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Ship behavior during encounters in ports and waterways based on AIS data: From theoretical definitions to empirical findings

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ABSTRACT

Currently, the research on ship behavior during encounters focuses on evasive behavior during specific situations with existing risks of collision. However, the preliminary selection of encounters to refine the presented ship behavior is biased. To obtain a full understanding of all ship behavior during different encounters in ports and waterways, the encounter is defined from the viewpoint of the spatial-temporal co-existence of ships in the same waterway segments during the same period. Based on this definition, this paper investigates ship behavior through the encounter process with other ships. The proposed approach starts from the moment when the distance in between is minimum as the critical moment to recognize ship behavior change (course alteration and speed change) based on the Sliding Window algorithm. Thus, the encounter process is identified by the key behavior feature point into phases, being before decision-making, before the critical moment, after the critical moment, and after being past and clear. The relative movement factors are calculated according to the behavior status of both ships to describe the conditions, timing, and objective of behavior change during the dynamic process of encounters. The empirical findings based on one-year Automatic Identification System data in the port of Rotterdam are presented. In the overtaking encounters, as the give-way ship, about 14% of the overtaking ships do not take any evasive actions. Among the ships with behavior changes, the preference for course alteration and speed change is equal. As the stand-on ship, about 87% of the overtaken ships take cooperative maneuvers to facilitate the encounter, in which deceleration seems the primary choice. The timing of overtaken ship's behavior change is later than overtaking ship. For overtaking ships, the objective of course alteration is a clear passing distance of about 5 times her beam, 100m for overtaken ships irrespective of her own size. Regarding speed, the overtaking ship aims to reach a relative speed of 0.3 times her own SOG, while the objective for the overtaken ship is fixed at around 2–3 m/s. In the encounters of ships sailing in the opposite direction, most of the ships take maneuvers to change their course or speed. However, within the influence distance of 2 km, over 76% of the ships do not take any evasive behavior, which implies a passing-by situation. Based on the recognized key feature points of behavior change, statistical tests show the objective of clear passing distance has been reached beforehand. The behavior change during head-on situations could be due to the precautionary behavior of officers onboard in case of interaction between ships. The findings enrich the knowledge of ship behavior during different types of encounters in real-life navigation, which can be further applied to simulation models for ship behavior in ports and waterways.

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 of 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

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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. In the current studies, there are three main approaches to analyze the ship behavior during encounters for collision avoidance, being domain-based approach, indicator-based approach, and process-based approach. All of them select the encounters with a prepositive definition of triggering condition, such as domain invasion or threshold value. *The development of ship domain is usually based on the collective sailing or evasive behavior preferences, which does not exactly describe the individual ship behavior and the detailed triggering conditions* (Du et al., 2021a; Szlapczynski et al., 2018). 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 (Ożoga and Montewka, 2018; Rong et al., 2022; Zhang et al., 2015). *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.* The process-based approaches detect the collision candidates and quantify the encounter as a dynamic process (Chen et al., 2018; Huang et al., 2019). *However, the candidate detection process still incorporates the selection of encounters at a certain risk level.* These studies only focus on the encounters with collision risk reflected by certain indicators, while the safe encounters without evasive behavior are not investigated.

Besides the above approaches describing the dynamic status of encounter, the analysis of ship collision avoidance behavior is also performed from the ships own perspective. The researches investigate the ships evasive behavior in compliance with the International Regulations for Preventing Collisions at Sea (COLREGs) (International Maritime Organization, 1972) (Cho et al., 2021; Hagen et al., 2022; Statheros et al., 2008; Xu et al., 2014). The researchers mostly further propose corresponding models of collision avoidance. Furthermore, from the viewpoint of the own ship, the ship behavior during encounters can be classified based on the approaching bearing (Cho et al., 2022; Gao et al., 2020; Gao and Shi, 2020). The intuitive results cover all possible encounter situations in the probabilistic way. However, the studies are mostly performed 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. For the research focusing on the ship behavior in ports and waterways, 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 are adopted in confined waterways. To simulate the ship behavior during head-on and overtaking situations, Xiao (2014) estimate the approximate distance range of potential impacts from historical Automatic Identification System (AIS) data. Therefore, to fully understand the ship behavior (both trajectory and speed) during encounter process in ports and waterways, the behavior of both ships and the potential triggering conditions of evasive behavior still needs to be studied. The investigation should not be based on a subjective definition of perceived risk level.

This paper aims *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 ship behavior in common scenarios of two-ship encounter in ports and waterways are theoretically analyzed in phases and empirically investigated from historical AIS data. The innovative contributions of this paper are trifold. Firstly, instead of a prepositive selection of encounters based on collision risk assessment, this paper analyzes ship behavior from the viewpoint of the spatial-temporal co-existence of ships irrespective of the approaching bearing. This way, the findings based on the behavior of all ships in encounters present the overview of ship behavior during the process, which shows the differences among individual ships. Secondly, from the perspectives of both ships, the influencing factors of ship behavior are analyzed in identified phases. Finally, