\cdot B^{-1} \tag{7.9}$$

So far, the regression models for v_{SOG} and γ to quantitatively analyze the wind and current impacts are generated for small and large ships. The impact variation among the different sizes of ships is also included. In this chapter, the models are estimated based on the data set of inbound and outbound ship behavior separately. The estimation results of the regression analysis are shown in Table 5.6 and Table 5.7.

Table 5.6. Estimation results of the regression model in final forms for the whole data set of inbound ship behavior.

		R^2	F-stat	Estimate	Std. error	t-stat	Std. estimate
Inbound Beam< 23m	$v_{SOG,s} = c_{SOG,B,s} \cdot \log(B) + c_{SOG,w,s} \cdot \left(-v_w \cos\left(\varphi - \theta_w\right)\right) + \left(c_{SOG,c,s1} \cdot B + c_{SOG,c,s2}\right) \cdot \left(v_c \cos\left(\theta_c - \varphi\right)\right) + c_{SOG,s}$						
	Model	0.743	48099.002				
	$c_{SOG,B,s}$			3.383	0.009	368.112	0.625
	$c_{SOG,w,s}$			0.025	4.58e-04	54.063	0.092
	$c_{SOG,c,s1}$			-0.051	0.001	-42.471	-0.315
	$c_{SOG,c,s2}$			1.833	0.020	92.090	0.683
	$c_{SOG,s}$			-3.825	0.025	-151.407	
	$\gamma_s = c_{\alpha,w,s} \cdot \left(\frac{v_w}{v_{SOG}}\right)^2 \sin(\psi - \theta_w) + \left(c_{\beta,c,s1} \cdot B + c_{\beta,c,s2}\right) \cdot \arcsin\left(\frac{v_c}{v_{SOG}} \sin(\theta_c - \psi)\right) + c_{\gamma,s}$						
	Model	0.288	2860.903				
	$c_{\alpha,w,s}$			0.121	0.003	44.686	0.110
	$c_{\beta,c,s1}$			0.013	0.003	4.817	0.049
	$c_{\beta,c,s2}$			0.631	0.042	15.181	0.153
	$c_{\gamma,s}$			-0.136	0.007	-18.826	
Inbound Beam⩾ 23m	$v_{SOG,l} = c_{SOG,B,l} \cdot \log(B) + c_{SOG,w,l} \cdot \left(-v_w \cos\left(\varphi - \theta_w\right)\right) + \frac{c_{SOG,c,l}}{B} \cdot \left(v_c \cos\left(\theta_c - \varphi\right)\right) + c_{SOG,l}$						
	Model	0.395	3667.836				
	$c_{SOG,B,l}$			-2.832	0.031	-92.419	-0.349
	$c_{SOG,w,l}$			0.012	0.001	10.916	0.041
	$c_{SOG,c,l}$			14.861	0.271	57.742	0.207
	$c_{SOG,l}$			15.393	0.102	150.399	
	$\gamma_l = c_{\alpha,w,l} \cdot \left(\frac{v_w}{v_{SOG}}\right)^2 \sin(\psi - \theta_w) + c_{\beta,c,l} \cdot \arcsin\left(\frac{v_c}{v_{SOG}} \sin(\theta_c - \psi)\right) + c_{\gamma,l}$						
	Model	0.254	2358.404				
	$c_{\alpha,w,l}$			0.121	0.003	37.017	0.149
	$c_{\beta,c,l}$			0.412	0.013	30.914	0.124
	$c_{\gamma,l}$			-0.561	0.008	-69.248	

* The estimated coefficients with different signs compared to outbound ships are marked as grey.

Table 5.7. Estimation results of the regression model in final forms for the whole data set of outbound ship behavior.

		R^2	F-stat	Estimate	Std. error	t-stat	Std. estimate
Outbound Beam< 23m	$v_{SOG,s} = c_{SOG,B,s} \cdot \log(B) + c_{SOG,w,s} \cdot \left(-v_w \cos\left(\varphi - \theta_w\right)\right) + \left(c_{SOG,c,s1} \cdot B + c_{SOG,c,s2}\right) \cdot \left(v_c \cos\left(\theta_c - \varphi\right)\right) + c_{SOG,s}$						
	Model	0.696	33215.208				
	$c_{SOG,B,s}$			2.549	0.009	288.901	0.554
	$c_{SOG,w,s}$			0.033	4.46e-04	74.203	0.142
	$c_{SOG,c,s1}$			-0.032	0.001	-27.083	-0.233
	$c_{SOG,c,s2}$			1.502	0.020	75.423	0.649
	$c_{SOG,s}$			-0.525	0.024	-21.501	
	$\gamma_s = c_{\alpha,w,s} \cdot \left(\frac{v_w}{v_{SOG}}\right)^2 \sin(\psi - \theta_w) + \left(c_{\beta,c,s1} \cdot B + c_{\beta,c,s2}\right) \cdot \arcsin\left(\frac{v_c}{v_{SOG}} \sin(\theta_c - \psi)\right) + c_{\gamma,s}$						
	Model	0.216	1761.709				
	$c_{\alpha,w,s}$			0.173	0.014	12.093	0.132
	$c_{\beta,c,s1}$			0.017	0.008	1.291	0.034
	$c_{\beta,c,s2}$			0.610	0.072	3.017	0.133
	$c_{\gamma,s}$			0.109	0.017	3.989	
Outbound Beam⩾ 23m	$v_{SOG,l} = c_{SOG,B,l} \cdot \log(B) + c_{SOG,w,l} \cdot \left(-v_w \cos\left(\varphi - \theta_w\right)\right) + \frac{c_{SOG,c,l}}{B} \cdot \left(v_c \cos\left(\theta_c - \varphi\right)\right) + c_{SOG,l}$						
	Model	0.440	4629.630				
	$c_{SOG,B,l}$			-2.617	0.027	-95.268	0.207
	$c_{SOG,w,l}$			0.014	0.001	15.166	0.031
	$c_{SOG,c,l}$			16.228	0.247	65.666	0.247
	$c_{SOG,l}$			15.391	0.091	168.242	
	$\gamma_l = c_{\alpha,w,l} \cdot \left(\frac{v_w}{v_{SOG}}\right)^2 \sin(\psi - \theta_w) + c_{\beta,c,l} \cdot \arcsin\left(\frac{v_c}{v_{SOG}} \sin(\theta_c - \psi)\right) + c_{\gamma,l}$						
	Model	0.236	2071.510				
	$c_{\alpha,w,l}$			0.379	0.016	22.953	0.125
	$c_{\beta,c,l}$			0.241	0.050	4.765	0.110
	$c_{\gamma,l}$			0.259	0.026	10.145	

* The estimated coefficients with different signs compared to inbound ships are marked as grey.

According to the regression analysis results, about 70% of the variance in SOG of small ships can be explained by the ship size, wind and current (R^2 is 0.743 for inbound ships and 0.696 for outbound ships). Comparing the standardized coefficients, the choice of SOG in unhindered situation accounts for the major weight of the final sailing speed, which is mostly determined due to the size of a ship. It means the ships only adjust their speed in unhindered situation when there are the impacts of wind and current. Looking at the unstandardized coefficients of unhindered SOG, the estimation results for inbound and outbound ships are different, which indicates the sailing direction also affects the speed choice. The impact of current on SOG of small ships (both inbound and outbound ships) outweighs the wind impact, which is the same when performing the regression analysis for ships in bins with similar size (see Figure 5.9). However, for large ships, the explained variance drops to around 40% (R^2 is 0.395 for inbound ships and 0.440 for outbound ships). Two reasons may explain this result. Firstly, there is a large variation of SOG for large ships in the unhindered situation, even between the ships with similar size (see Figure 5.8). The variance of speed by individual ships cannot be precisely predicted by the generic model. It also holds when comparing the results of inbound and outbound ships, in which the model performs better for outbound ships than inbound ships. When sailing in the study area, most of the outbound ships try to reach their desired speed at sea. However, the inbound ships need to decelerate or keep their speed depending on the distance to their destination terminal, which is different for individual ships. Thus, there is more variation in the choice of speed for inbound ships. The other reason is that the detailed impacts of wind and current on the speed of large ships need to consider the specific above- and under-water ship hull, which is hard to achieve for ships in an area.

Compared to the explanation of SOG, the wind and current impacts only account for 25% of the variance in leeway and drift angle, which seems that the relationship between external factors and the drift angle is not very strong. The standardized coefficients also indicate similar results. According to the ordinary practice of seamen, the set of leeway and drift angle is based on the surrounding sailing situation, including wind, current and waterway layout. However, the instant decision differs among individual officers onboard, considering their sailing habit and experience. In the same situation, some officers may take several degrees of drift angle, but the other officers may keep sailing without heading change. Even with the same wheel order, the observed results of leeway and drift angle (the difference between heading and COG) still depend on the rate of turn of individual ships. Besides, the precision of both heading and COG are the same as 1 degree in the collected data after the official data processing. It can happen that the values are the same while there exist a small difference in actual situation. Or the leeway and drift angle is calculated where the actual difference is quite small at a precision of 0.1 degree. Therefore, the explanation of the variance in γ is not as good as SOG.

The signs of the coefficients together with the functions in the regression model explain the relationship between behavior variables and the impact of ship size, wind and current. The results prove that the theoretical expression of the impact mechanism and the revealed impact variation over ship size by analyzing the subsets of data are correct, when analyzing the whole data set consisting of ships with different sizes.

Comparing the weights of wind and current impacts by standardized coefficients in Table 5.6 and Table 5.7, the result for the whole data set is similar to the regression analysis using the subsets of inbound ship behavior with the same size (see Figure 5.9 and Figure 5.10), which follows our expectation. Regarding the impacts on SOG, the current impact outweighs the wind. However, the impact of current on drift angle is slightly larger than the wind on leeway angle. For the current impact on small ships, $c_{SOG,c2}$ and $c_{\beta,c2}$

represents the generic impacts, while $c_{SOG,c1}$ and $c_{\beta,c1}$ indicates the variation due to the size differences. Comparing their standardized estimates, the weight of the direct impact of the current itself is larger than the correction regressor for ship size.

The constant in the model of SOG plays a dual role. On the one hand, it corrects the unhindered speed due to ship size. Besides, it includes the other impacts of unexplained external factors. Regarding the constant for γ, it is expected to be zero in an ideal sailing situation without wind and current when sailing in the straight waterway. However, the estimated results are with different signs for inbound and outbound ships, which are marked as grey in Figure 5.6 and Figure 5.7. The main reason is that the study area is not exactly straight with parallel banks (see Figure 5.1). For inbound ships, the waterway slightly bends to the starboard side. The negative sign of c_{γ} indicates that the heading of a ship directs to the starboard side comparing to the $o-x$ direction of the ship-fixed coordinate system. It follows good seamanship that a ship will take a series of small-angle alteration to follow the designed route, rather than a sharp turning at the waypoint considering the ship maneuverability. For outbound ships, the positive sign represents the turning direction to the port side to follow the layout of the waterway. It also proves that the leeway and drift angle of a ship in inland waterways is affected by the bank besides the wind and current impacts. The bending direction of the waterway indicates the sign of the coefficient.

The estimated regression model provides a quantification of the wind and current impacts. Some behavior following good seamanship is also statistically revealed by the estimated regression model.

5.5 Conclusions

This chapter proposes a regression model to quantitatively analyze the impact of wind and current on ship behavior (speed over ground and drift angle) derived from AIS data. The variations of ship behavior and the external impacts due to the size differences are also included during the analysis.

The variation of speed over ground in the unhindered situation due to ship size can be observed. The correlation analysis shows that the ship beam is better to indicate the relationship with v_{SOG} than length, which can be described through a logarithmic function.

The wind and current impact on ship behavior also vary for ships of different sizes. For small ships, both wind and current impacts on v_{SOG} decrease when the ships get larger. However, for large ships, the impact of wind on v_{SOG} gradually increases along with growing ship size, but the impact on the leeway angle fluctuates with a decrease. The current impact on v_{SOG} of larger ships is smaller, but the impact on the drift angle is larger. For the coefficients that are significantly correlated to the ship's size by correlation analysis, the functions best estimate the relationship are adopted in the regression models.

According to the regression analysis results using the whole data set of ship behavior consisting of different sizes, about 70% of the variance in v_{SOG} of small ships can be explained by the factors of ship size, wind, and current. The choice of v_{SOG} in unhindered situation accounts for the major weight of the final sailing speed, which is mainly due to the ship size. However, for large ships, the explained variance drops to around 40%, possibly due to the large variation in the unhindered situation and the complex interaction of wind and current forces on ship hull. Compared to v_{SOG}, the wind and current impacts only account for 25% of the variance in leeway and drift angle, which is due to the instant decision differences between individual officers onboard and the maneuverability of individual ships. The results prove that the proposed theoretical expression of the impact mechanism and the revealed impact variation over ship size by analyzing the subsets of data are correct.

The estimated regression model provides the quantitative relationship of wind and current impacts on ship behavior considering ship size variation. Some conventional sailing habits of course alteration to follow the designed route in line with good seamanship are also statistically revealed by the estimate results. The analysis result could benefit both researchers and the port authority. For the researcher, a quantification of the impact mechanism of wind and current helps to further simulate ship behavior in such external conditions. For the port authority, the revealed insight into the relations between ship behavior and external factors will help the ship traffic management under different wind and current conditions and the corresponding risk control in port.

Within this chapter, a nearly straight waterway is studied, which eliminates the impact of the waterway layout on ship behavior. As indicated by the estimated result, a port area with the more complex layout should be analyzed to identify such impact. According to the comparison of inbound and outbound ships, the distance to destination or the sailing direction of approaching or departing from a terminal also affects the speed choice, which can be further investigated. Based on a series of quantitative analyses looking into the relationship between the observed ship behavior and the external factors, a new nautical traffic model can be expected to predict the ship behavior under different conditions.

Appendix

As stated in section 5.3.1, the two sets of behavior variables (v_{SOG}, γ and u, v) basically describe the same phenomenon of the ship motion. To show similar results as an example, the standardized coefficients of wind and current impact on surge and sway speed (u and v) are shown in Figure 5.11 and Figure 5.12. The corresponding results for speed over ground and leeway and drift angle are presented in Figure 5.9 and Figure 5.10 in section 5.4.2.1. It can be observed that the estimated results for these two sets of behavior variables are the same in trend and close in value. Thus, in this chapter, only the results for the variables directly derived from AIS data are explained in detail.

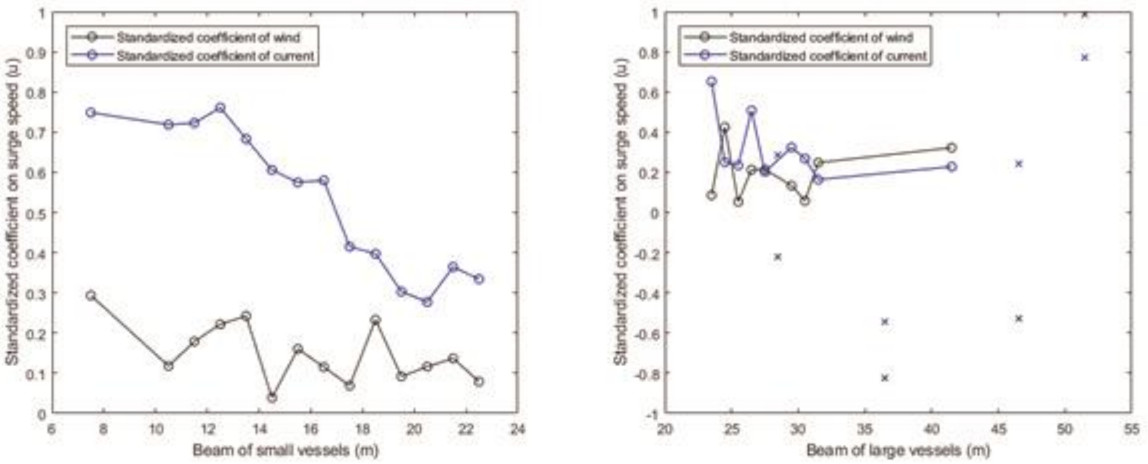

Figure 5.11. Standardized coefficients of wind and current impact on surge speed u (wind in black and current in blue) as a function of ship beam (The subsets containing less than 30 trajectories are marked as crosses in the right figure).

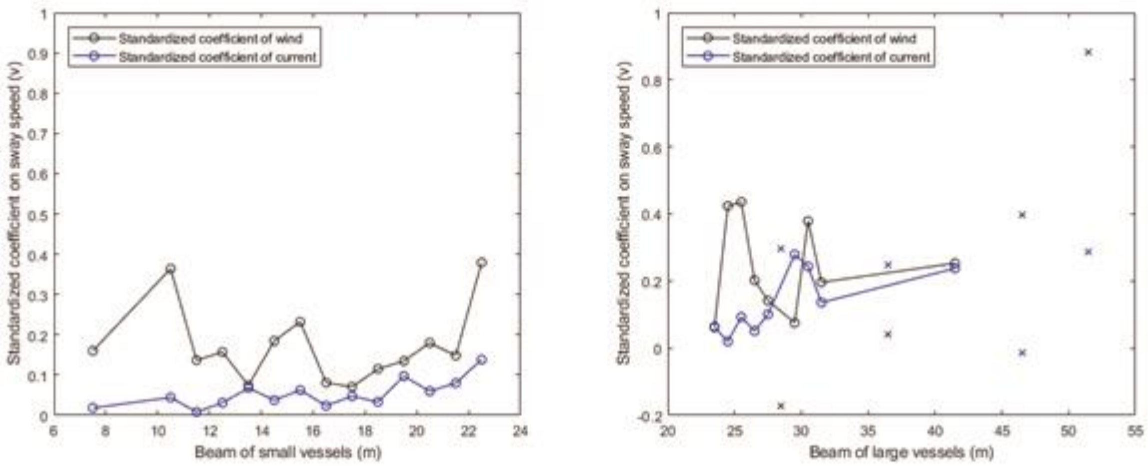

Figure 5.12. Standardized coefficients of wind and current impact on sway speed v (wind in black and current in blue) as a function of ship beam (The subsets containing less than 30 trajectories are marked as crosses in the right figure).

6. Ship Behavior during Encounters

Currently, the research on ship behavior during encounters focuses on the evasive behavior during specific situations with existing risk of collision. However, different methods of collision risk identification and a select of ship behavior in typical situations refine the ship behavior to be as theoretical as requested by international or local rules. To provide an overview of ship behavior during different encounters in ports and waterways, this chapter systematically investigates the ship behavior through phases with other ships, irrespective of the subjective judgment of collision risks.

The proposed approach incorporates four main steps: (1) a direct encounter extraction from the viewpoint of the spatial-temporal co-existence of ships in the same waterway segments during the same time period; (2) calculation of relative movement factors to describe the dynamic process of encounters; (3) behavior change recognition (course alteration and speed change) based on Sliding Window algorithm; (4) investigation of the conditions, timing, and objective of ship behavior through the identified phases of encounters. The findings enrich the knowledge of ship behavior during different types of encounters in real-life navigation, which can be further applied to simulating the ship behavior in ports and waterways.

This chapter is currently under review for journal publication:
Zhou, Y., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. Ship behavior during encounters in ports and waterways based on AIS data: from theoretical definitions to empirical findings. *Ocean Engineering*.

6.1 Introduction

Waterborne transport has become one of the most important freight transportation modes, which takes over 80 percent of the volume of international trade in goods in 2021, with an increase of 4.3 percent to the shock by the COVID-19 pandemic in the year 2020 (United Nations Conference on Trade and Development, 2021). Due to the large amount of cargo carried by individual ships and the complex sailing environment, maritime accidents tend to cause large loss of life and property and damage to the environment and local infrastructure. The navigation safety of ships has therefore attracted much attention from researchers. According to the analysis of global maritime accidents, ship-ship collision and grounding are the major causes (Zhang et al., 2021). The grounding accidents occur due to the insufficient under keel clearance, which is mostly because of the extreme weather or inappropriate sailing behavior of individual ships. However, the reasons for ship-ship collisions can be various, e.g., uncoordinated behavior between the ships, inappropriate timing or magnitude of collision avoidance behavior, etc., Therefore, to avoid ship collision in ports and waterways where the navigable water is confined, it is important to investigate the ship behavior characteristics when encountering other ships.

Due to the limited data of collision accidents, to address ship behavior during encounters, most of the studies focus on the critical encounters, namely near-miss situations. According to the definition by the International Maritime Organization (2008), a near-miss refers to "a sequence of events and/or conditions that could have resulted in loss", which was prevented only by the ship evasive behavior, a fortuitous break in the chain of events and/or conditions. Thus, besides the ship evasive behavior itself, the timing or the conditions triggering the officers on watch (OOW) to take such actions also need to be investigated.

To analyze realistic ship behavior, all approaches use Automatic Identification System (AIS) data as the source, which provides the information of ship's identify, position, speed, course, heading, etc. Generally, there are three main approaches to define an encounter and to analyze the ship evasive behavior, being domain-based approach, indicator-based approach, and process-based approach. (1) The concept of ship domain was initially proposed by Fujii and Tanaka (1971) and Goodwin (1975). It represents an area around a ship that needs to be clear from any other ships. Based on the concept, ship evasive behavior is usually triggered by the intrusion of a ship domain, i.e., an encounter refers to the period when the ship domains overlap. By checking the overlap of a Fuzzy Quaternion ship domain at a certain time interval in strait of Singapore, the local ship collision risk can be assessed (Qu et al., 2011). Szlapczynski et al. (2018) apply the ship domain to determine the last moment for a particular collision avoidance maneuver, with the criterion that ship domain will not be intruded. However, the ship domain only reflects the collective sailing or collision avoidance behavior preferences in the local area, which does not exactly describe the ship evasive behavior and the detailed triggering conditions. To deal with the problem, the ship's first evasive maneuvering action and the perceived collision risk level are incorporated in the concept of ship domain (Du et al., 2021a). However, the judgment of risk level is still subjective to the perception by OOW, which can be biased according to the definition. (2) For the indicator-based approach, the relative bearing, relative distance, relative speed, Distance to Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA) are frequently adopted, which describes the relative movement between the involved ships. Using the intuitive relative motion indicators, Zhang et al. (2015) combine the relative bearing, relative distance and relative bearing based on the ship domain concept to rank the collision risk among encounters, which further applies to detect near-miss situations. Based on the geometric relative motion relationship, DCPA and TCPA are calculated to indicate the distance and time to the closest point of approach if both ships keep their behavior. Ożoga and Montewka (2018) incorporate DCPA and TCPA into a decision support system for individual ships to obtain a safe heading when encountering other ships. Using DCPA and TCPA to extract typical encounter situations, the ship evasive behavior of course change off the coast of Portugal is studied via analyzing the rate of turn adopting sliding window algorithm (Rong et al., 2022). Since the indicator-based approach requires a threshold value to trigger the ship evasive behavior, the selection of encounters depends on the threshold determination by the researchers. (3) Unlike the domain-based and indicator-based approaches analyzing the collision avoidance process at certain time slices, Chen et al. (2018) propose a Time Discrete Non-linear Velocity Obstacle method for individual ship to detect collision candidate, which quantifies the encounter as a process. However, the candidate detection process still incorporates the selection of encounters at a certain risk level.

The above-mentioned studies only focus on the critical encounters with collision risk reflected by certain indicators, while the safe encounters are not investigated. Besides, most of the studies apply their approaches in cases in open waters where ships are free to maneuver during encounter. Thus, course alteration is always the primary evasive behavior in the studies. However, for ships sailing in ports and inland waterways, the space room for course alteration is limited. Especially considering the intention of approaching to or departing from a terminal, and the bank effects, as well as the hydrodynamic interaction effects between ships, the ship behavior during encounters is more complex. Besides, unlike relying on electronic devices, such as radar, to detect collision candidates at long distances, ships sailing in inland waterways mostly rely on the visual navigation of OOW and sometimes pilots on board. The relative distance is much shorter, and the reaction time to take evasive actions as well. Investigating the ship behavior in Port of Rotterdam, Shu et al. (2017) compares the ship behavior during head-on and overtaking situations to unhindered behavior (the ship behavior under the circumstances where the external impacts are eliminated), discovering that both course alteration and speed change play a role during such encounters in confined waterways. In order to simulate the ship behavior during head-on and overtaking situations, Xiao (2014) estimate the approximate distance range of potential impacts from historical AIS data. Therefore, to fully understand the real-life ship behavior (both trajectory and speed) during encounter process in ports and waterways, the behavior of both ships and the potential triggering conditions in the cases with evasive behavior still needs to be studied. The investigation should not be based on a subjective definition of perceived risk level.

The aim of this chapter is *to systematically investigate the ship behavior during the processes of different encounter situations with other ships in ports and waterways*. Starting from the basic geometric classification of encounters, the common scenarios of two-ship encounter in ports and waterways are covered. Without a prepositive selection of encounters with collision risk, this chapter analyzes ship behavior in all situations when ships approach each other from any bearing. From the perspectives of both ships, the influencing factors of ship behavior during the whole process of encounters are theoretically analyzed, while distinguishing different phases in the encounter process. The relative movement between the ships can be quantified by the ship behavior dynamics from historical AIS data. By investigating the features of ship behavior pattern, the timing and magnitude of individual ship behavior change is revealed. The characteristics of relative movement factors at the corresponding time are further analyzed, and the probable underlying reasons as well.

The remainder of this chapter is organized as follows. Section 6.2 explains the definition and classification of encounters by the International Regulations for Preventing Collisions at Sea (COLREGs) (International Maritime Organization, 1972) and qualitatively analyzes the processes of different encounters from the perspectives of both ships. In section 6.3, the research approach from data preprocessing to quantitatively analyzing the ship behavior during encounter processes is elaborated. Section 6.4 introduces the research area and the overview of observed encounters from AIS data, while the detailed analysis results are illustrated in section 6.5. Finally, section 6.6 concludes the chapter with discussion and recommendations for further research.

6.2 Definition, classification, and processes of encounters

In this section, the definition of encounter in this chapter and the classification by COLREGs is introduced in section 6.2.1. Subsequently, section 6.2.2 qualitatively analyzes the processes of different encounters considering the influencing factors from the perspective of both ships.

6.2.1 Definition and classification of encounter situations by COLREGs

COLREGs provide the instructive requirements of ship behavior for collision avoidance when encountering another ship. When there are no special rules defined by the local government or port authority, COLREGs also apply in ports and waterways. However, there is no explicit definition of an encounter in COLREGs. In this chapter, to perceive a full understanding of ship behavior in different situations in ports and waterways, *an encounter is identified when two ships are physically approaching each other from any bearing or when there exists such a possibility of approaching if either or both ships change their behavior*. From the viewpoint of ship trajectories, an encounter happens when two ships sail in the waterway segments during the same time period. The waterway segmentation can be marked by waterway layout change points or navigational infrastructures, such as bridges, waterway intersections, etc. When more than two ships sail in the same waterway, it can be deemed as a series of encounters with consecutive individual ships. In this chapter, we focus on the two-ship encounter situations.

In Section II (Conduct of vessels in sight of one another) of Part B (Steering and Sailing) in COLREGs (International Maritime Organization, 1972), three types of encounter situations are implicitly defined with the instructions of ship behavior for collision avoidance, namely overtaking situation in *Rule 13*, head-on situation in *Rule 14*, and crossing situation in *Rule 15*.

Basically, the three types of encounter situations are geometrically classified according to the approaching bearing of target ship (TS) to the own ship (OS). However, from the clauses, the constitutive elements of these three types of encounter situations are different. For overtaking situation, any OS approaching TS from the sternlight coverage direction of TS leads to such a situation, where OS is the overtaking ship and TS is the one being overtaken. However, for the head-on situation and the crossing situation, they form an encounter only when there is risk of collision involved. Strictly speaking, if there is no risk of collision judged by either OOW, the behavior during the encounter can be different compared to the instructions in the rules. Especially for encounters in bi-directional waterways, there is one more additional rule of behavior instruction for narrow waterways (*Rule 9*) in Section I (Conduct of vessels in any condition of visibility) of Part B in COLREGs (International Maritime Organization, 1972).

Combining the instructions of *Rule 9* and *Rule 14*, in ports and waterways with limited navigable width, it could happen that two ships sailing in opposite directions approach each other without clear course alteration to the starboard side. In this situation, both ships already comply with the instruction of sailing as close to the starboard side boundary as possible. Though they are approaching on reciprocal or nearly reciprocal courses, no risk of collision exists, i.e., it should not be classified as a head-on situation with course alteration required by COLREGs. However, according to the definition of encounters in this chapter, two ships are sailing in the same waterway segment at the same time. Thus, to make a distinction, this type of encounter is defined as a *passing-by situation* in this chapter. Besides, considering the different waterway layout, there possibly exists intersections of waterways in ports. In such area, even if both ships sail along the starboard side boundary of the waterway, when they are approaching from the bearing other than ahead or astern, risk of collision may also exist. Thus, the definition of crossing situation in COLREGs still applies from the geometric point of view in confined waterways. The classification of encounter situations in ports and waterways is presented in Figure 6.1.

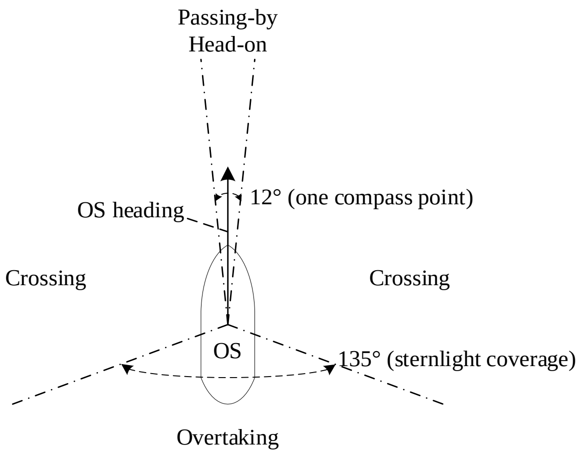

Figure 6.1. Classification of encounter situations in ports and waterways.

6.2.2 Encounter situations in waterways

In this chapter, we analyze the encounters in relatively simple waterways with physical or virtual boundaries on both sides. According to the above-mentioned definitions, when two ships sail to the same direction, their encounter is probably an overtaking situation; when two ships sail to the opposite directions, their encounter is either a passing-by situation or a head-on situation. The encounter processes are qualitatively analyzed considering the influencing factors of ship behavior (speed over ground (SOG) and course over ground (COG)) from the perspectives of both ships in this section.

6.2.2.1 Sailing in the same direction (overtaking)

As defined by COLREGs, any ship (OS) approaching another ship (TS) from a direction and distance of her sternlight coverage (TS), she (OS) is overtaking. As required, the visibility range for ships with length larger than 50 meters is 3 nm (5.6 km). Considering the usual waterway width, any two ships sailing in the same direction with a distance less than 5.6 km in between geometrically forms an overtaking situation. However, considering the speed of both ships, only when the latter ship sails faster than the front one, there exists the physical process of overtaking. When the latter ship is slower than the front one, though the situation is overtaking by definition, the behavior of latter ship is following.

In the full process of an overtaking situation, four phases are defined in this research. Phase 0 refers to both ships sailing without any encounter of other ships. When the ship is approaching another ship in front of it, it enters phase 1, where the latter ship needs to decide whether to overtake or follow the front ship. Once the decision of overtaking is made, both ships could take actions during the encounter in phase 2. After the overtaking ship is finally past and clear as required by COLREGs (International Maritime Organization, 1972), the ships may adjust to their original sailing plan, which is phase 3 (after encounter).

Three types of impact factors are identified throughout the overtaking situations. The environmental impact factors include navigational infrastructures (e.g., waterway layout, Aids to Navigation), wind and current, which continuously influence the ship behavior through the whole voyage. The second type are the intrinsic impact factors of the ships, such as ship size, sailing directions, sailing habit of the OOW, etc. The last group of impact factors intuitively describe the dynamic relative movement between the two ships, referring to the relative speed, distance in between, and relative bearing.

Given the above-mentioned phases of ship behavior during overtaking and the potential influencing factors, the process of an overtaking situation is shown in Figure 6.2. The potential impacts are numbered in the figure and introduced as follows.

Among the environmental factors, the impacts of wind and current on ship behavior (both SOG and COG) (impact (1) in Figure 6.2) in this area have been quantitatively analyzed in previous research (Zhou et al., 2020). In the complex waterway layout, the SOG of ships may change to ensure maneuvering controllability, which can be marked by the navigational infrastructures following the ordinary practice of seamen when sailing in ports and waterways (impact (2)) (Zhou et al., 2022). Meanwhile, the ships also need to adjust their COG to follow the geometry of the waterway (impact (3)). With respect to the ships own factors, the SOG differences among different sizes of ships (impact (4)) have been elaborated (Zhou et al., 2019a), which also presents the SOG differences for inbound and outbound ships (impact (5)). Together with the geometry of waterway layout, the sailing direction of ships (approaching to or departing from the port) determines the possible range of COG of ships (impact (6)). These intrinsic factors impose their impacts on ship behavior from phase 0 when ships sailing alone without any encounter of other ships, and last in all phases throughout the full voyage.

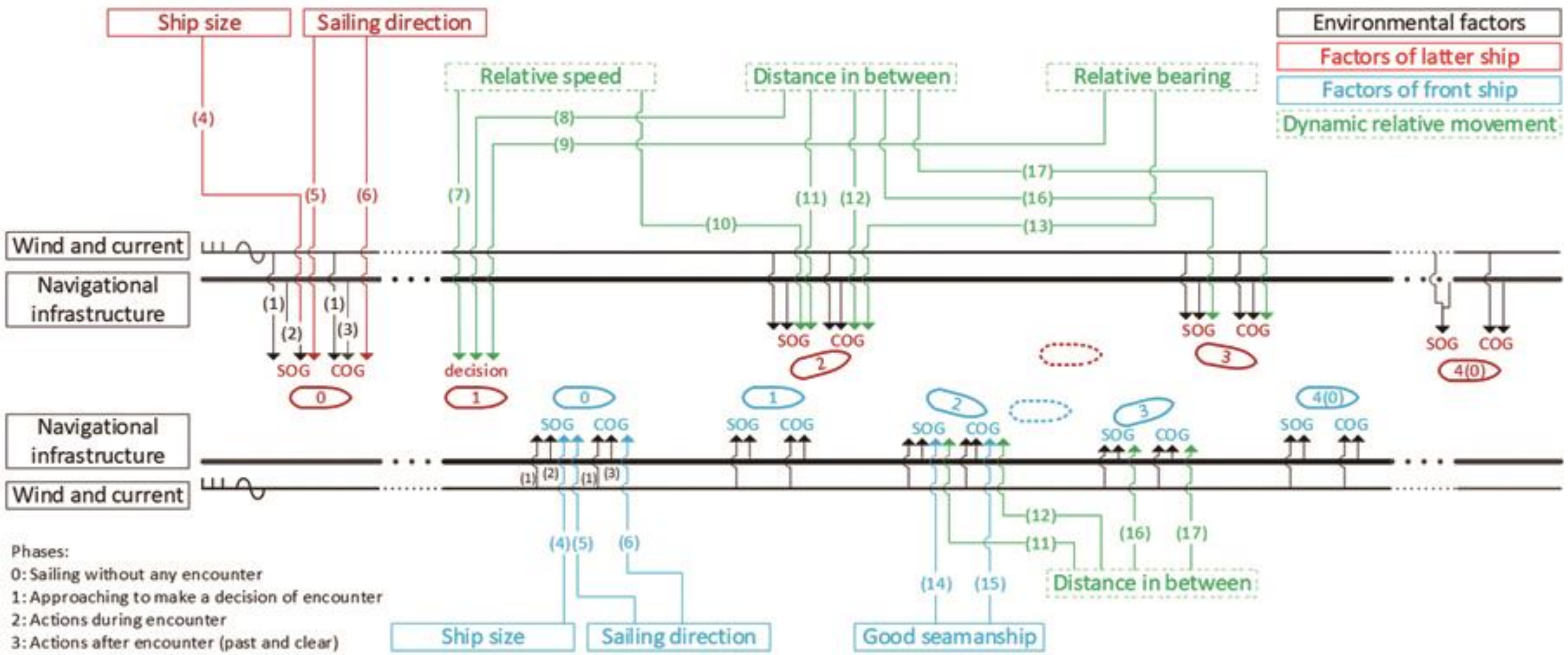

Figure 6.2. Visualization of the impacts on both ship behavior during the overtaking process. The black thick lines refer to the waterway boundaries, while the black fine line refer to the existence of wind and current impacts throughout the voyage. The dashed position marks the moment when the latter ship (in red) overtakes the front one (in blue). The numbers inside both ships correspond to the phases of overtaking situation.

When the latter ship is approaching the front ship, a decision of following or overtaking is needed for the latter one, which is phase 1. The latter ship makes such a decision mainly according to the relative motion to the front ship, namely relative speed, relative bearing, and the distance in between (impacts (7), (8), and (9)). For the OOW, these three relative motion factors can be directly observed or perceived via visual navigation (Zhang et al., 2015).

Once the latter ship starts to overtake, she becomes the give-way ship as stipulated by COLREGs, while the front ship is the stand-on one, i.e., phase 2 in Figure 6.2. Considering the relative speed and the distance in between, the overtaking ship may change her SOG, mostly increase, in order to quickly pass the overtaken ship (impacts (10) and (11)). To guarantee the safety when passing the ship, the overtaking ship may alter her COG to keep lateral distance in between, according to their relative bearing and lateral distance (impacts (12) and (13)). For the overtaken ship in phase 2, as the stand-on ship, she shall keep her course and speed through the process. However, considering the distance in between (impacts (11) and (12)), to ensure a safe and quick overtaking, the overtaken ship may decelerate and/or alter to the other side in a coordinated way owing to the good seamanship (impacts (14) and (15)).

When the overtaking ship is past and clear in phase 3 as required by COLREGs (International Maritime Organization, 1972), both ships may change their SOG and COG back to their intended manner to continue the voyage (impacts (16) and (17)).

6.2.2.2 Sailing to the opposite direction (passing-by and head-on)

As discussed in section 6.2.1, for two ships sailing to the opposite direction, they are approaching on reciprocal or nearly reciprocal courses. Depending on the existence of risk collision, the encounter can be either passing-by or head-on situation.

Similar to the overtaking process, four phases are defined for the encounter of ships sailing to the opposite direction as shown in Figure 6.3. As both ships bear the same responsibility, the behavior of only one ship is explained in detail, which holds for the other ship as well. Phase 0 is when the ship is sailing without encountering other ships ahead from the other direction. Once there is another ship approaching from ahead, it comes to phase 1. According to the judgment by the OOW onboard, if there is no risk of collision, the encounter is a passing-by situation. Both ships keep their course and sail as close to the starboard side boundary of the waterway as is safe and practicable. If there exists risk of collision from the viewpoint of OOW onboard, it is a head-on situation as defined by COLREGs. In such an encounter situation, both ships bear the same responsibility to alter their course to starboard side until being past and clear. Afterwards, the ships adjust their course back to continue their voyage, which is phase 3 after encounter.

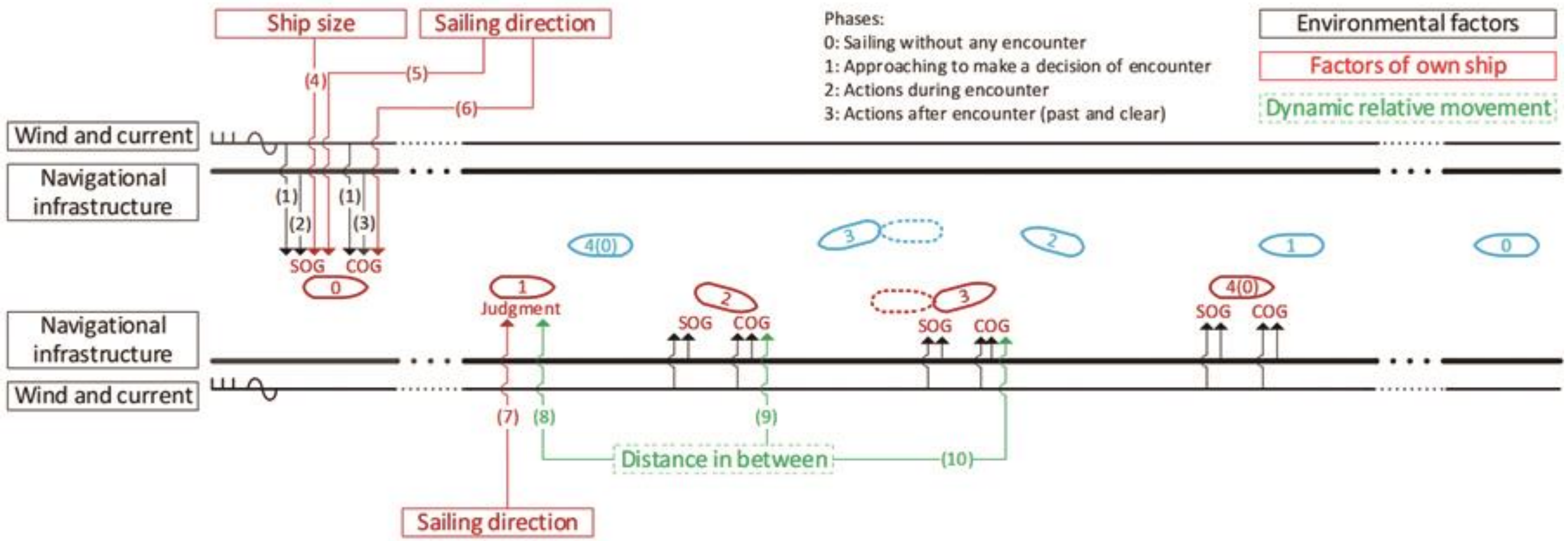

Figure 6.3. Visualization of the impacts on either ship behavior during the head-on process. The black thick lines refer to the waterway boundaries, while the black fine line refer to the existence of wind and current impacts throughout the voyage. Both ships (in red and in blue) bear the same responsibility. The factors marked for the red ship also impact the blue ship. The dashed position marks the moment when the distance between two ships is minimum. The numbers inside both ships correspond to the phases of head-on process.

During the head-on process, according to the qualitative comparison analysis by Shu et al. (2017), no obvious speed change is observed during the encounter. However, for the ships sailing to different directions, the original speed is different, which is the impact (7) in Figure 6.3. The purpose of course alteration is to enlarge the lateral distance. Thus, the dynamic distance in between influences to what extent the ships alter their COG to pass by each other (impacts (9)). When the overtaking ship is past and clear in phase 3, both ships may alter their COG back to their intended manner to continue the voyage (impacts (10)).

6.3 Research approach

The flow diagram in Figure 6.4 illustrates the steps of the research approach, which are further explained in this section. To ensure the data reliability, the AIS data is firstly pre-processed to generate the ship trajectory data set. According to the spatial-temporal characteristics of ships, the trajectory pairs of ships involved in encounters are extracted. The trajectory data of each pair of ship trajectories constituting encounters are used to investigate both the potential triggering conditions of ship behavior change and the ship behavior itself. On the one hand, the factors to describe dynamic relative movement are calculated, for both the ships sailing to the same direction and the ships sailing to the opposite directions. On the other hand, the key feature points of ship behavior change are recognized, which indicate the moment ships take certain actions. Combined with the encounter process discussed in section 6.2.2, the characteristics of relative movement status at the corresponding points are analyzed.

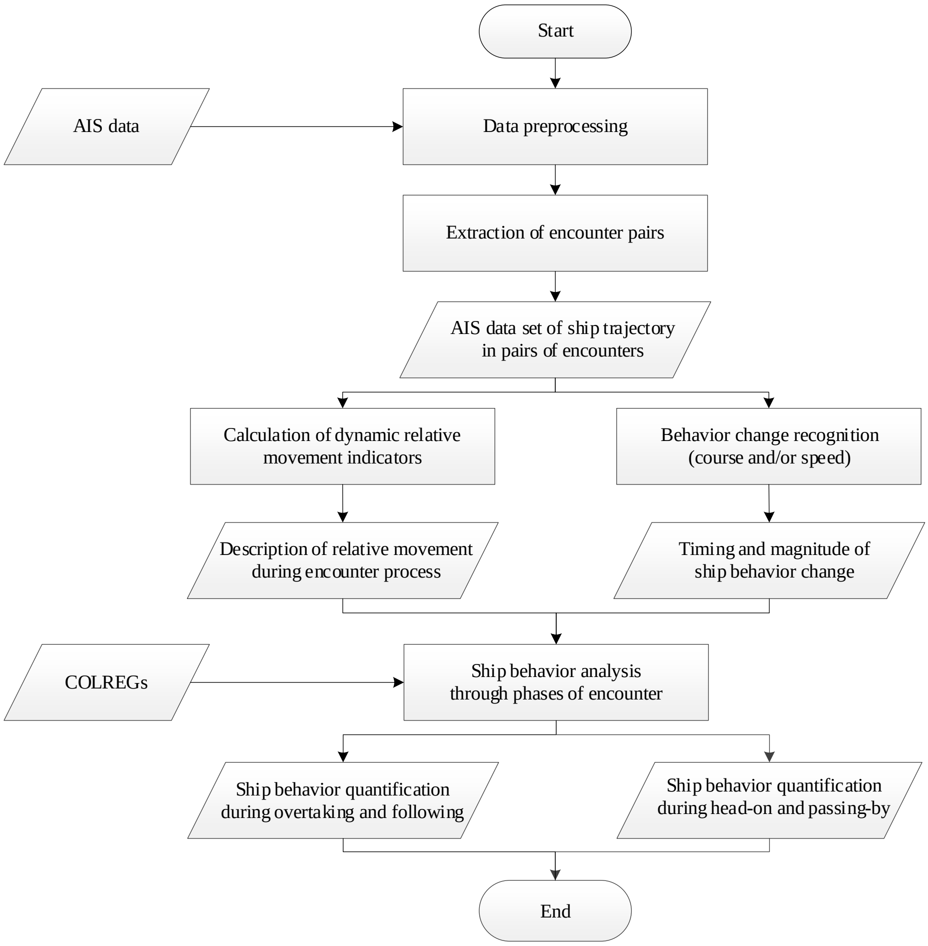

Figure 6.4. Flow diagram of data pre-processing and data analysis. The ship behavior quantification refers to the empirical analysis to acquire the general characteristics of ship behavior pattern during encounters.

6.3.1 Data preprocessing

In this research, AIS data are used to describe the ship behavior. AIS is an automated tracking system onboard ships, which also automatically transmits the information to other nearby ships and the local authorities. Thus, the kinematic information used in this analysis can be fully perceived by the OOW of both ships during their navigation.

According to the guidelines by International Maritime Organization (2003), three categories of information are recorded in AIS data: (1) static information (Maritime Mobile Service Identity number, IMO number, ship name, radio call sign, ship type, overall length, beam, etc.); (2) dynamic information (UTC time, ship position, speed over ground (SOG), course over ground (COG), heading, navigational status, etc.); and (3) voyage-related information (draught, destination, etc.). In this research focusing on ship behavior, the data including SOG, COG, heading, and position are used. Due to the wind and current impacts, there is a leeway and drift angle between COG and heading. COG indicates the direction of SOG, while heading indicates the direction of a ship is truly pointing to, which is also the reference of the moving ship-fixed coordinate system.

As indicated by the International Telecommunication Union (2014), the reporting interval of AIS messages depends on the ship's speed and course alteration. For most trajectories in the ports and waterways, the time interval is 6 seconds, or at least the messages are transmitted at an interval of 10 seconds when the ships sail at a low speed. The frequent reporting messages provide a detailed record of the ship behavior. However, it is inevitable that noise exists in AIS data. The speed and position of ships are processed and updated via the procedure proposed by Qu et al. (2011), which is based on Newton's laws of ship movement. Since the maneuvering actions of ships in inland waterways are slight and frequent, especially the subtle course alterations to control path, heading and COG may fluctuate along the waterway direction, which happens in real-life navigation other than noise in data. Thus, for the data of heading and COG, only the sudden changes of larger than 6 degrees (half campus point) in the adjacent messages are deemed as error to be removed, considering the navigational practice in inland waterways.

Since every single ship reports her AIS messages at her own time intervals, the AIS data by different ships in an area are not always at the same time. To obtain the snapshot of the encounter situations, ship trajectories described by AIS data need to be synchronized at the same time stamp. Considering the reporting interval in inland waterways as introduced above, all AIS data are linearly interpolated at an interval of 10 seconds.

6.3.2 Extraction of encounters

As stated before, in order to investigate the ship behavior during different encounter situations, a broader definition of encounter is adopted in this chapter to include all trajectory pairs of encounters irrespective of collision risks. From the viewpoint of the spatial-temporal co-existence of ships, the trajectory pairs of encounters are extracted if there are two ships sailing in the same waterway segments during the same time period.

Given one waterway segment marked by layout change or navigational infrastructures, ship i enters at t_{arr}^{i} and leaves at t_{dep}^{i}, and ship j enters the waterway segment at t_{arr}^{j} and leaves at t_{dep}^{j}. Ship i and ship j is considered as a pair of encounter candidates satisfying the following criterion

$$\left[t_{arr}^{i}, t_{dep}^{i}\right] \cap \left[t_{arr}^{j}, t_{dep}^{j}\right] \neq \varnothing \tag{6.1}$$

To analyze the full trajectory of ships during encounter, once two ships are identified as a pair of encounter candidates, the whole trajectory of both ships will be extracted from the AIS data set. Comparing the COG of trajectories, the relationship of sailing to the same or opposite directions can be easily identified.

6.3.3 Calculation of dynamic relative movement during encounter process

The coordinate system to present the relative movement of two ships at a time stamp is shown in Figure 6.5. The AIS data provides dynamic information in the space-fixed coordinate system $o_0 - x_0 y_0$, while the relative movement indicators are mostly calculated in the moving OS ship-fixed coordinate system $o - xy$. Compared to the geographical coordinate system, the x direction points to the heading of OS. The ship heading ψ is defined as the angle between x and x_0 axes.

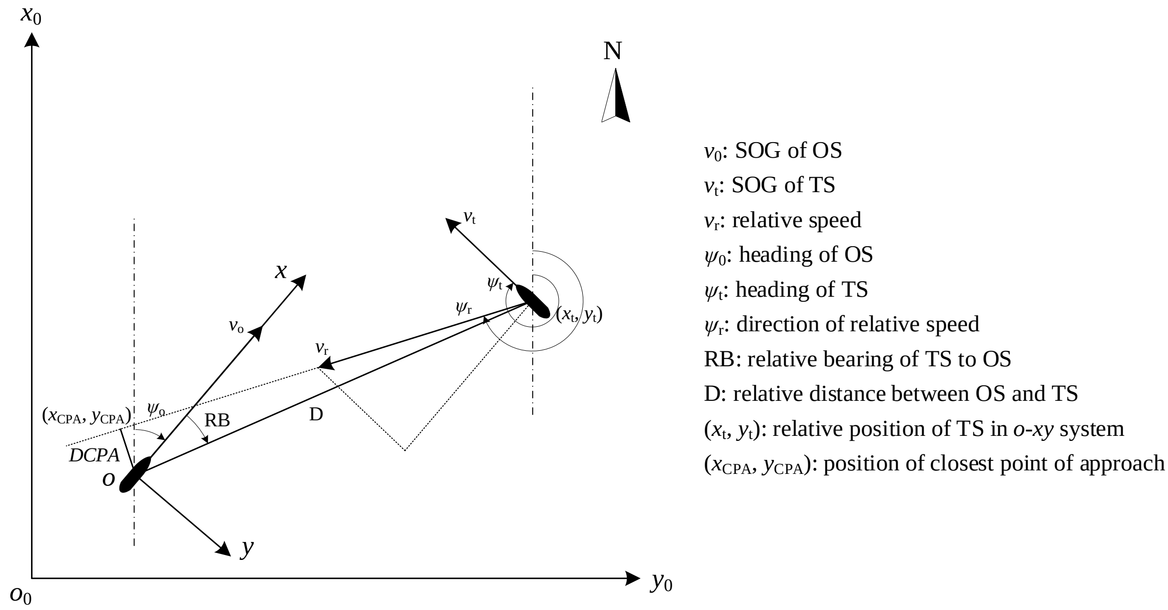

Figure 6.5. Illustration of dynamic relative movement of TS (right) to OS (left) at one time stamp in the coordinate systems from the perspective of OS.

The relative movement indicators should be calculated at each time stamp to describe the relative motion relationship between TS and OS. Using the synchronized AIS data set after preprocessing, the intuitive indicators such as relative distance D, relative bearing RB of TS to OS can be directly calculated in the space-fixed coordinate system $o_0 - x_0 y_0$.

In real-life inland sailing based on visual navigation, the relative bearing, relative distance, and relative speed are the intuitive relative movement factors, which can be observed by the OOW. DCPA and TCPA have been widely used to identify encounters and analyze ship evasive behavior at open sea, which are also claimed to be applicable in inland waterways. To analyze and compare the change of comprehensive relative movement indicators during encounter, DCPA and TCPA are also calculated for each time stamp in the moving ship-fixed coordinate system $o - xy$. Firstly, relative speed v_r and the direction of relative speed ψ_r can be calculated by solving the velocity vector triangle.

$$v_r = \sqrt{v_o^2 + v_t^2 - 2 v_o v_t \cos\left(\psi_t - \psi_o\right)} \tag{6.2}$$

$$\psi_r = \psi_t - \arccos \frac{v_t^2 + v_r^2 - v_0^2}{2 v_t v_r} \tag{6.3}$$

In the OS ship-fixed coordinate system, the relative position of TS (x_t, y_t) can be calculated using the distance and relative bearing calculate above. When drawing a perpendicular line from OS to the relative speed vector passing TS, the foot point denotes the point of Closest Point of Approach (CPA) (x_{CPA}, y_{CPA}). Therefore, DCPA and TCPA can be calculated in the coordinate system.

$$\begin{cases} x_t = D\cos(RB) \\ y_t = D\sin(RB) \end{cases} \tag{6.4}$$

$$\begin{cases} x_{CPA} = \sin(\psi_r - \psi_0)\left(\sin(\psi_r - \psi_0)x_t - \cos(\psi_r - \psi_0)y_t\right) \\ y_{CPA} = \cos(\psi_r - \psi_0)\left(\cos(\psi_r - \psi_0)y_t - \sin(\psi_r - \psi_0)x_t\right) \end{cases} \tag{6.5}$$

$$DCPA = \sqrt{x_{CPA}^2 + y_{CPA}^2} \tag{6.6}$$

$$TCPA = \frac{\sqrt{(x_t - x_{CPA})^2 + (y_t - y_{CPA})^2}}{v_r} \tag{6.7}$$

It should be noted that $TCPA$ is infinity when v_r equals zero. To represent the physical position change during encounter, $TCPA$ becomes negative when TS has passed the CPA point in real-life navigation.

6.3.4 Behavior change recognition

In section 6.2.2, the processes of two-ship encounters have been qualitatively described. From a theoretical perspective, when entering a new phase of any encounter (phase 1, 2, and 3), the OOW of both ships will make a decision and take corresponding actions according to the status of their own ship and relative movements to other ships. At least, the give-way ship in overtaking situation (the latter ship) and both ships bearing the same responsibility in head-on situation shall perform the decision-making process and take evasive actions as requested by COLREGs. To the best of our literature review on ship behavior during encounters or in near-miss situations, the give-way ship will take evasive behavior and the stand-on ship will mostly behave in a coordinated way. The behavior of both ships is reflected by course change and/or speed change. In this section, the algorithm to detect these course and speed changes from ship trajectory data will be introduced, respectively.

6.3.4.1 Course alteration

During the encounters, the purpose of course alteration is usually to enlarge the distance with the other ship when passing each other. In the current studies analyzing near-miss situations in open waters, the course alteration is large and consistent until passing the closest point of approach, presented by COG, heading or ship position (P. Chen et al., 2018; Du et al., 2021b; Goerlandt et al., 2012; Li et al., 2021; Silveira et al., 2013). Besides, the rate of turn in AIS data can even be directly adopted to identify the ship collision avoidance behavior (Rong et al., 2022). However, in the collective comparison of ship behavior during encounters in inland waterways, the course alteration is observed to be subtle with fluctuations (Shu et al., 2017). Additionally considering the external impacts of wind, current, navigational infrastructures, equipment error, and sailing preferences of OOW, the observed COG and heading in AIS data fluctuate along the trajectories, which can hardly be investigated to indicate the behavior change pattern during encounters (Shu et al., 2017; Zhou et al., 2020). Therefore, in this research, the ship trajectory presented by the reporting positions is used to describe the result of course alteration.

If the local rules admit, encounters of ships may occur anywhere in ports and waterways. Considering the intrinsic ship behavior differences when sailing in different waterway stretches under different external conditions, a comparison of ship's trajectory during encounters with the unhindered trajectories is not reasonable to reveal the detailed evasive behavior pattern. As explained in section 6.2, the impacts of intrinsic ship characteristics, navigational infrastructures and environmental factors last throughout the full voyage, which will cause substantial change suddenly. Thus, the course alteration points need to be figured directly from the ship trajectory itself. The sliding window algorithm iteratively compares the ship behavior in adjacent time windows to find out the points describing the key features of the trajectory (Gao and Shi, 2019; Wei et al., 2020; Zhu and Ma, 2021). The algorithm fits the requirements of this research to figure out the timing with course alteration. Such course alteration contributes to the trajectory change represented by ships position, when the trajectory is not smoothly following the waterway direction. During the process of sliding window algorithm, the initial time window (P_1, P_2, P_3) including three points needs to be determined, in which the initial point P_1 is set as the first key feature point to retain. By calculating the Euclidean vertical distance between the middle point P_2 and the line connecting both end points of the window P_1P_3, if it is larger than a threshold value, the middle point is retained, while the next sliding window becomes (P_2, P_3, P_4). If not, P_2 is discarded, and the next sliding window becomes (P_1, P_3, P_4). The iteration is repeated until the Euclidean distance of the last but one point is judged. The last point is always retained as the key feature point.

In this research, the ship behavior pattern during encounters has been theoretically analyzed in phases in section 6.2.2.1. The initial points and threshold value can be determined according to the status of encounter phase, which will be explained in detail in section 6.3.5.

6.3.4.2 Speed change

Currently, most of the studies on key feature points extraction only consider the identification of turning points (course alteration through the voyage). The probable reason is that the research area is open waters, where speed change is less likely to occur. Also, for collision avoidance, course alteration is their primary choice. However, when ships sail in ports and waterways, their engine is always stand-by in case of emergent maneuvering. The speed change is also more frequent than in open waters, for the purpose of approaching to or departing from a terminal, adjusting the safe speed in accordance with the local circumstances, etc.

In ports and waterways, the speed change is achieved by a succession of continuous small changes. Thus, it can be assumed that the acceleration rate for a ship in a certain area follows a Gaussian distribution (Wei et al., 2020). Similar to the principle to recognize the course alteration points, the ship's speed change should be compared to the adjacent time steps. Therefore, the sliding window algorithm is also adopted for the key points recognition of speed change, i.e., a fixed size of sliding window involving three points comparison. Instead of calculating the Euclidean vertical distance representing the lateral position deviation, the acceleration of a ship at the point is assessed. Similarly, the initial and end points are deemed as feature points. The mean acceleration μ_a and standard deviation of acceleration σ_a of the ship during this trajectory are calculated. For a sliding window of ship speed (v_{i-1}, v_i, v_{i+1}), the acceleration rate a_{i-1} and a_i are calculated. When either of the following conditions is met, the point v_i is retained: (1) $sign(a_{i-1}) \cdot sign(a_i) \neq 1$; (2) a_i exceeds a threshold value considering a_{i-1}, μ_a and σ_a. Then the next sliding window becomes (v_i, v_{i+1}, v_{i+2}). If not, the point v_i is discarded, and the next sliding window is $(v_{i-1}, v_{i+1}, v_{i+2})$. The threshold determination of speed change recognition also needs to consider the process of encounter, which will be explained in the next section.

6.3.5 Ship behavior through phases of encounter

In section 6.3.4, the sliding window algorithms to recognize the key feature points of course alteration and speed change have been elaborated. Both algorithms require a reasonable threshold determination. In this section, the adopted method will be explained considering the process of encounters sailing in the same direction and sailing to the opposite directions, respectively.

6.3.5.1 Sailing in the same direction

According to the encounter process in Figure 6.2 and the comparison analysis of ship behavior during overtaking to unhindered behavior (Shu et al., 2017), the behavior of both ships can be expected to be as follows:

- Latter ship (overtaking): (1) alter course to enlarge the lateral distance when passing the front ship, and alter course back to continue her own voyage after overtaking the front ship at a certain distance; (2) accelerate until passing the front ship or after overtaking the front ship for a certain distance, which depends on the specific situation, and decelerate to the intended own speed to continue her voyage.

- Front ship (overtaken): (1) alter course in coordination with the overtaking ship to enlarge the lateral distance, and alter back to continue her own voyage after being overtaken; (2) decelerate in coordination with the overtaking ship, and after being overtaken, accelerate to continue her voyage.

However, if the initial relative speed of the latter ship to the front one is large enough or the lateral distance is already sufficient according to the sailing experience of the OOW, it is possible that the overtaking ship does not take additional evasive actions. The basic responsibility of the overtaken ship is to sail as close to the starboard side boundary as is safe and practicable (*Rule 9*) and keep her course and speed as a stand-on ship (*Rule 13*). The coordinative behavior of course alteration and deceleration depend on the good seamanship of the OOW onboard the overtaken ship, which is not compulsory. Thus, it is possible that the overtaken ship does not take additional actions to change behavior. Under certain circumstances, the overtaken ship could even change her behavior counterintuitive to the overtaking process. For example, when the waterway width becomes narrower ahead, the ship accelerates to maintain her maneuverability in case of strong hydrodynamic forces.

Putting the behavior differences due to the occasional environmental impacts and individual sailing habits of the OOW onboard aside, the possible behavior change pattern of overtaking and overtaken ships are illustrated in Figure 6.6, taking portside overtaking as an example. Considering the overtaken ships sailing as close to the starboard boundary as possible, the portside overtaking occurs more than overtaking at the starboard side of the overtaken ship. The overtaking moment is marked by the time moment of the minimum distance between two ships during the whole process. Besides the initial and end points of trajectory as stated in the sliding window algorithm, the schematic diagram marks the key feature points of their behavior change (course alteration and speed change) during the encounter process. However, in real-life navigation, the behavior change occurs by a succession of small changes smoothly.

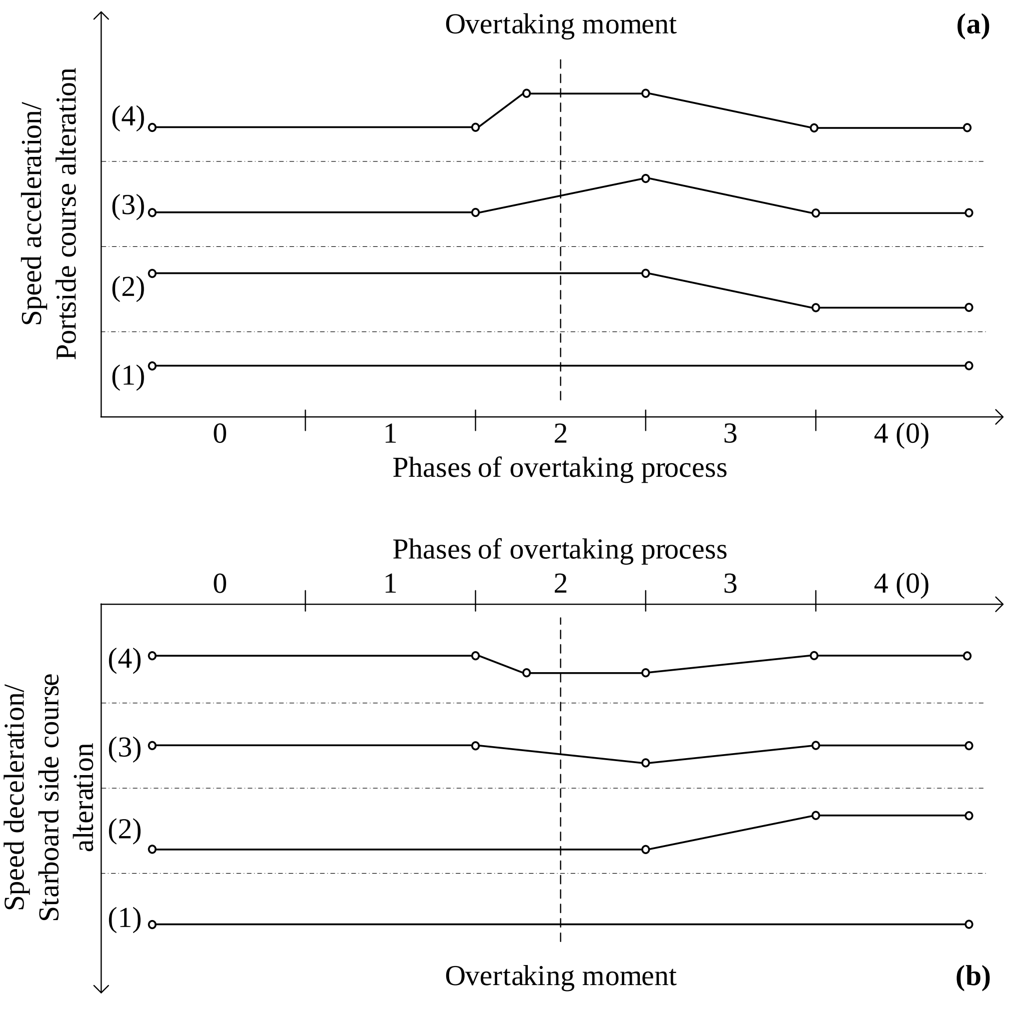

Figure 6.6. Schematic diagram of ship behavior pattern through phases of overtaking process: (a) overtaking ship; (b) overtaken ship. The vertical dashed line refers to the overtaking moment in different patterns.

It should be noted that the patterns only illustrate the possible behavior change in different scenarios, without regard to the individual ship behavior due to any specific circumstances. The patterns of overtaking and overtaken ships do not always happen correspondingly in a single encounter. The encounter scenarios behind the four behavior patterns are explained as follows:

- Pattern (1): The initial speed of the overtaking ship (overtaken ship) is high (low) enough for the purpose of overtaking, so the ship does not change her speed. The lateral distance is sufficient for overtaking from the viewpoint of the OOW, thus the ship does not alter her course.

- Pattern (2): Compared to pattern (1), the speed of overtaking ship (overtaken ship) is too high (low) for her following voyages. Thus, after the overtaking, the overtaking ship (overtaken ship) accelerates (decelerates) for her own sailing purpose. The lateral position of overtaking ship (overtaken ship) is too close to the portside (starboard side) boundary of the waterway, so the ship alters her course to continue the voyage along the waterway.

- Pattern (3): The overtaking ship (overtaken ship) accelerates (decelerates) to facilitate the overtaking process, or the ship alters her course to the other direction to enlarge the lateral distance in between. After the situation being past and clear, the ship returns to her original behavior.

- Pattern (4): Compared to pattern (3), the ship reaches her intended speed or lateral distance before the overtaking moment and keeps the behavior until it is past and clear. Afterwards, the ship returns to her original behavior.

Besides the above-mentioned coordinated behavior patterns during overtaking, intended uncoordinated overtaking processes also may occur. For example, without asking for permission via sound signals, the latter ship proceeds to overtake the ship with a small relative speed. To avoid long-time encounter processes, the front ship accelerates to lengthen the longitudinal distance in between to explicitly terminate the overtaking process.

From the schematic diagram, it can be found that the overtaking moment is critical during the process for behavior analysis. Thus, the overtaking moment is selected as the initial key feature point, instead of the point entering the area. The behavior before and after the overtaking moment is analyzed separately, in which the behavior before overtaking bears more possibility considering the different status of own ship and relative movement. There could exists 2 to 4 key feature points of behavior change, including the entering point and the critical overtaking moment.

As explained in the sliding window algorithm, a smaller threshold will lead to more points recognized as behavior change, in which the behavior fluctuations of individual ship will be also included. A too large threshold will skip the key feature points during the process. To determine the appropriate threshold value, the compression rate has been widely adopted as the criterion for trajectory simplification (Wei et al., 2020; Zhang et al., 2016). Instead, the threshold value leading to reasonable number of key feature points of behavior change will be selected, i.e., 2 to 4 points before overtaking moment.

Once the key feature points of course alteration and speed change are recognized, the characteristics of dynamic status of both ships can be investigated, including the factors listed in Figure 6.2 and the dynamic relative movement factors calculated in section 6.3.3.

6.3.5.2 Sailing to the opposite direction

Regarding the encounter of ships sailing to the opposite direction, both involved ships bear the same responsibility according to *Rule 14* in COLREGs. The behavior of speed change and course alteration during head-on situation is simpler compared to the overtaking situation (Shu et al., 2017). No obvious speed changes are expected during the process for both ships. However, both ships alter their course to the starboard side to ensure a sufficient lateral distance when passing each other. After being past and clear, the ships alter back to continue their original trajectory. The course alteration pattern is similar to pattern (4) in Figure 6.6(b). However, it can be expected that if either or both ships have already followed the instruction by *Rule 9* to sail as close to the starboard side boundary as possible, there will be no further course alterations during the encounter process (see course alteration pattern (1) in Figure 6.6). In such a case, from the viewpoint of the OOW, there is no risk of collision. Thus, the type of encounter is passing-by as defined in section 6.2.1.

Similar to the overtaking situation, the moment with minimum distance in between is selected as the critical moment. Therefore, before the ships physically passing by each other, the expected number of recognized key feature points of course alteration is also 2 to 4. The characteristics of the encounter situation will be investigated accordingly.

6.4 Research area and data description

In this section, the research area is introduced in detail in section 6.4.1, followed by the collected AIS data providing information on ship behavior in section 6.4.2.

6.4.1 Research area

The research area is located at the entrance of the port of Rotterdam, the Netherlands, as shown in Figure 6.7. The Maasgeul channel splits into the Nieuwe Waterweg and the Calandkanaal, which are physically separated by a slightly bent mole, named the Splitsingsdam. For the convenience of ferries and small cargo ships sailing between the Nieuwe Waterweg to the Maasvlakte and the Europoort, there is an interconnecting area in the middle of the Nieuwe Waterweg for shortcut turning. In our preliminary analysis, the unhindered ship behavior and the wind and current impacts are studied in the nearly straight waterway stretch with a physical boundary on both sides, the Nieuwe Waterweg (Zhou et al., 2019a, 2020). Extending the research area from the waterway on both ends to a longer stretch, the waterway layout becomes more complex with richer navigational infrastructures (Aids to Navigation, e.g., buoys). The impact of the navigational infrastructures on ship speed is investigated in (Zhou et al., 2022). The findings in the preliminary analyses are also incorporated in the investigation in this chapter.

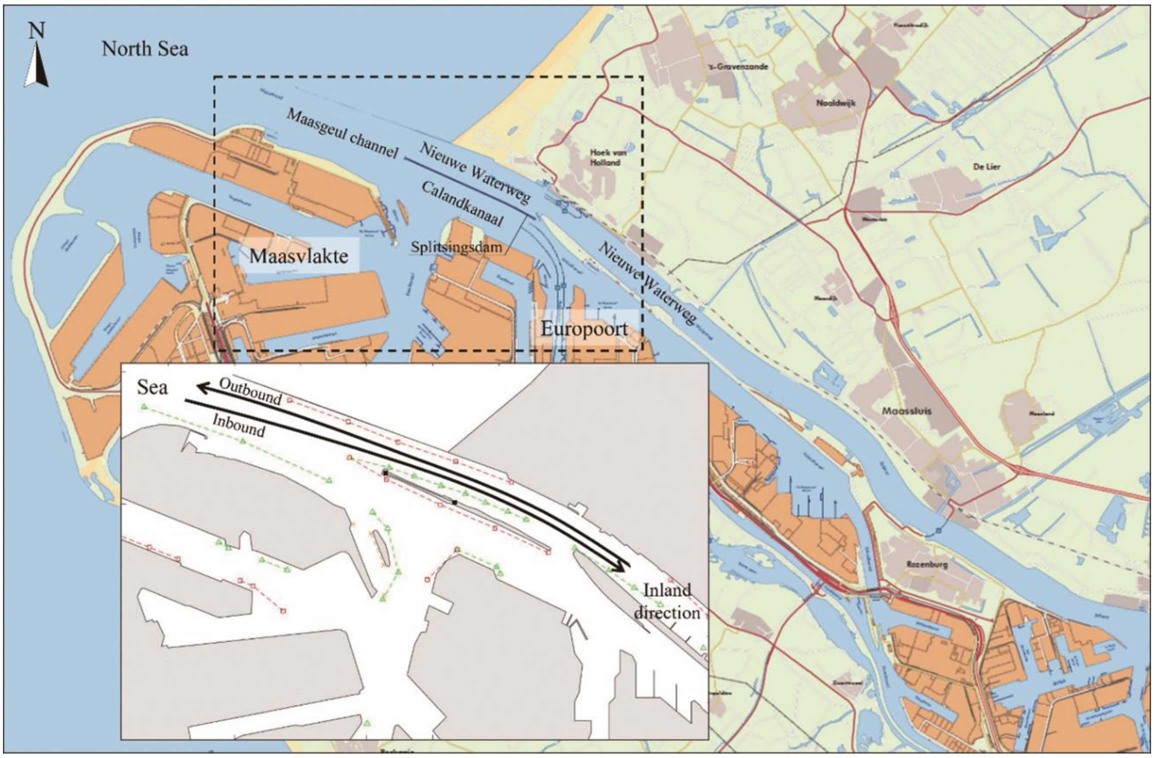

Figure 6.7. Location of the research area in port of Rotterdam with specified ship traffic flow for analysis in the study.

The data of all ships equipped with AIS sailing in the dashed rectangle are collected from the port authority of Rotterdam, covering the whole year of 2014. In order to investigate the ship behavior during the full process of encounters as much as possible, the trajectories of inbound ships sailing from the North Sea (northwest corner of the research area) to the Nieuwe Waterweg (the north waterway on the east boundary of the research area) and the trajectories of outbound ships sailing in the opposite sailing direction are selected (see grey picture-in-picture in Figure 6.7). The waterway stretch is about 10.2 km long, curved with a total direction change of about 20 degrees.

6.4.2 AIS data

In this research, AIS data are employed to describe the dynamic ship behavior along the waterway. As required by IMO (1974) in the International Convention for the Safety of Life at Sea and the resolution by Central Commission for the Navigation of the Rhine (2013), all seagoing ships have installed AIS equipment and use it all the time as required by the local port authority.

For most trajectories in the collected dataset, the AIS reporting time interval is 6 seconds, or at least at an interval of 10 seconds when the ships sail slowly. The ship position is recorded in the Dutch geographical coordinate system, the Rijksdriehoeksmeting (RD system). In total, the collected AIS data in the research area contain 1,732,980 messages involving 34,345 ship trajectories. According to the criteria for encounter extraction in section 6.3.2, pairs of ship trajectories are extracted. To cover the full process of encounter as much as possible, for the encounters of ships sailing in opposite directions and the encounters of ships sailing into the same direction with successful overtaking, only the pairs with their closest point of approach located in the Nieuwe Waterweg are selected for detailed analysis (see Figure 6.8). The number of the selected encounters extracted from the data set is listed in Table 6.1.

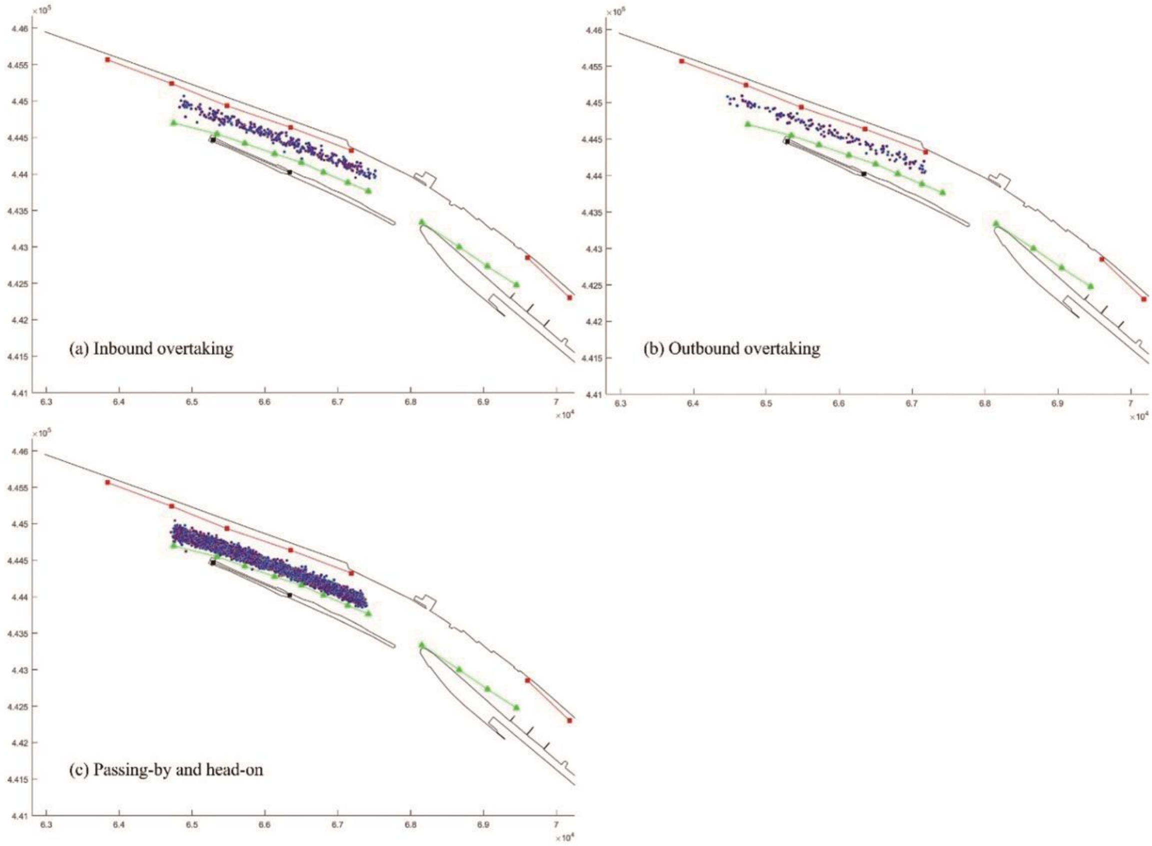

Figure 6.8. Location of ships when the distance with the other ship is minimum during the encounter process: (a) location of inbound overtaking ship; (b) location of outbound overtaking ship; (c) location of inbound ship in passing-by and head-on situations.

Table 6.1. Number of extracted ship trajectory pairs of encounters in the research area.

	Sailing into the same direction		Sailing in the opposite direction
	Successful overtaking	Others	
Inbound direction	353	2010	5976
Outbound direction	148	2469	

For the encounters of ships sailing into the same direction, all of them meet the definition of an overtaking situation as stated in section 6.2.2.1. However, only part of the latter ships (overtaking ships) successfully passes the front ship in the research area, according to the collected data set. Thus, combing the definition of encounter in section 6.2.1, the other encounters sailing into the same direction include two situations: (1) the latter ship has been physically overtaking the front ship, but has not successfully passed the front ship in the research area; (2) the speed of the latter ship is slower than the front ship, but there exists a possibility of overtaking if either or both ships change their speed.

According to our previous findings on the impacts of navigational infrastructures on ship speed, both inbound and outbound ships decelerate before entering the interconnecting area and accelerate back to the original speed after passing the area (Zhou et al., 2022). The interconnecting area locates right on the east end of Splitsingdam, which is also the area to the east of the points with minimum distance in between (see Figure 6.8). Therefore, to avoid investigating combined impacts of both navigational infrastructure and the encounter on ship behavior, for inbound ships, the behavior before the critical overtaking or passing-by moment are analyzed, while the behavior after the critical moment is investigated among outbound ships.

6.5 Results and analyses

Applying the proposed sliding window algorithm to recognize the key feature points of behavior change (course alteration and speed change) during encounters in the research area, the thresholds are determined in section 6.5.1. The ship behavior and the corresponding dynamic movement characteristics at the recognized key feature points are elaborated for the two types of encounters, namely encounters with ships sailing into the same direction in section 6.5.2 and encounters with ships sailing in the opposite direction in section 6.5.3.

6.5.1 Threshold determination for behavior change recognition

The methods to determine the threshold value for course alteration and speed change are presented in this section.

6.5.1.1 Course alteration

As introduced in section 6.3.4.1, the threshold to recognize the course alteration presented in the resulting position deviation is based on ship beam, considering the geometric relationship when two ships sail parallel along the waterway. To compare the number of recognized key feature points using different threshold values, the results for threshold coefficients $\{0.2, 0.3, 0.4, 0.5, 0.6\}$ are shown in Figure 6.9 and Figure 6.10. With an increase of the coefficients, the number of recognized key feature points is expected to decrease. The minimum number is two, which are the initial and end points.

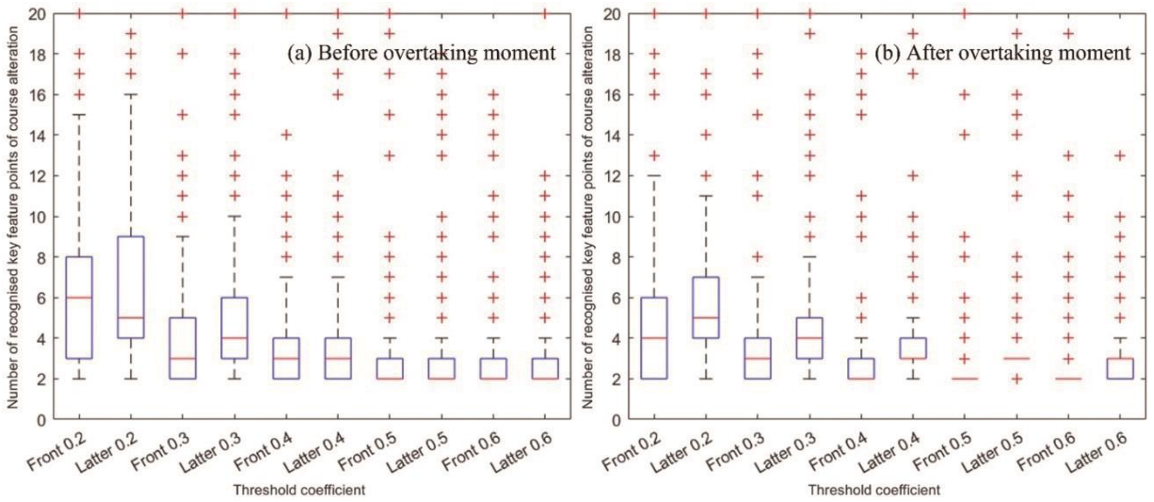

Figure 6.9. Number of recognized key feature points of course alteration during the overtaking process using different threshold coefficients: (a) before overtaking moment; (b) after overtaking moment.

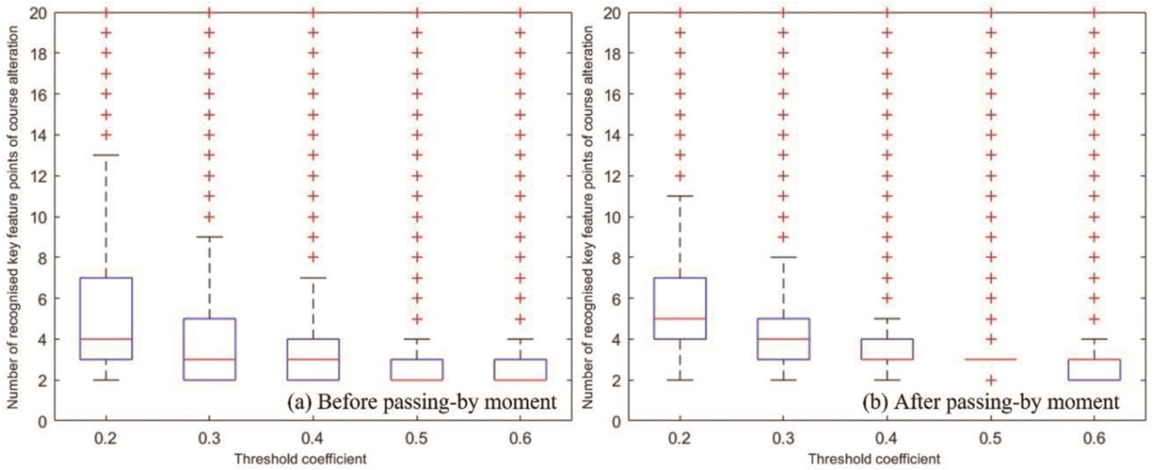

Figure 6.10. Number of recognized key feature points of course alteration during the passing-by and head-on process using different threshold coefficients: (a) before passing-by moment; (b) after passing-by moment.

Unlike the stable path with auto-pilot sailing in open waters, the ships often adjust their trajectories in ports and waterways to adapt to the sailing circumstances. The sailing habits of the OOW onboard also vary, where some OOW prefers instant substantial behavior change, while others prefer a succession of small changes. In both encounter situations, the number of recognized key feature points for a number of ships are much bigger than the theoretical value analyzed in section 6.3.5.

From the results, it can also be proved that with a too small threshold value (0.2 times of the ship beam), the occasional behavior to adjust the ship position is also recognized as key feature points. On the contrary, when the threshold is too large (0.6 times of the ship beam), only the initial point and critical point are recognized. It means the position deviations due to intended course alterations during the encounter processes are omitted. In section 3.5, for both encounter situations, the theoretical number of course alteration key feature points during the processes have been analyzed, which is 2 to 4. The recognition result of 5 course alteration points is probably due to the obvious direction change of the waterway close to the interconnecting area (see Figure 6.7). Therefore, comparing the results based on different threshold coefficients, 0.4 times of the ship beam is selected as the threshold to extract course alteration key feature points. The numbers of key feature points in different encounter situations based on this threshold value all follows the theoretical analysis, which should not always be 2.

6.5.1.2 Speed change

Similar to the threshold determination for course alteration recognition, different thresholds are used to recognize the key feature points of speed change. Due to the impact of navigational infrastructure on ship speed in the research area revealed in (Zhou et al., 2022), ships change their speed even without encountering other ships. Therefore, besides avoiding investigating the ship behavior in the interconnecting area (see Figure 6.7), a speed change within 10 percent of original speed in the west segment of Nieuwe Waterweg is deemed as the behavior due to the local waterway layout according to our previous study (Zhou et al., 2022), other than evasive behavior during encounter process. However, more points can still be expected compared to the theoretical analysis in section 6.3.5 considering individual behavior. The results of the recognized key feature points number are shown in Figure 6.11 and Figure 6.12.

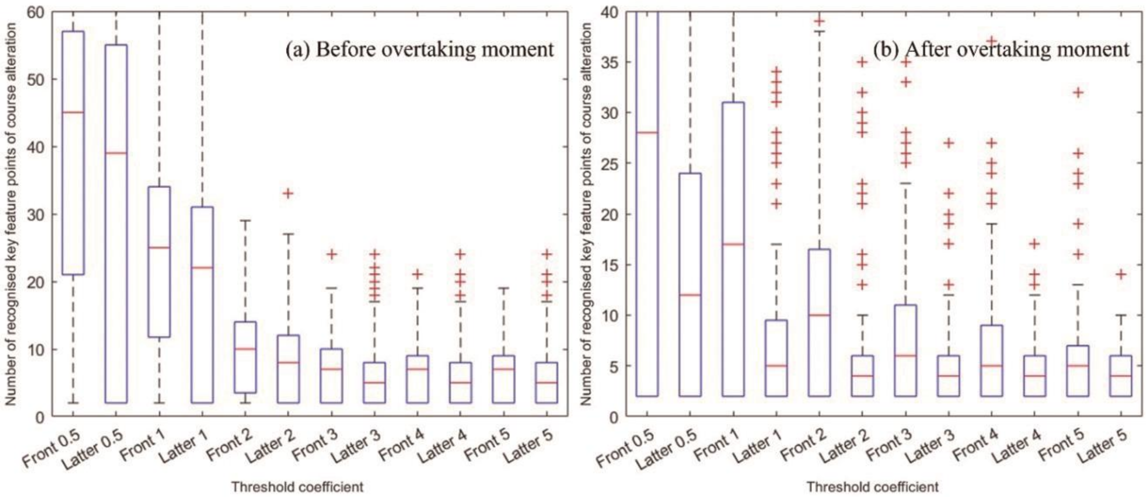

Figure 6.11. Number of recognized key feature points of speed change during the overtaking process using different threshold coefficients: (a) before overtaking moment; (b) after overtaking moment.

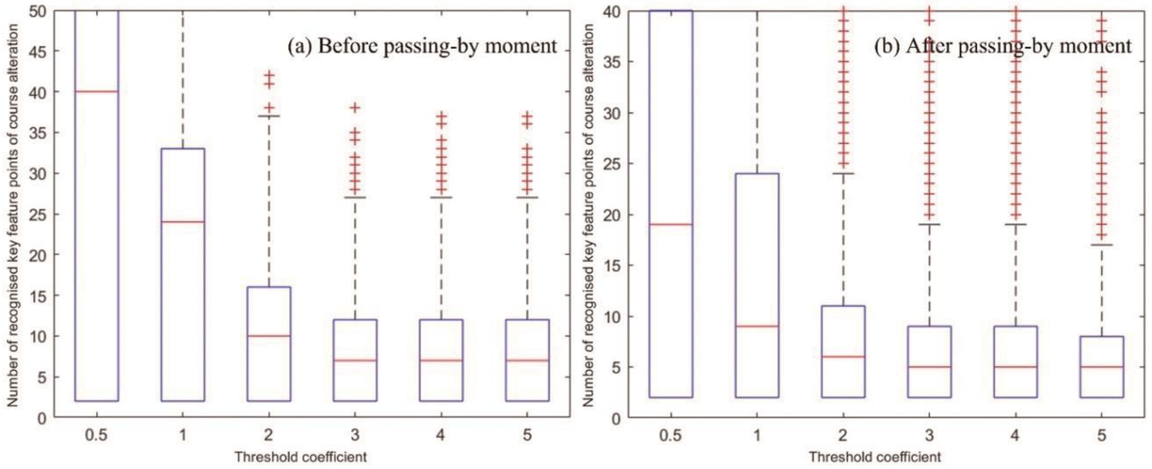

Figure 6.12. Number of recognized key feature points of speed change during the passing-by and head-on process using different threshold coefficients: (a) before passing-by moment; (b) after passing-by moment.

It can be observed that, similar to course alteration, when the threshold value is too small, the speed change behavior due to the own circumstances will be more included. However, compared to ship course which is only affected by waterway layout and the encounter, since the initial speed and ship size are different for every single ship, the individual needs of speed change are also different. A single threshold value can hardly fit all ships to recognize appropriate number of key feature points of speed change. Therefore, for each single trajectory, with an increase of the threshold coefficient, the smallest one resulting in a stable number of key feature points is adopted. To show the process, the threshold determination of one trajectory is shown in Figure 6.13. It can be found that in Figure 6.13(e) and (f), the number of key feature points becomes stable at 4, which indicates the major speed changing points. In this case, the threshold coefficient is determined as 4.

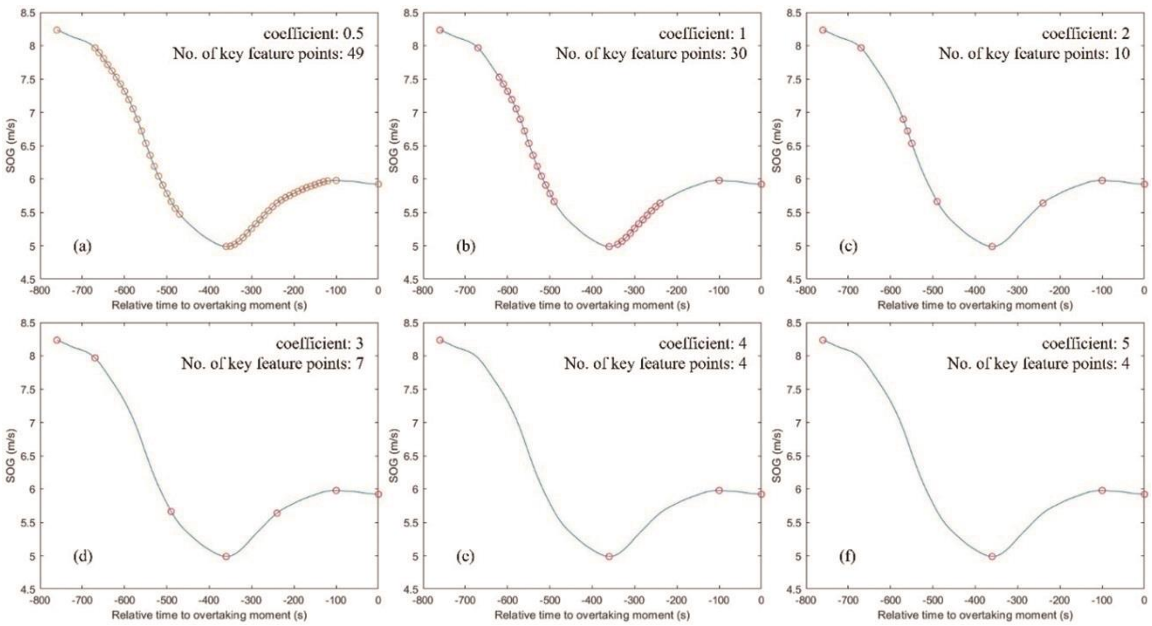

Figure 6.13. Process of threshold determination for speed change key feature point recognition taking one trajectory as an example: (a)-(e) with an increase of coefficient adopted.

6.5.2 Encounter of ships sailing to the same direction

Due to the limited size of the research area, the full voyages of both ships heading to their destinations after overtaking are not included in the dataset. Thus, the impacts and ship behavior in phase 3 (see Figure 6.2) cannot be fully elaborated in this chapter. In this section, the findings on behavior change for both overtaking and overtaken ships are introduced first. Based on the recognized key feature points representing ship behavior changes, the ship behavior and the corresponding dynamic relative movement conditions before the critical overtaking moment are discussed in phases.

6.5.2.1 Overview of ship behavior in overtaking situation

To analyze the behavior preferences during overtaking situations, the encounter process is marked by the critical overtaking moment. According to the proposed sliding window algorithm in section 6.3.4, if the number of recognized key feature points is larger than 2 (initial point and end point), there are one or more behavior changes in between. Based on the results, the statistics of different evasive behavior occurrence in overtaking situation is presented in Table 6.2.

Table 6.2. Occurrence of evasive behavior with recognized key feature points for both ships in overtaking situation.

		Before overtaking moment (Inbound direction: 353)	After overtaking moment (Outbound direction: 148)
Overtaking ship	Neither	51 (0)	6
	Course alteration	74 (0)	44
	Speed change	89 (0) [35]	11
	Both	139 (3) [44]	87
Overtaken ship	Neither	47 (1)	32
	Course alteration	44 (0)	13
	Speed change	120 (1) {18}	67
	Both	142 (1) {23}	36

The number in round brackets () indicates starboard side overtaking. The number in square brackets [] refers to the overtaking reaches the intended highest speed before overtaking moment. The number in braces {} indicates the occurrence of uncoordinated acceleration behavior of the overtaken ship.

From the statistics, it can be found that part of the overtaking encounters is achieved without any behavior change by either ship. It means under the circumstances with sufficient relative speed and lateral distance, the evasive behavior is not always necessary, even in the confined waterways. For overtaking ships (give-way as requested by COLREGs), no preference is observed in choosing from course alteration and/or speed change. Regarding the acceleration to facilitate the process, most of the overtaking ships keep the acceleration or at least keep the speed until the situation is fully past and clear. About one third of the overtaking ships started deceleration before the physical overtaking moment. For the stand-on ship in COLREGs, only about 13% overtaken ships do not perform any behavior change, i.e., keep her speed and course. It means most of the overtaken ships in the ports and waterways will take coordinated behavior to facilitate the overtaking process, which is in accordance with the good seamanship. Among their behavior options, more than 70% adjust their speed, which is the primary choice, and about half take coordinated course alteration with the overtaking ship to enlarge the lateral distance in between.

After the overtaking moment, the great majority of overtaking ships take course and/or speed change to continue their voyage. The proportion of neither behavior change is far smaller than before the overtaking moment. It means some of the overtaking ships postpone the deceleration and/or the course alteration to intended path until the situation is fully past and clear. Regarding the overtaken ships, probably due to a small range of course alteration during the overtaking, some ships do not take explicit course alteration afterwards. But most of the ships adjust their speed after the moment, which is in line with their behavior choices before the overtaking moment.

The statistical results reveal the behavior preferences of overtaking and overtaken ships during the process for the first time. It can be observed that analyzing the behavior in single typical pair of trajectories of encounters is not sufficient to discover the individual behavior differences, especially for the encounters in ports and waterways. The common characteristics of dynamic relative movement at the key feature points of behavior change will be analyzed in the following sections, which indicates the triggering conditions of such behavior change during encounters.

6.5.2.2 Decision of overtaking (phase 1)

According to the overtaking process shown in Figure 6.2, when a ship is approaching another ship with the same sailing direction , phase 1 is when the latter ship needs to decide whether to overtake or follow the front ship.

Besides the successful overtaking occurred within the area, there are many more encounters with ships sailing to the same direction in the collected data. Comparing the distance between the ships when entering the research area and leaving the area, the following assumption is made: (1) if the initial distance is the minimum during the full process, though the situation is overtaking according to the definition, the behavior of latter ship is deemed as following; (2) if the end distance is the minimum, the behavior of latter ship is deemed overtaking, which is not fully accomplished in the research area; (3) if the distance fluctuates during the process, the behavior of either or both ships vary, in which case the relationship also changes. Based on the assumptions, the number of different behaviors occurred in the collected data is present in Table 6.3. In this chapter, we focus on the full following and overtaking behavior during the encounter process.

Table 6.3. Occurrence of different types of latter ship behavior in overtaking encounters.

Type of behavior	Overtaking behavior	Following behavior	Changing behavior
Inbound direction	411	344	1255
Outbound direction	490	209	1770

As shown in Figure 6.2, for a ship with a certain sailing direction (inbound or outbound), the intrinsic factors influencing the process include ship size and SOG, while the relative movement status is described by relative bearing, distance in between ships, and relative speed. These three factors are intuitive for the OOW onboard, which can be visually obtained . In ports and waterways, in case of two ships sailing into the same direction but with a large distance, the relative bearing of the front ship to the latter ship differs little. It can be expected that the decisive factors are the relative speed and the distance in between, which determines the speed and time of approaching process. Considering the intrinsic differences among ships, the ship size is adopted as a distinction criterion when analyzing the distance, while the instant SOG of the latter ship as OS, the give-way ship in overtaking situation, for relative speed. According to our previous studies, ship beam is selected as the indicator to distinguish ship size (Zhou et al., 2019a). The initial status of distance and relative speed, the starting point of approaching in phase 0 in Figure 6.2, for complete overtaking encounters, incomplete overtaking encounters, and following encounters are presented in Figure 6.14.

When comparing the initial status between complete and incomplete overtaking encounters, it can be observed that the initial distance between the ships in incomplete overtaking encounters are about 1 km longer than in the complete overtaking situations, while the relative speed is similar. This is probably the reason that those ships with a longer distance to overtake, which can hardly be complete in the research area. On the contrary, the initial distance in following encounters is around 1km, which is smaller than in either overtaking encounter. But the relative speed of the latter ship to the front one is all negative irrespective of the speed of the latter ship. Thus, for the encounters of ships sailing to the same direction, even the distance in between is short, the relative speed still decides the latter ship’s choice of following behavior, rather than substantial acceleration to overtake the front one.

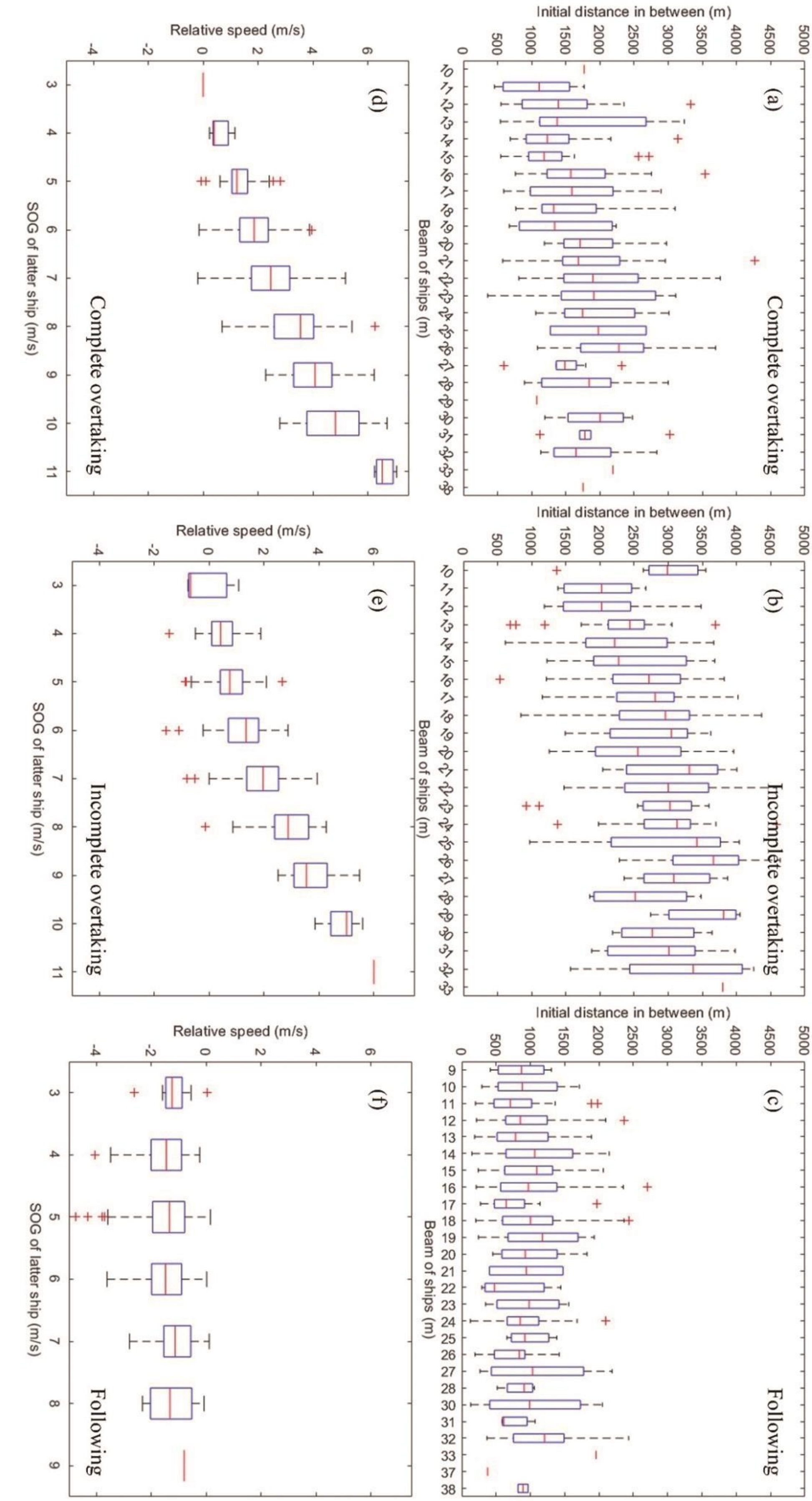

Figure 6.14. Initial status of distance (upper row) and relative speed (lower row) between the two ships in different encounters: (a, d) complete overtaking; (b, e) incomplete overtaking; (c, f) following.

6.5.2.3 Behavior of overtaking ships (phase 2)

In this section, the sailing status of the latter ship and the conditions of relative movement with the front ship at the first key feature point of behavior change by the latter ship are investigated. Besides the direct descriptive factors mentioned above, considering the geometric relative movement relationship, the indices DCPA and TCPA are calculated. Using the historical data, the time stamp of the key behavior change point can be transferred to the relative time to the overtaking moment.

From the calculation results, when taking evasive actions, the relative bearing of the front ship to the latter ship is around 0-10°, which seems to exceed the range by the definition in Figure 6.1. It is due to the bending of the waterway (see Figure 6.7). When the distance between two ships is around 1.5-2 km, the direction change of the waterway is already incorporated in the relative bearing calculation. Thus, the relative bearing cannot be used for decision-making. Similarly, considering the calculation principles of DCPA and TCPA, the impact of waterway direction change can hardly be eliminated. No explicit generic characteristics can be observed among different sizes of ships. For ships with different instant SOG, DCPA at the point is around 200m. But the values already lose their physical meaning considering the waterway. The values also fluctuate with the frequent heading changes for ships sailing in ports and waterways, which is also observed during encountering ships in open waters (P. Chen et al., 2018). Therefore, these two indices are only applicable for ships sailing with stable course in open waters or straight waterways. In ports with complex layout, they can hardly illustrate the encounter situation.

From the perspective of relative speed, the great majority of latter ships sail at a higher speed than the front one. The higher the speed of the latter ship, the larger the relative speed when they perform evasive maneuvers. However, the relationship between the relative speed and the ship size is not observed. The remaining two factors, being distance in between and relative time to the overtaking moment, depict the point of behavior change over the full process from the spatial and temporal viewpoints. Both factors considering the intrinsic differences of ships at the first course alteration point and the first speed change point are presented in Figure 6.15.

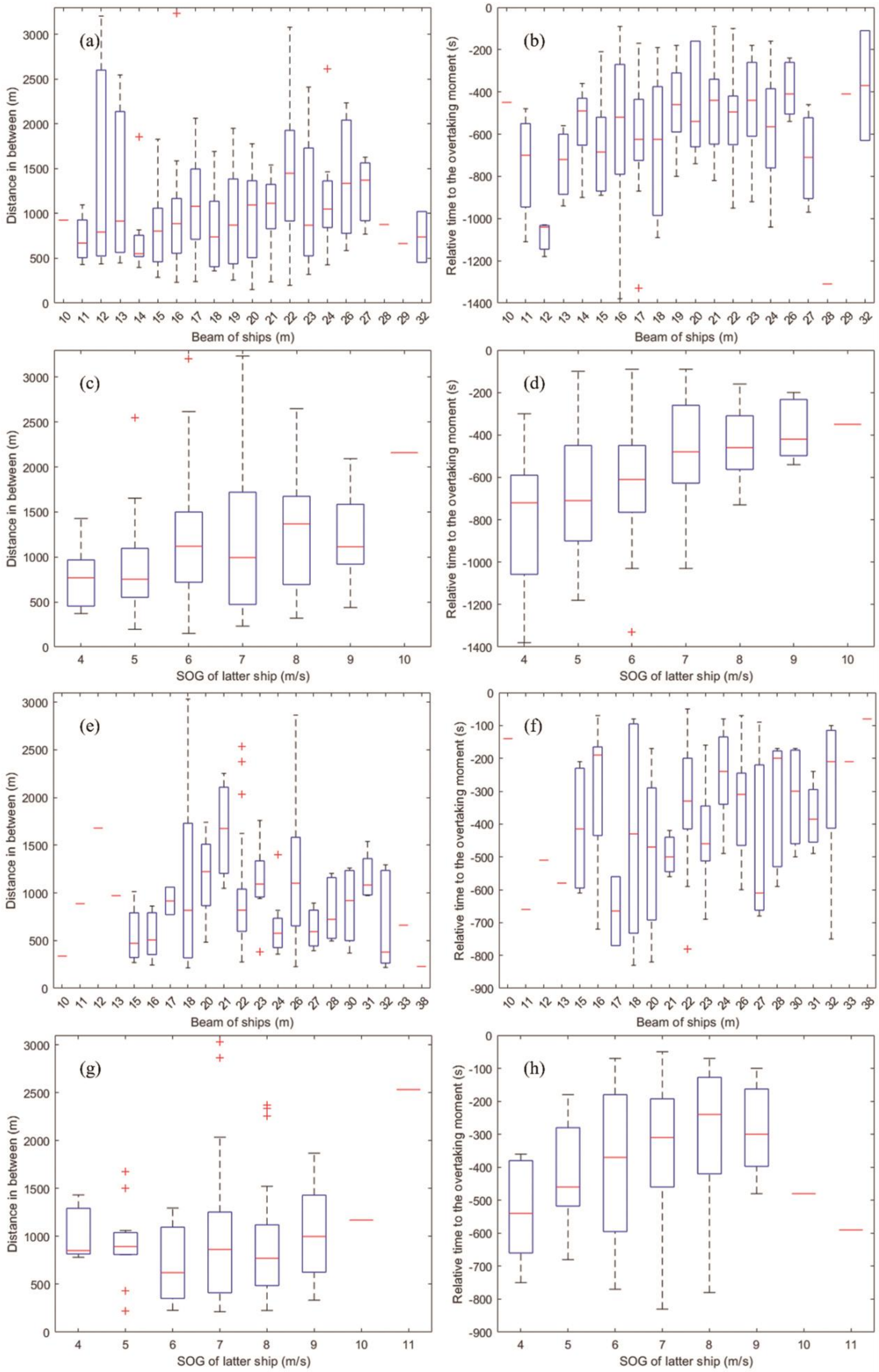

Figure 6.15. The distance in between (left) and relative time to the overtaking moment (right) at the first course alteration point (upper four figures) and the first speed change point (lower four figures) considering the intrinsic characteristics of latter ship.

When the latter ship starts evasive actions, the visual distance in between is around 0.8-1.5 km (see left in Figure 6.15), while the time is about 10 min for course alteration (see Figure 6.15(b),(d)) and 5-10 min for speed change (see Figure 6.15(f),(h)). Therefore, from the perspective of the OOW onboard, the higher the speed of OS, the longer the distance to initiating evasive action , which can be around 1.5 km. The speed change behavior (acceleration) mostly starts later than course alteration. From the perspective of historical data analysis or maritime traffic model to simulate such behavior, based on the calculated or predicted time of physical overtaking moment, the latter ship starts the evasive actions about 10 min in advance.

During phase 2, the physical overtaking moment marks the critical relative movement status between the ships. As stated in section 6.3.4, the purpose of course alteration is to enlarge the passing distance when overtaking the front ship, while the speed change is to keep sufficient relative speed for a successful overtaking. For the ships taking neither behavior change, the probable reason is that from the perspective of the OOW onboard, the distance and relative speed is already sufficient, where additional behavior change is not necessary. Therefore, the passing lateral distance and the relative speed at the critical moment can be adopted as the behavior objectives for the latter ship, no matter whether it is the original behavior or the results of behavioral changes. It should be noted that the passing distance refers to the clear distance, in which the width of both ship hulls should be excluded. In this research, the location of the AIS antenna is assumed to be located at the horizontal geometric center of the ship. Thus, the clear distance refers to the distance calculated by AIS data minus half the beam of both ships. Considering the intrinsic differences among ships, the ship beam is used as criterion for distance, while the instant SOG is taken at the moment for speed. The distance at the overtaking moment for different sizes of ships is shown in Figure 6.16, and the relative speed status in Figure 6.17.

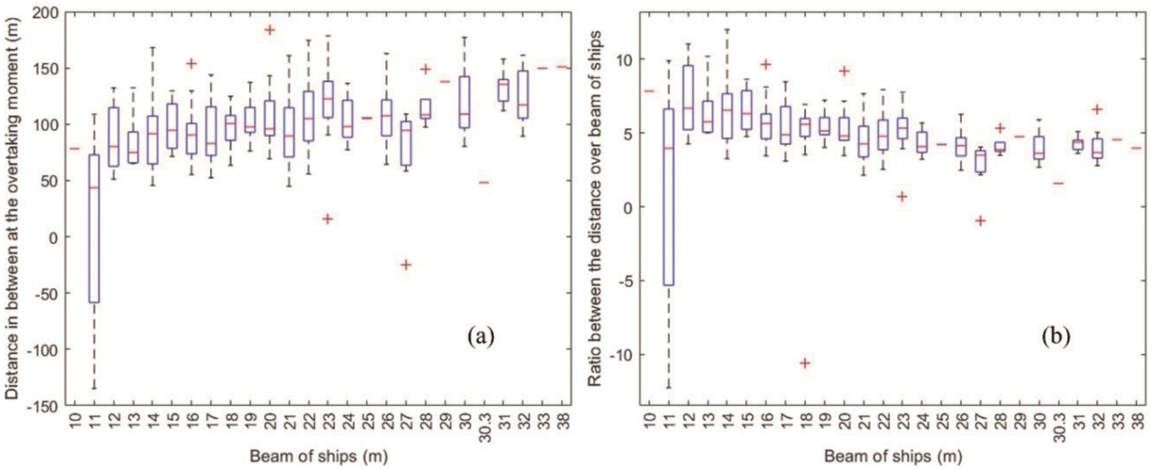

Figure 6.16. The distance status at the overtaking moment (the negative value refers to the overtaking on the starboard side of the front ship): (a) the distance between ships; (b) the ratio between the distance over beam of the latter ship.

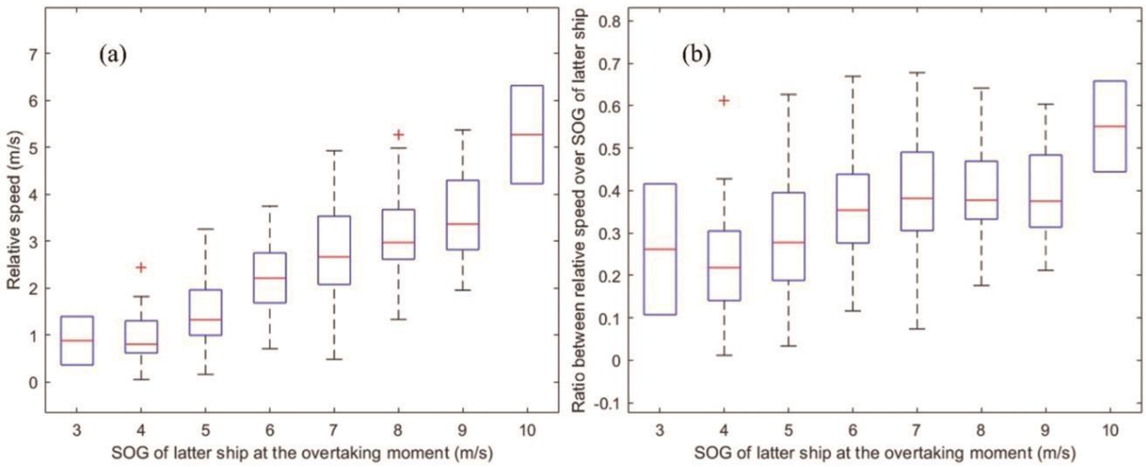

Figure 6.17. The relative speed status at the overtaking moment: (a) the relative speed; (b) the ratio between the relative speed over the instant SOG of the latter ship.

It can be observed in Figure 6.16(a) that the intended clear distance to overtake the front ship is about 50-150m. With an increase of ship size, the clear distance also becomes larger. Considering the ship size factor, in Figure 6.16(b), the ratio between the lateral distance over ship beam is stable around 5. Thus, 5 times of ship beam can be deemed a safety passing distance from the perspective of the OOW onboard the overtaking ship. The relative speed at the overtaking moment increases when the speed of latter ship becomes higher. For example, a higher speed of the latter ship with a relatively stable low-speed front ship, the relative speed gets larger. Such relative speed can also be presented as ratio of the SOG of the overtaking ship in Figure 6.17(b). The value is approximately stable around 0.3, which means the intended speed of overtaking ship to pass the front ship is around 1.43 times of the SOG of front ship. Here, the encounters with and without speed change during the processes are all included. Thus, no matter whether the overtaken ship changes her speed to cooperate or not, the speed objective of the overtaking ship at the critical moment can be generalized from the instant speed of overtaken ships. As the pattern (4) shown in Figure 6.6, if the overtaking ship reaches her speed objective before passing the front ship, she will keep her speed without further acceleration. An example of such speed change is illustrated in Figure 6.18. The overtaking ship accelerates around 5min before the overtaking moment with a distance around 500m. When she reaches her objective speed, the overtaking ship keeps her speed until the overtaking moment. However, the overtaken ship starts to accelerate, which reduces the relative speed. Therefore, during the overtaking process, the behavior of overtaken ship is worth further investigation.

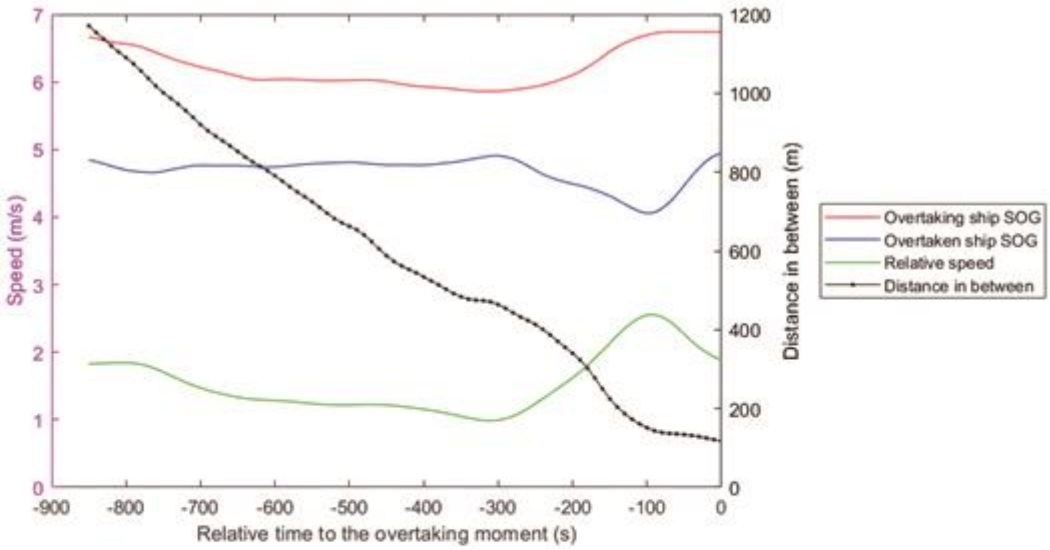

Figure 6.18. An example of overtaking ship reaching her objective speed before the overtaking moment.

6.5.2.4 Behavior of overtaken ships (phase 2)

In the example shown above, about 5 min before the overtaking moment, the overtaken ship starts to decelerate, which facilitates the overtaking process. However, around 100 sec before the critical moment, the overtaken ship accelerates, which can be deemed as kind of uncooperative behavior. Therefore, for overtaken ships as stand-on ship defined by COLREGs, instead of analyzing the relative movement conditions and sailing behavior at the first key feature point of behavior change, their behavior before the overtaking moment requires more attention.

From the statistical results in Table 6.2, it can be found that about 75% of overtaken ships take cooperative behavior to facilitate the overtaking process, including altering their course to enlarge the passing distance and/or deceleration. Based on the findings of decisive factors for overtaking ships to take evasive actions, the distance in between and the relative time to overtaking moment at the last but one key feature point of behavior change are investigated, as shown in Figure 6.19. The last key feature point refers to the overtaking moment.

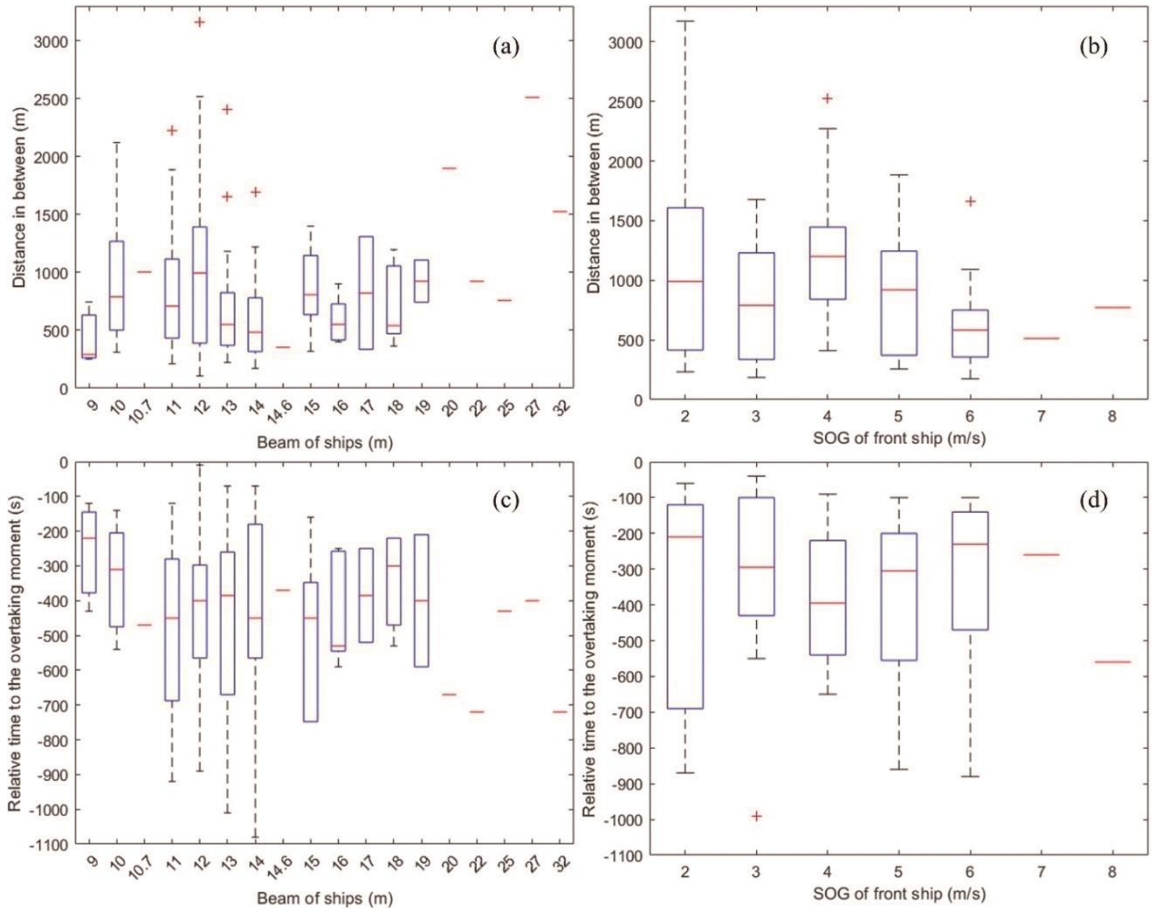

Figure 6.19. The relative movement status (upper row for distance in between; lower row for relative time to overtaking moment) at the last behavior changing point of front ship: (a,c) course alteration; (b,d) speed change.

Comparing the timing of course alteration (Figure 6.19 (a, c)) and speed change (Figure 6.19 (b, d)), the relative distance is similar, which is about 0.5-1km. Regarding the relative time to the critical moment, the speed change of the overtaken ship is about 1 min later (closer to the overtaking moment) than course alteration, which is similar to overtaking ships with a 5-min difference. It will take some time to achieve a larger passing distance after the maneuver of course alteration. Applying the same method as overtaking ship to analyze the objective behavior of overtaken ships, the results are presented in Figure 6.20. It can be observed that irrespective of the size and speed differences of the front ship, the objective of her behavior is to achieve a relative speed around 2-3 m/s and a clear passing distance at about 100m.

As an example of starboard side overtaking in Figure 6.16(a) and Figure 6.20(b), the front ship is a large ship with a beam of 28m, while the latter ship is much smaller with a beam of 11m. Considering the draught of different ships, it can be expected that the front ship needs to sail closer to the centerline of the waterway to guarantee sufficient underkeel clearance. In such circumstances, the latter small ship overtakes on the starboard side of the front ship is to avoid sailing into the opposite direction of the waterway, which stills follows the good seamanship when sailing in narrow waterways.

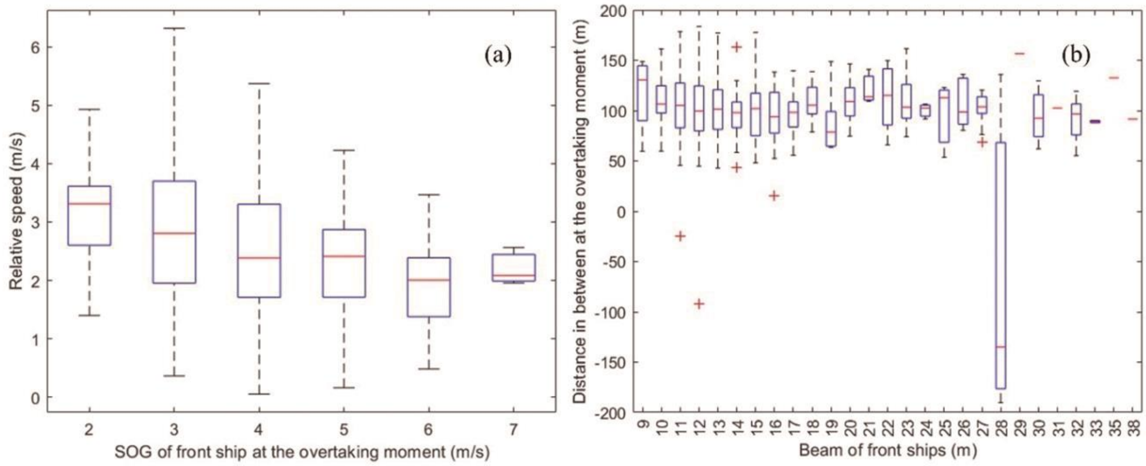

Figure 6.20. The distance (a) and relative speed (b) status at the overtaking moment from the perspective of overtaken ship (the negative value refers to the overtaking on the starboard side of the front ship).

It should be noted due to the limitations of the research area, the behavior of both ships in phase 3, after the overtaking ship is past and clear, are not analyzed in this chapter.

6.5.3 Encounter of ships sailing into the opposite direction

The overview of both ships' behavior during the encounters when sailing into the opposite direction is generalized in section 6.5.3.1, followed by the ship behavior and the corresponding dynamic relative movement conditions in phases of passing-by and head-on situations in section 6.5.3.2.

6.5.3.1 Overview of ship behavior when approaching from the opposite direction

Similar to the analysis of ship behavior preferences during overtaking encounters in section 6.5.2.1, the behavior of both ships when approaching from the opposite directions is generalized. As shown in Figure 6.8(c), the points with minimum distance between the ships are located in the Nieuwe Waterweg. Thus, the inbound ships are used to analyze the behavior before the passing-by moment, while the outbound ships are used to show the behavior after the passing-by moment. In this chapter, we compare the statistics of ship behavior during their full trajectory and during the period within a distance of 2 km (about 1 n mile) when approaching from opposite directions are presented in Figure 6.21.

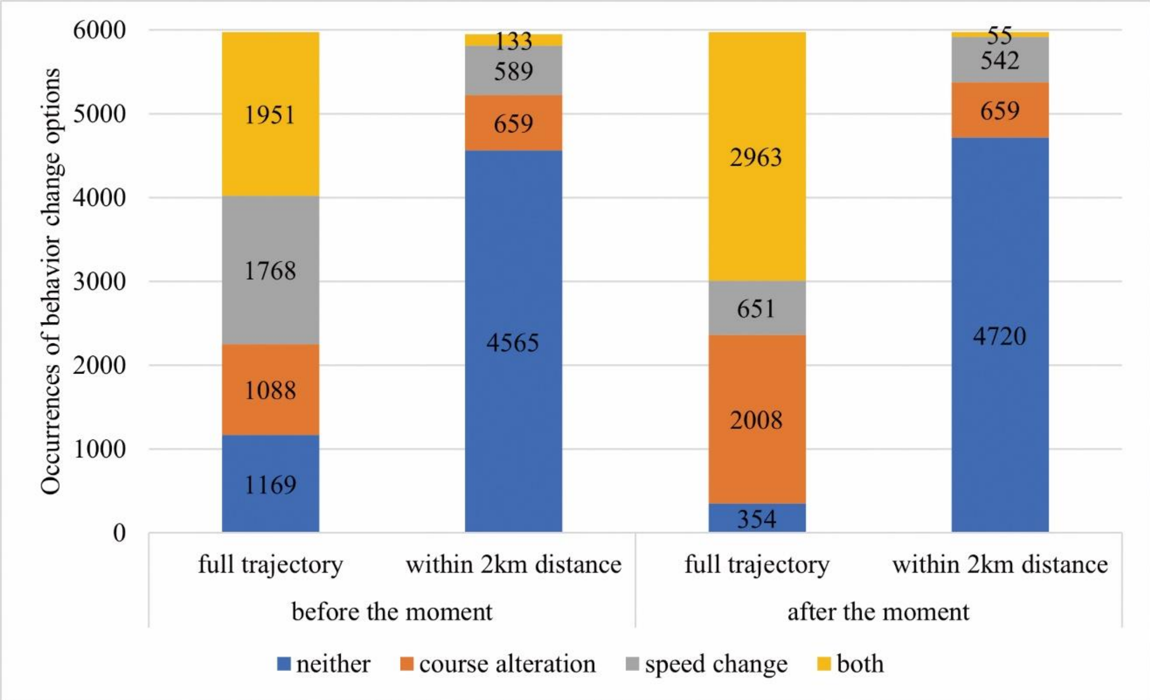

Figure 6.21. Occurrences of behavior change options of ships when approaching from the opposite direction.

When the ships approaching closer, the occurrence of ship behavior changes becomes less, including both course alteration and speed change. The recognized behavior changes points before reaching the influence distance are mostly the adjustment for individual sailing purposes. According to the definition of passing-by and head-on situation in section 6.2.1, 4565 out of 5976 inbound ships do not present behavior change within the last 2km distance right before passing-by moment. It means within this period, these OOWs judge the encounter as a passing-by situation. In such a case, probably the ship has already been sailing as close to the starboard boundary as possible. Or from the perspective of OOW, the distance in between and/or the relative speed is sufficient for the encounter, which could be the result of their earlier behavior change before approaching to 2km distance. In the other cases, the OOW onboard ships deem the encounter to have a collision risk, which is a head-on situation as defined by COLREGs. Thus, the ships need to take some evasive behavior. However, there is no obvious preference between course alteration and speed change, which depends on the specific circumstances. However, after the passing moment, the great majority of ships alter their courses to continue the voyage in the long run. Investigating the ships with speed change, more than half ships accelerate, which is probably because the outbound ships are sailing to the open sea where usually a higher speed is preferred, even when the ships are sailing alone in the waterway without encountering other ships (Zhou et al., 2015). In this chapter, to eliminate the impacts of sailing directions on substantial speed change, we focus on the behavior analysis before the passing-by moment.

6.5.3.2 Ship behavior during the encountering process

Based on the findings in section 6.5.2, a safe lateral distance is the objective of altering course, which also works in the passing-by and head-on situations. As the ships approach from opposite directions, the relative speed is large, i.e., the approaching speed is fast compared to overtaking situations. Considering the time is short, the KS test is used to test whether the lateral distances at the different moments (the key feature point of behavior change and the critical passing moment) come from the same distribution. The null hypothesis is that "the lateral distance at key feature points of behavior change and the lateral distance at the passing-by moment are from the same distribution". If the hypothesis is rejected, the process of behavior change is to achieve the lateral distance at the passing-by moment as their objectives. It also implies that if a ship holds such objective lateral distance before the critical moment, no behavior change is necessarily required. The statistical results of KS test for both course alteration and speed change accept the null hypothesis that the lateral distance come from the same distribution. Using the beam of own ship to distinguish the ship size, the lateral distance at the key feature points of behavior changes and at the passing-by moment are shown in Figure 6.22.

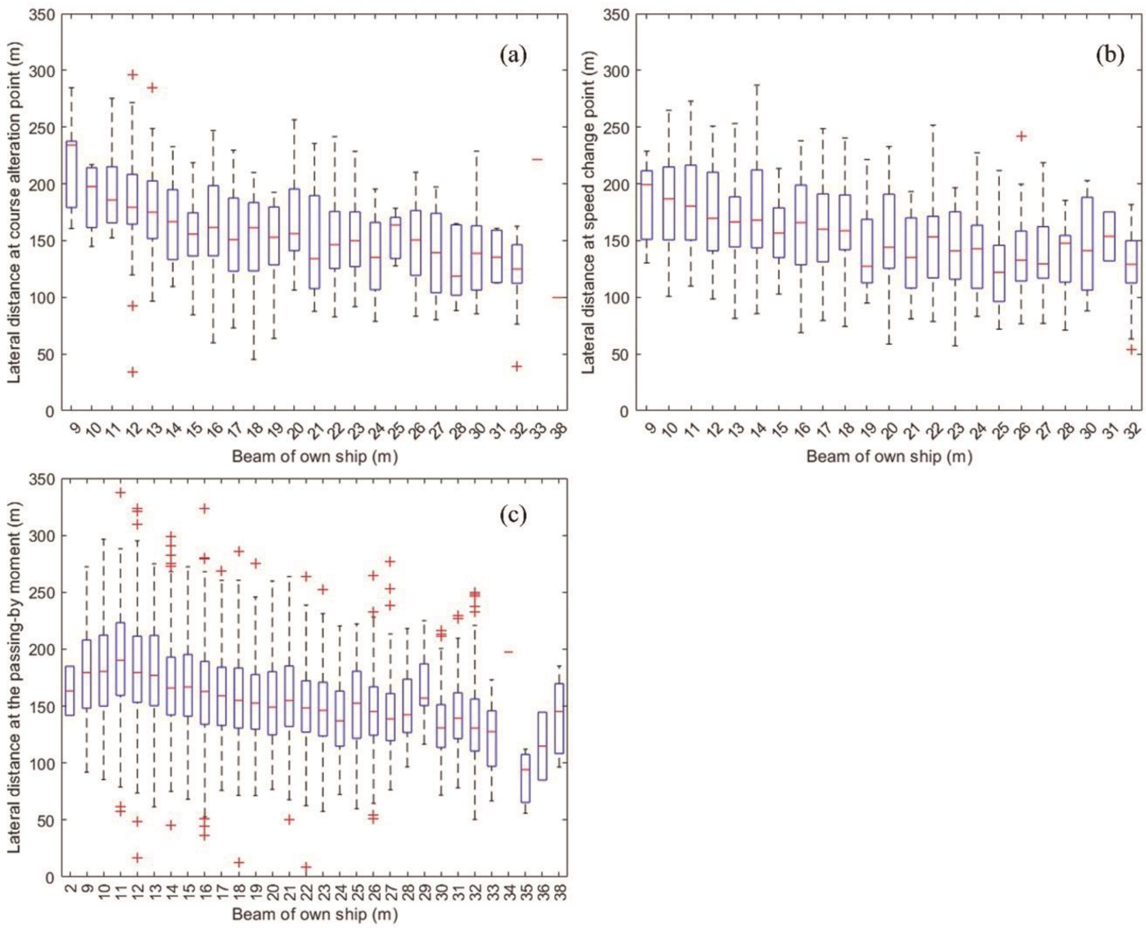

Figure 6.22. Comparison of lateral distance between ships: (a) at point of course alteration; (b) at point of speed change; (c) at the passing-by moment.

Since there are no significant differences of lateral distances between the behavior change points and the critical moment, it can be understood that the ships already adjust their lateral position from a longer distance through a succession of small changes. Or the waterway width is wide enough for two ships to pass by each other without making evasive behavior when both ships have been sailing as close to the starboard boundary as possible. It can also be deemed as the individual behavior when sailing in ports and waterways, since the navigational circumstances is more complex compared to open waters. For the encounters with ship behavior change, to analyze the timing of ships performing evasive maneuvers, the relative distance and relative time to the passing-by moment are analyzed in Figure 6.23.

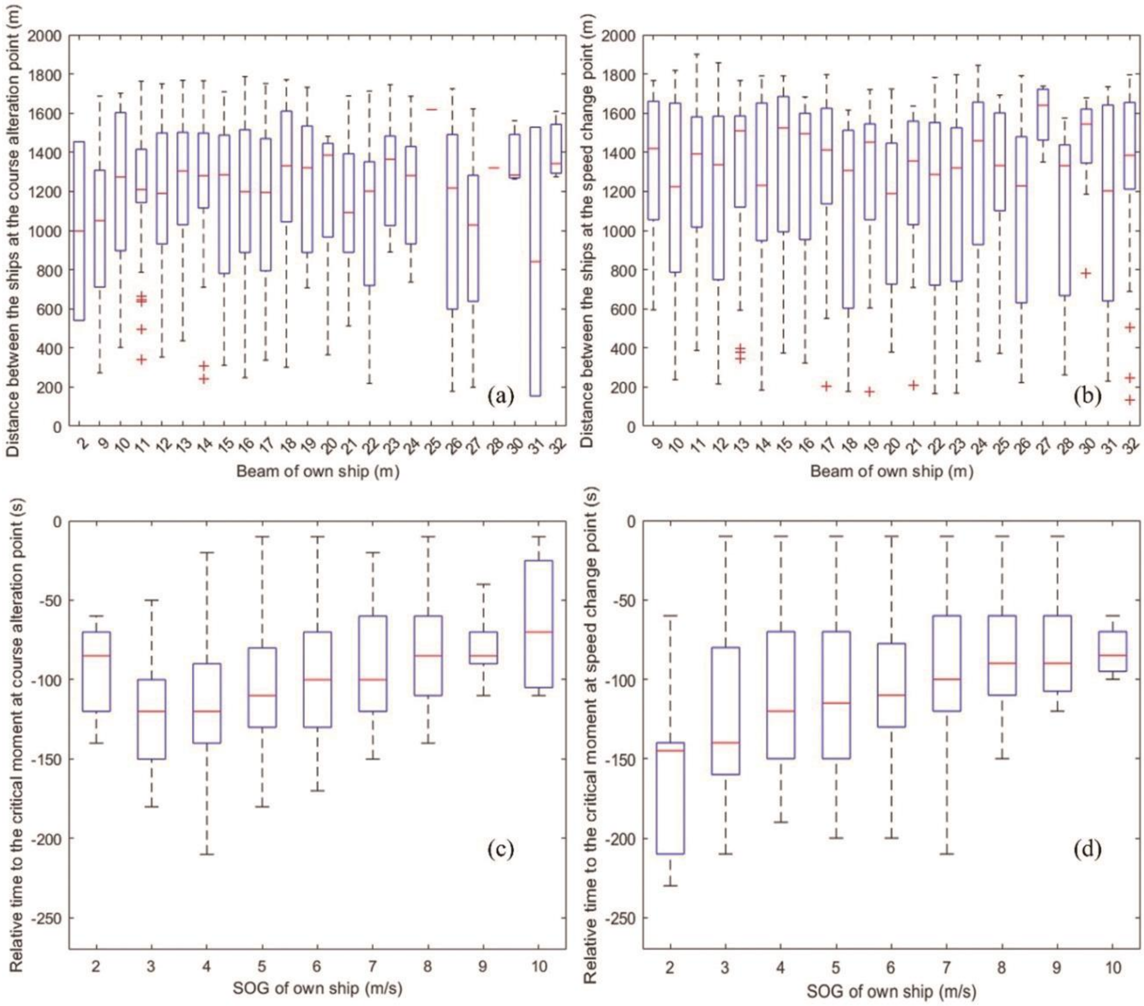

Figure 6.23. The relative movement status (upper row for distance in between; lower row for relative time to the passing-by moment) at the behavior change point: (a,c) course alteration; (b,d) speed change.

The distance to the other ship differs among the ships with different size when they alter their course or change the speed. Most of the ships take the maneuver when the distance is around 1-1.6km. However, in the temporal respect, the time for these two actions is both around 1.5-2min, in which speed change is slightly earlier than course alteration. Since the KS test shows that the lateral distance at the behavior change point is already sufficient for a common objective at the passing-by moment, ships taking such maneuvers do so mostly due to the sailing preferences of the OOW onboard. When there is another ship approaching to pass by, the OOW onboard could adjust the sailing status in case of the interaction between ships. It also implies that most ships sailing in the inland waterways already comply with *Rule 9*(a) to sail close to the starboard side of the boundary. From the behavior modeling perspective, besides the normal sailing behavior close to the starboard side boundary, a variation of slight course and speed change should also be included to integrate the individual differences, which can be observed in real-life navigation in ports and waterways.

6.6 Conclusions

Starting from the definition of encounters in ports and waterways, this chapter systematically investigates the ship behavior during the processes of different encounter situations, being overtaking situations when ships sail in the same direction and passing-by or head-on situations when ships sail in the opposite direction. Instead of looking into specific encounter cases, the real-life sailing behavior of both ships and the relative movement conditions before the critical moment of ships passing by each other are generically revealed through the analysis using one-year of AIS data in the port of Rotterdam, the Netherlands. It should be noted that the relative movement conditions at the critical moment with minimum distance in between the ships is the results of both ship behavior. From the perspectives of both ships, their decisions and behavior intensions are analyzed.

The encounters of ships sailing into the same direction are considered as overtaking situations, as defined by COLREGs. However, according to the initial distance and relative speed between the two ships, the behavior of the latter ship can be categorized as overtaking behavior and following behavior. When the distance between ships is around 1km and the latter ship sails slower than the front one, the latter ship will follow the front ship without acceleration. If the latter ship sails faster than the front one, overtaking behavior can be observed. During the overtaking process, about 14% of the overtaking ships do not take any evasive actions, even when they are identified as give-way ship by COLREGs. The reason is that their relative motion suffices the overtaking ship to pass the front ship at a safe lateral distance. On the contrary, as the stand-on ship in the situation, only about 13% of the overtaken ships keep their speed and course. The other overtaken ships mostly take cooperative maneuvers to facilitate the overtaking process. Regarding their behavior options, more than 70% reduce their speed, which seems the primary choice. As instructed by COLREGs, the overtaken ships may already sail close to the starboard boundary of the waterway. When the latter ship overtakes on the port side, the maneuvering space to starboard side is limited. Thus, deceleration to facilitates the overtaking process is the feasible option for overtaken ship. Among the overtaking ships with behavior changes, the preference on course alteration and speed change is equal. Comparing the status of different relative movement indicators to describe the timing of behavior change, the impact of waterway direction change can hardly be eliminated in relative bearing, DCPA and TCPA. Thus, the intuitive factors relative speed and distance between the ships are used to describe the relative movement status. When the visual distance is around 0.8-1.5 km, the latter ships start the evasive actions. Overtaken ships, however, take the maneuvers when the distance is around 0.5-1km, which is probably after observing the overtaking behavior of latter ships. For overtaking ships, the objective of course alteration is to achieve a clear passing distance about 50-150m, which is 5 times of her beam. However, for overtaken ships, irrespective of her own beam, they intend to maintain a clear distance of 100m. The reason in the perception difference of clear passing distance is dual. Firstly, the overtaking ship takes the initiative to take evasive behavior during the encounter, which is also requested by COLREGs. On the other hand, in most cases of portside overtaking, the maneuvering space of overtaking ship to achieve a larger clear distance is also larger. In the speed respect, a higher-speed overtaking ship aims to reach a higher relative speed when passing the front ship, which is 0.3 times of her own SOG. While for overtaken ships, irrespective of their own SOG, the objective of their speed change is to achieve a relative speed around 2-3 m/s. The speed change requires more fuel consumption than course alteration. The overtaking ship bearing the legal responsibility of collision avoidance aims to complete the process as soon as possible, considering both the safety requirement. However, for the overtaken ship as the stand-on one, the coordinated deceleration is mostly due to good seamanship to facilitate the process, which is not mandatory considering the potential fuel efforts.

In the encounters of ships sailing to the opposite direction, when looking at the full trajectory of ships before the passing-by moment, most of the ships take maneuvers to change their course or speed. The ships tend to change their speed to prepare for the encounter. But there is no obvious preference between acceleration and deceleration, which depends on the specific circumstances. However, when investigating the behavior pattern when the approaching distance is about 1 n mile right before the passing moment, over 76% of the ships do not take any evasive behavior as required by COLREGs. According to the definition in *Rule 14*, these OOW onboard judge the encounter as without risk of collision, which should be identified as a passing-by situation without requirement on evasive maneuvers. Among the ships taking course alteration and/or speed change, the lateral distance at the key feature points and the passing-by moment area compared via KS test. The results accept the null hypothesis that they come from the same distribution. It implies that the lateral distance at the key feature points is already sufficient for a safe passing-by. The behavior change maneuvers could be due to the sailing preferences of OOW onboard in case of the interaction between ships. Regarding the timing of such maneuvers, most of the ships start when the approaching distance is around 1-1.6km. From the temporal perspective, the time is around 1.5-2min before the passing moment, in which speed change is slightly earlier than course alteration. It can be understood that when the sailing speed is sufficient to maintain the turning maneuverability, the evasive effects of course alteration come faster than speed change. Thus, to achieve their objectives, speed change needs to be performed earlier.

The proposed behavior analysis methodology systematically identifies the behavior in different encounters in inland waterways. Compared to the typical evasive behavior during collision avoidance in literature research, some conventional sailing behavior during encounters in ports and waterways are also revealed. When the objectives of own behavior have been reached, ships will not take unnecessary evasive maneuver as generally instructed by COLREGs. The analysis result could benefit both the port authority and the researchers. For the port authority, the detailed look into ship behavior during encounters helps the ship traffic management when the traffic density is high. For the researcher, the findings enrich the knowledge on diverse ship behavior, in which not only the theoretical evasive behavior will happen. By investigating the conditions, timing, and objective of ship behavior before the critical moment, the behavior during the encounters can be simulated accordingly.

Due to the limitation of the research area, the ship behavior after the critical moment of encounters is not fully investigated. The ship behavior in a crossing situation at the intersections in ports is left, either. The mathematical models based on the findings to quantitatively describe and predict the behavior can be developed. Based on a systematic look into detailed ship behavior under different external factors in confined waters, including environmental factors and dynamic encounters, a new maritime traffic model can be expected to simulate the ship behavior in ports and waterways.

7. Conclusions, Implications, and Recommendations

This dissertation investigates ship behavior in ports and waterways. The overall objective is to gain empirical knowledge of ship behavior in real-life sailing environments and the impacts of intrinsic and external factors. The intrinsic ship characteristics distinguish the unhindered behavior among different ships, while the external factors depicting the sailing environment, including static navigational infrastructures, dynamic environmental factors, and dynamic encounter with other ships.

This final chapter summarizes the dissertation with the main findings of this research in section 7.1 and the overall conclusion in section 7.2. The practical implications of the research are presented in section 7.3. Finally, section 7.4 outlines the recommendations for future research.

7.1 Main findings

The main findings of this dissertation are summarized by answering the research questions formulated in section 1.2, which contributes to achieve the research objective.

1. *What are characteristics and limitations of the current maritime traffic models in describing the ship behavior under external impacts and the interactions between individual ships?*

The literature review on maritime traffic models presented in chapter 2 classifies the underlying paradigms into six categories, namely Cellular Automata, generic rule-based models, specific rule-based models, artificial potential field models, optimal control models, and system dynamics models. All maritime traffic models can describe the traffic state to different levels of details, which fulfils their stated application purposes. Before 2010, most maritime traffic models are developed to simulate the generic traffic state in one-dimensional space. After the mandatory use of AIS equipment onboard, the developed models can be calibrated and/or validated with AIS data. They can capture more details of ship behavior when modeling the maritime traffic.

Two types of limitations are also discovered in the current models. Firstly, for models with a generic description of maritime traffic state, the behavior variation between ships and (relevant) external impacts are generally oversimplified. Moreover, none of the existing models describe all dynamic kinetic information in detail for different ships and consider the impacts from the full range of external factors. Secondly, the existing models capturing more details of ship behavior and the external impacts can be applied in less sailing situations due to the requirement of specification on ship maneuvering for calibration and validation. We thus conclude that a maritime traffic model capable of simulating different ship behavior under different circumstances is needed, which in turn requires a systematic understanding of ship behavior and the influencing mechanisms.

2. *Not considering external impacts, what are the behavior characteristics between different ships in unhindered situations? From the ship behavior perspective, how to objectively classify ships using the intrinsic ship characteristics?*

A new coherent methodology is proposed in chapter 3 to cluster ship behavior in an area and to classify ships into these clusters based on the static ship characteristics. The ship behavior clustering methodology is based on *k*-means clustering theory and modified to overcome its drawbacks in terms of the subjective decision the user needs to make on number of clusters and sensitivity to initialization and stopping criteria. The proposed algorithm is stable in clustering results without these subjective decisions in the initialization phase. The clustering result can recognize both the fully different behavior patterns over the whole research area and the different behavior change patterns for some clusters of ships.

The *integral* ship behavior patterns (including both speed and path) can also be revealed. The ship classifier is developed according to the principle of Naive Bayesian classification, which uses intrinsic ship characteristics (such as length, beam) to classify ships into the behavior clusters. Instead of assuming a distribution to estimate the prior probability, two discretization methods (unsupervised Equal Width Binning and supervised Chi2) are tested to calculate the probability. With the holdout method, the developed classifier (based on training data set) has been used to classify ships (in testing data set) to the corresponding behavior cluster. The evaluation results of classification show that the Chi2 algorithm tends to perform better than EWB. The classifications based on length and beam outperform the ones based on a single criterion. The results reveal the underlying relation between ship characteristics and behavior patterns.

3. *When individual ships sailing in ports and waterways, how do the static navigational infrastructures influence the ship behavior?*

A framework is provided in chapter 4 to investigate the impact of external impacts on ship speed in ports and waterways with fully equipped navigational infrastructures. The navigational infrastructure is defined as all components for a safe and efficient water transportation system, including but not limited to waterway, jetty, bridge, river training structure, lock-and-dam facility and the supporting aids to navigation set by the local authority. Firstly, due to the physical conditions of the waterway layout, the potential impacts of varying current conditions are qualitatively analyzed from two aspects, being the tidal pattern and the current velocity. Based on a statistical analysis using AIS data during two typical one-week tidal period (the week with lowest and highest water level of the year), neither will influence the observed ship speed control behavior (twice deceleration-and-acceleration in the waterway stretch). Applying the ship classifier developed in chapter 3, the corresponding speed cluster of ships can be predicted. Based on the ship speed change patterns in clusters, the first acceleration of the low-speed inbound clusters is to maintain their maneuverability in case of the potential stronger bank effects in narrower waterway. The other deceleration-and-acceleration behavior is taken to prepare a safe speed to keep necessary precautions in the interconnecting area ahead, which complies with the good seamanship. Considering the distribution of navigational infrastructures along the waterway stretch, three Aids to Navigation are adopted as reference marks for waterway segmentation in the research area. By describing the statistical characteristics of ship behavior in clusters based on the waterway segmentation, the impacts of navigational infrastructures on ship speed in a complex waterway layout can be generalized.

4. *How do the environmental factors, such as wind and current, influence the individual ship behavior?*

A regression model is developed in chapter 5 to quantitatively analyze the impact of wind and current on ship behavior (Speed over Ground (SOG) and drift angle) derived from AIS data, and the variations of ship behavior and the external impacts due to the size differences.

The theoretical expression of the wind and impact mechanism is proposed based on the theory in dead reckoning to estimate ship position. The variation of SOG in the unhindered situation due to ship size is observed, which can be reflected by ship beam through a logarithmic function. The wind and current impact on ship behavior also vary for ships of different sizes. For small ships, both wind and current impacts decrease when the ships get larger. However, for large ships, the impact of wind on SOG gradually increases along with growing ship size, but the impact on the leeway angle fluctuates with a decrease. The impact of current on SOG for larger ships is smaller, but the impact on the drift angle is larger. For the coefficients that are significantly correlated to the ship's size by correlation analysis, the functions best estimate the relationship are adopted in the regression models. The results prove that the proposed theoretical expression of the impact mechanism and the revealed impact variation over ship size by analyzing the subsets of data are correct.

5. *How do ships change the speed and/or course during encounters in ports and waterways?*

As a first step to study all encounters in ports and waterways, an encounter is identified from the viewpoint of the spatial-temporal co-existence of ships in chapter 6. Instead of looking into specific encounter cases according to the subjective risk judgment, the sailing behavior of both ships are investigated by recognizing key feature points of behavior change adopting a Sliding Window Algorithm. The relative movement conditions at the critical moments are calculated and compared. It is shown that for ships sailing in ports and waterways relying on visual navigation, the intuitive relative movement indicators, such as the distance in between or the time to pass by each other, better describe the timing of behavior change than the geometrically calculated indicators.

The encounters of ships sailing to the same direction are considered as *overtaking situations*. When the distance between ships is around 1 km and the latter ship sails slower than the front one, the latter ship will follow the front ship without overtaking tendency. If the latter ship sails faster than the front one, the overtaking behavior can be observed. During the overtaking process, about 14% of the overtaking ships do not take any evasive actions, while for the ones changing behavior, the selection between course alteration and speed change is equal. Around 87% overtaken ships take cooperative maneuvers to facilitate the overtaking process, in which more than 70% adjust their speed. The timing for the overtaking ship taking evasive behavior is when the visual distance is around 0.8–1.5 km, which is 0.5–1 km for overtaken ships. For overtaking ships, the objective of course alteration is to achieve a clear passing distance about 50–150 m, which is 5 times of her beam. But for overtaken ships, the objective of clear distance is 100m. In the speed respect, a higher-speed overtaking ship aims to reach a higher relative speed when passing the front ship, which is 0.3 times of her own SOG. While for overtaken ships, irrespective of her own SOG, the objective of her speed control is to achieve a relative speed around 2–3 m/s.

In the encounters of ships sailing to the opposite direction, most of the ships maneuver to change their course or speed far before the passing-by moment, with a preference to speed change. Within the influence distance of 2 km, over 76% of the ships do not take any evasive behavior as required by the International Regulations for Preventing Collisions at Sea (COLREGs). According to the definition, these officers onboard judge the encounter as without risk of collision, which is identified as a passing-by situation without requirement on evasive maneuvers. Among the ships changing behavior, the lateral distance at the key feature points is already sufficient for a safe passing-by. The behavior change maneuvers are probably due to the sailing preferences of officers onboard in case of the interaction effects between ships. The start of such maneuvers is mostly at a distance of around 1–1.6 km, and about 1.5–2 min before the passing moment, in which speed change is slightly earlier than course alteration.

7.2 Overall conclusions

Based on the findings of individual chapters to answer research questions, the overall conclusions are drawn in response to the main objective of this dissertation. The ship behavior in real-life sailing environment in ports and waterways can be deemed as the unhindered behavior distinguished by the intrinsic ship characteristics incorporated with the impacts from external factors external factors depicting the sailing environment, including static navigational infrastructures, dynamic environmental factors, and dynamic encounter with other ships. So far, such ship behavior is not yet fully covered in the existing behavior analysis and maritime traffic models.

In respect of unhindered ship behavior, this dissertation reveals the *non-negligible variation* among different ships. The proposed coherent methodology can recognize the behavior patterns in an area via behavior clustering techniques, while the ships can be classified to such behavior clusters based on their own intrinsic characteristics. The results also show that the intrinsic behavior distinction underlies the different resulting behavior under external impacts as well.

Regarding *external factors*, different approaches are adopted in this research to investigate the impacts, from the static permanent ones to the dynamic occasional ones. Considering the nature of visual navigation in ports and waterways instead of automatic steering at sea relying on electronic devices, the impact of navigational infrastructures on ship speed is generalized by describing the statistical characteristics of speed in ship behavior clusters in waterway segments marked by the infrastructures, such as Aids to Navigation. From the viewpoint of navigation practice, the theory of dead reckoning to estimate ship position by officers onboard is adopted to formulate the impacts of wind and current on ship speed and drift angle, which can be further quantified by the proposed regression model. Finally, the ship behavior during encounters can be described by the conditions of relative movement indicators at the recognized key feature points of behavior change and the behavior objectives at the critical moment when the distance in between is minimum. All revealed external impacts reflect the practical decision-making and maneuvering process of officers onboard, which follows the good seamanship and the ordinary practice of seaman.

7.3 Implications for practice

This research aims to investigate the ship behavior from the empirical perspective, which is derived from the empirical evidence and expected to be used by the practitioners in the maritime traffic field. In this section, the practical implications of the main findings are discussed.

The ship behavior clustering results reveal the ship behavior patterns and the ship behavior change patterns in an area, while the developed classifiers can be used to predict the behavior patterns of ships. Upon receiving the arrival report of a ship via Vessel Traffic Services (VTS) in the area, the port authority can predict the general behavior pattern based on the basic intrinsic ship characteristics, such as the possible speed range or lateral position in the waterway. For the port authority, based on the knowledge of all ships, *they can generally estimate the ship traffic state*, especially when the ship traffic is busy or there are ships sailing with specific requirement, such as LNG ships, etc.

The findings on the external impacts by local environmental factors, i.e., navigational infrastructures, wind and current, provide theoretical references and empirical evidence for local traffic management policies regarding ship behavior suggestions along the navigational infrastructures and temporary traffic control measures under specific circumstances for navigation risk control. Since this research already incorporates the decision-making logic and sailing process of officers onboard during empirical analysis, the obtained knowledge of such impacts follows the navigational practices. Thus, *the policies or measures based on such results fulfil both the local sailing habits and requirements of the officers onboard and the safety and capacity requirement of the port authority*.

The findings on ship behavior during encounters provide a systematic overview of the possible behavior patterns at different stages of encounter processes, which can be used for temporary traffic management under high traffic density. The results are in accordance with the conventional sailing behavior in ports and waterways, which is different from the behavior in open waters. Thus, *traffic control measures can be developed appropriate to the situations*.

The overall findings on ship behavior and the influencing mechanisms of relevant factors direct to the development of a new maritime traffic model describing the ship behavior as in real-life situations. The findings on different factors can be integrated to simulate the ship behavior under different circumstances. Such a model can be used as a support tool to predict the traffic state in different scenarios of port expansions or new port designs.

7.4 Recommendations for future research

This dissertation has provided a systematic framework to understand the ship behavior in real-life environment from an empirical perspective. However, due to the limitations of the research area and available data, future research to complete the understanding and further modeling of ship behavior is still needed.

Investigating intrinsic ship behavior differences. Considering the reliability of data, only length and beam are taken as intrinsic ship characteristics in this research. Future research can include more ship characteristics. With a more comprehensive data set of ship particulars (e.g., Gross Tonnage, Deadweight Tonnage, actual draught), the most appropriate intrinsic factor distinguishing unhindered ship behavior can be identified. For example, the loading status and information of actual draught are usually orally reported via Vessel Traffic Service report upon the arrival of a ship. With such voyage-related information, the proposed classifier performances can be further improved to indicate ship behavior patterns.

Completing the base cases of ship behavior. In the literature research to assess the application of existing maritime traffic models, an overview of the ship movement base cases in ports and waterways is provided in chapter 2. In the research area of this dissertation, only straight flows and bending flows are fully investigated in a waterway with changing width and a interconnecting area. It is still far from complete understanding of ship behavior in different waterway layout and traffic flow compositions. Future research can be performed in other research area to investigate the ship behavior in different base cases, which will provide a full image of possible scenarios in ports and waterways. It is necessary for the application in port planning and design.

Investigating the post-encounter ship behavior. Due to the limitation of the research area in the dissertation, the ship behavior after the critical moment of encounters is not fully investigated. Future research needs to investigate the post-encounter ship behavior after being past and clear as stated in chapter 6. The ship behavior in a crossing situation at the intersections in ports is left, either. The investigation of ship behavior in crossing situations can be incorporated with the base cases of crossing flows in ports and waterways, since the definition of crossing situation may also need to be adapted to inland environment.

Developing the new maritime traffic model. The main findings in this dissertation provide a framework to describe the ship behavior in real-life environment. The unhindered ship behavior distinguished by intrinsic ship characteristics forms the basis. The impact of navigational infrastructures is generalized as rules of behavior for ship clusters via descriptive statistics, which provides the probability distribution or the restrictive conditions of ship behavior in certain area. Given the wind and current conditions, the proposed regression model can predict the ship behavior under specific circumstances. With the dynamic behavior information of ships simulated in the area, based on the given definition of encounter and its process, the timing and objectives for either involved ship to change her behavior are provided according to the relative movement conditions. Such a generic model would meet both requirements of capturing different ship behavioral details and being applicable for different purposes in different area. The source of Automatic Identification System data also makes calibration and validation of the models possible.

Adapting the methodologies to the mixed traffic of manned and autonomous ships. With the rapid development of autonomous ships, they are expected to sail in ports and waterways in the near future. In the research on autonomous ships, it is assumed to be a system with ships all smart, coordinated, and autonomous. However, we are still far away from the full autonomous shipping. It can be expected that the mixed traffic of both manned and autonomous ships will last a long time. The findings in this dissertation focus on the current manned ships, while the developed methodologies can be adapted to investigate the ship behavior in mixed traffic state.

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Summary

As one of the most important freight transportation modes, maritime transport has been the backbone of international trade and global economy. From the cargo flow point of view, seaports and inland shipping link the individual countries and the global waterborne transportation networks. To analyze the current ship traffic and port performance or predict future scenarios, understanding ship behavior in ports and waterways is necessary. However, the depicted sailing environment is in the current studies far simpler than the real-life ports and waterways. To this end, we formulate the following research objective:

to gain empirical knowledge of ship behavior in real-life sailing environments and to empirically investigate the influencing mechanisms of intrinsic and external factors.

To achieve this goal, we start with a broad and in-depth literature review of existing maritime traffic models, which generalizes the overall sailing environment of ships and figures out the limitations in understanding and modeling ship behavior. It is shown that maritime traffic models describe the traffic state to different levels of detail according to their stated application purposes. However, there reveals two main limitations. Firstly, for models generically describing maritime traffic state, the behavior differences between individual ships and the external impacts are simplified to a large extent. None of the existing models describe all dynamic kinetic information in detail for individual ships and consider the impacts from the relevant range of external factors. Secondly, the models to capture details of ship behavior and external impacts cannot be applied in general situations, since the data of ship maneuvering specifications for calibration and validation is not always available. Hence, a systematic understanding of the generic ship behavior and the influencing mechanisms from environmental factors are needed.

The ship behavior in ports and waterways is deemed as the unhindered behavior distinguished by the intrinsic ship characteristics incorporated with the impacts from external factors depicting the sailing environment, including static navigational infrastructures, dynamic environmental factors, and dynamic encounters with other ships. Different approaches have been adopted in this dissertation for empirical investigation using one-year Automatic Identification System data in port of Rotterdam. The main findings and the corresponding practical implications are introduced as follows.

Regarding unhindered ship behavior, a new coherent methodology has been proposed to cluster observed ship behavior in an area and to characterize ships in these clusters based on the (static) ship characteristics. The result can identify both the different behavior patterns over the whole research area and the behavior change patterns for some ship clusters. Thus, the integral ship behavior pattern can be identified. With the holdout method, the developed classifier has been used to classify ships to the corresponding behavior cluster. The results explain the underlying relationship between intrinsic ship characteristics and identified behavior patterns. This way, upon the arrival of a ship, the port authorities are capable of predicting the general behavior patterns based on the basic intrinsic ship characteristics.

To investigate the impact of static navigational infrastructures, such as the waterway layout and Aids to Navigation, on ship speed in a complex waterway layout, a framework is provided. Besides the navigational infrastructures themselves, the potential impact of varying current conditions due to the physical conditions is also included. Based on the statistical analyses, neither the tidal pattern nor the velocity of the current influence the observed ship speed control phenomena. In ports and waterways, the officers on board rely on visual navigation following the distribution of navigational infrastructures along the waterway stretch. Thus, the Aids to Navigation are adopted as reference marks for waterway segmentation. It generalizes the impact of navigational infrastructures by the statistical characteristics of observed speed in clusters of ships in the area.

To quantify the impacts of environmental factors, i.e., wind and current, a regression model is developed for ship speed and drift angle, and the variations of ship behavior and the external impacts due to the size differences. The wind and current impact mechanism is formulated based on the theory of dead reckoning. The variations of speed in unhindered situation and the impacts due to ship size are reflected by the functions best estimate the relationship via correlation analysis. From the analysis results using the subsets of data, the proposed theoretical expression of the impact mechanism correctly explains the impact variation over ship size. The findings provide empirical evidence to justify the deployment of certain temporary traffic control measures, such as speed limit under specific circumstances.

Regarding the ship behavior during encounters, as a first step to include all encounters in ports and waterways, the encounter is identified from the viewpoint of the spatial-temporal co-existence of ships. Instead of looking into specifically selected cases according to the subjective risk judgment, the sailing behavior of both ships in all encounters is investigated by recognizing their key feature points of behavior change during the encounter processes. The findings on ship behavior during encounters provide a systematic overview of the possible behavior patterns at different stages of encounter. The relative movement conditions at the recognized key feature points and the critical moment with minimum distance between the ships are revealed through an empirical analysis. It is shown that for ships sailing in ports and waterways relying on visual navigation, the intuitive relative movement indicators, such as the distance in between or the time to pass by each other, better describe the timing of behavior change than the geometrically calculated indicators. The results can be used for temporary traffic management under high traffic density.

Despite the scientific and practical contributions presented in this dissertation, future research is still needed to further our understanding and comprehensive modeling of ship behavior in ports and waterways. Firstly, more reliable and generic ship specifications can be included to identify the appropriate intrinsic characteristics distinguishing the unhindered behavior. Secondly, directing to a complete and systematic understanding of ship behavior, the ship movement base cases can be adopted to guide future investigation, which will provide a full image of possible scenarios in ports and waterways. Thirdly, a generic model capturing different ship behavioral details in different sailing environments can be developed. The findings of this dissertation to describe the ship behavior in real-life environment can be adopted, including the unhindered behavior distinguished by intrinsic factors and the influencing mechanisms by external factors. Last but not least, with the rapid development of autonomous ships, the methodologies proposed in this dissertation can be adapted to investigate the ship behavior in mixed traffic of manned and autonomous ships, which will last for a long time.

Samenvatting

Als een van de belangrijkste modaliteiten voor het vervoeren van vracht is het maritime vervoer de ruggengraat van de internationale handel en de wereldeconomie. Zeehavens en binnenvaart verbinden afzonderlijke landen en wereldwijde vervoersnetwerken over water om goederen te vervoeren. Om het huidige scheepsverkeer en de prestaties van havens te analyseren of toekomstscenario's te voorspellen, is inzicht in het gedrag van schepen (en hun bemanning) in havens en vaarwegen noodzakelijk. De vaaromgeving die in de huidige studies wordt gebruikt, is echter veel eenvoudiger dan de werkelijke omgeving van havens en waterwegen. Daarom is de volgende onderzoeksdoelstelling geformuleerd:

het opdoen van empirische kennis van het gedrag van schepen in realistische vaaromgevingen en het doen van empirisch onderzoek naar de mechanismen waarmee intrinsieke en externe factoren dit gedrag beïnvloeden.

Om dit doel te bereiken, is gestart met een breed en diepgaand literatuuroverzicht van bestaande maritieme verkeersmodellen, waarbij de volledige vaaromgeving van schepen wordt gegeneraliseerd en de beperkingen van het begrijpen en modelleren van scheepsgedrag in kaart worden gebracht. Het blijkt dat bestaande maritieme verkeersmodellen de verkeerssituatie op verschillende detailniveaus beschrijven, afhankelijk van de bijbehorende toepassingen. Er zijn echter twee belangrijke tekortkomingen. Ten eerste worden in modellen die de algemene verkeerssituatie op zee beschrijven de variaties in het gedrag van individuele schepen en de externe effecten sterk vereenvoudigd. Geen van de bestaande modellen beschrijft alle relevante dynamische kinetische informatie in detail voor individuele schepen en houdt rekening met de effecten van alle relevante externe factoren. Ten tweede hebben de modellen een beperkte algemene toepasbaarheid. Om details van het scheepsgedrag en de externe effecten te kalibreren en te valideren, is informatie nodig over de manoeuvres van individuele schepen. Deze informatie is echter beperkt beschikbaar, zodat modellen niet in algemene situaties worden toegepast. Er is dus behoefte aan een systematisch inzicht in het algemene gedrag van schepen en de mechanismen waarmee omgevingsfactoren dit gedrag beïnvloeden.

Het gedrag van schepen in havens en waterwegen wordt beschouwd als het ongehinderde gedrag dat wordt gekenmerkt door de intrinsieke kenmerken van het schip in combinatie met de effecten van externe factoren, waaronder statische navigatie-infrastructuur, dynamische omgevingsfactoren en dynamische ontmoetingen met andere schepen. Voor het empirisch onderzoek in dit proefschrift zijn verschillende benaderingen gevolgd, waarbij gebruik is gemaakt van gegevens van het Automatisch Identificatie Systeem in de haven van Rotterdam voor de periode van één jaar. De belangrijkste bevindingen en de bijbehorende praktische implicaties worden hieronder toegelicht.

Voor het onderzoeken van ongehinderd scheepsgedrag is een nieuwe coherente methodologie voorgesteld om waargenomen scheepsgedrag in een gebied te clusteren en schepen in deze clusters te karakteriseren op basis van hun (statische) scheepskenmerken. Met het resultaat kunnen zowel de verschillende gedragspatronen over het hele onderzoeksgebied als de patronen in gedragsveranderingen voor sommige scheepsclusters worden geïdentificeerd. Aldus kan het integrale scheepsgedragspatroon worden geïdentificeerd. De ontwikkelde classificator is gebruikt om schepen in te delen in overeenkomstige gedragsclusters. De resultaten verklaren de onderliggende relatie tussen intrinsieke scheepskenmerken en geïdentificeerde gedragspatronen. Zo kunnen de havenautoriteiten bij aankomst van een schip de algemene gedragspatronen voorspellen op basis van de intrinsieke kenmerken van het schip.

Om het effect van statische navigatie-infrastructuur, zoals de vaarwegindeling en navigatiehulpmiddelen, op de scheepssnelheid in een complexe vaarwegconfiguratie te onderzoeken, is een raamwerk ontwikkeld, waarmee de invloed van de onderliggende factoren in kaart kan worden gebracht. In dit raamwerk wordt niet alleen de navigatie-infrastructuur, maar ook het potentiële effect van wisselende stromingsomstandigheden als gevolg van de fysieke omstandigheden meegenomen. Uit de statistische analyses blijkt dat noch het getijdenpatroon noch de stroomsnelheid van invloed zijn op de waargenomen snelheden. Aangezien de navigatie in havens en waterwegen visueel georiënteerd is, wordt de navigatie-infrastructuur langs de waterweg gebruikt voor de segmentatie van de waterweg. Daardoor wordt het effect van navigatie-infrastructuur veralgemeniseerd aan de hand van de statistische kenmerken van de snelheid van schepen in clusters in het gebied.

Om de effecten van de omgevingsfactoren wind en stroming te kwantificeren is een regressiemodel ontwikkeld, dat de scheepssnelheid en de drifthoek verklaart ten gevolge van de variaties in het gedrag van het schip en de externe effecten als gevolg van de verschillen in de grootte van het schip. Het wind- en stroming- impactmechanisme wordt geformuleerd op basis van het gegist bestek. De variaties in de snelheid in een ongehinderde situatie en de effecten als gevolg van de scheepsgrootte worden weergegeven door de functies die dit verband het best schatten middels correlatieanalyse. Uit de analyseresultaten van subsets van gegevens blijkt dat de voorgestelde theoretische formulering van het impactmechanisme de impactvariatie als gevolg van de scheepsgrootte correct verklaart. De bevindingen leveren de theoretische en empirische onderbouwing voor het instellen van tijdelijke verkeersmaatregelen, zoals snelheidsbeperking onder specifieke omstandigheden.

Voor het analyseren van het scheepsgedrag tijdens interacties wordt een interactie geïdentificeerd vanuit het oogpunt van de ruimtelijk-temporele coëxistentie van schepen. Op deze manier kunnen interacties die op verschillende locaties en verschillende momenten plaatsvinden worden vergeleken, zodat we ons niet hoeven te beperken tot een select aantal interacties volgens een subjectieve risico-identificatie. Het vaargedrag van beide schepen in een interactie wordt onderzocht door de belangrijkste (sleutel)punten van hun gedragsverandering tijdens de interactie te herkennen. De bevindingen over het gedrag van schepen tijdens interacties geven een systematisch overzicht van de mogelijke gedragspatronen in de verschillende stadia van het interactieproces. De relatieve bewegingscondities op de sleutelpunten tijdens de interactie en het kritieke moment waarop schepen een minimale afstand houden worden geïdentificeerd door middel van een empirische analyse. Voor schepen die varen in havens en waterwegen die afhankelijk zijn van visuele navigatie, blijken de intuïtieve relatieve bewegingsindicatoren, zoals de onderlinge afstand of de tijd om elkaar te passeren, de timing van gedragsverandering beter te beschrijven dan de geometrisch berekende indicatoren. Deze resultaten kunnen worden gebruikt voor tijdelijk verkeersmanagement bij hoge verkeersdichtheden.

Ondanks de wetenschappelijke en praktische bijdragen die in dit proefschrift zijn gepresenteerd, is toekomstig onderzoek nog steeds nodig om ons begrip en de uitgebreide modellering van het gedrag van schepen in havens en waterwegen verder te brengen. Ten eerste kunnen meer betrouwbare en generieke scheepsspecificaties worden opgenomen om de juiste intrinsieke kenmerken te bepalen die het ongehinderde gedrag van schepen beschrijven. Ten tweede kunnen de basis-interacties tussen schepen worden gebruikt als leidraad voor toekomstig onderzoek om een volledig en systematisch inzicht te krijgen in het gedrag van schepen. Daardoor ontstaat een volledig beeld van mogelijke verkeersscenario's in havens en waterwegen. Ten derde kan een generiek model worden ontwikkeld dat details van scheepsgedrag in verschillende vaaromgevingen beschrijft. De bevindingen van dit proefschrift over het scheepsgedrag in een realistische omgeving kunnen worden overgenomen, met inbegrip van de mechanismen waarmee intrinsieke en externe factoren dit scheepsgedrag beïnvloeden. En last but not least, kunnen de in dit proefschrift voorgestelde methodologieën worden aangepast om het scheepsgedrag in gemengd verkeer van bemensde en autonome schepen te onderzoeken.

About the author

Yang Zhou was born in Wuhan, Hubei, China, on September 21st, 1989. She received the B.Sc. degree in Maritime Administration from Wuhan University of Technology, and the dual B.Sc. degree in English Languages and Literatures from Huazhong University of Science and Technology, Hubei, China, in 2011. In the same year, she started her master programme at Wuhan University of Technology under the supervision of Prof. Jianjun Weng. She obtained her M.Sc. degree in Traffic Information Engineering and Control from Wuhan University of Technology in 2014. Her master thesis was entitled "Heterogeneous port traffic of ships and seaplanes and its simulation".

In September 2013, sponsored by China Scholarship Council, Yang Zhou started her PhD research in the Department of Hydraulic Engineering and the Department of Transport and Planning, Delft University of Technology. Under the supervision of Dr.ir. Winnie Daamen, Prof.dr.ir. Serge P. Hoogendoorn, and Prof.ir. Tiedo Vellinga, she worked on the investigation of ship behavior in ports and waterways via empirical analysis using Automatic Identification System (AIS) data in port of Rotterdam. During this research, she has presented various papers and posters in the Netherlands and at international conferences and published several articles in international journals.

In the future, Yang Zhou will continue her career in the field of maritime traffic as an educator and researcher. Her research interests include but not limited to ship collision avoidance, ship behavior analysis and simulation, maritime traffic modeling, AIS data analysis for maritime transport.

List of publications

Journal articles

1. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2020). Impacts of wind and current on ship behavior in ports and waterways: A quantitative analysis based on AIS data. *Ocean Engineering*, 213, 107774.

2. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2019). Review of nautical traffic models from vessel behavior modelling perspective. *Transportation Research Part C: Emerging Technologies*, 105, 323-345.

3. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2019). Ship classification based on ship behavior clustering from AIS data. *Ocean Engineering*, 175, 176-187.

4. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2015). Vessel classification method based on vessel behavior in the port of Rotterdam. *Scientific Journals of the Maritime University of Szczecin*, 114, 86-92.

The following articles are currently under review or prepared for submission:

5. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. Empirical analysis on impact of navigational infrastructure on ship speed in a complex waterway layout. *Physica A: Statistical Mechanics and its Applications*. (under review)

6. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. Ship behavior during encounters in ports and waterways based on AIS data: from theoretical definitions to empirical findings. (prepared for submission)

Conference contributions

7. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2017). AIS data analysis for the impacts of wind and current on ship behavior in straight waterways. In *Proceedings of International Congress of the International Maritime Association of the Mediterranean 2017*, 265-272, Lisbon, Portugal.

8. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2017). AIS data analysis for nautical traffic modelling. *PIANC the Netherlands: Sailing towards tomorrow* (poster), Rotterdam, the Netherlands.

9. **Zhou, Y.**, Weng, J., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2015). Heterogeneous port traffic of ships and seaplanes and its simulation. *Transportation Research Board Annual Meeting*, Paper No. 15-3697 (poster), Washington D.C., USA.

10. **Zhou, Y.**, Weng, J., Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2014). Heterogeneous port traffic of general ships and seaplanes and its simulation. In *Proceedings of the International Workshop on Nautical Traffic Models*, 46-51, Wuhan, China.

11. **Zhou, Y.**, Daamen, W., Vellinga, T. and Hoogendoorn, S.P. (2014). Nautical traffic modelling for safe and efficient ports. *The 3rd Erasmus Smart Port Rotterdam / Port Research Centre Rotterdam-Delft poster session* (poster), Rotterdam, the Netherlands.

Technical article in press

12. **Zhou, Y.** and Bellsolà Olba, X. (2018). Autonomous ships: nautical traffic in ports. *Port Technology International*, Edition 78: Linking the Supply Chain: 94-95.

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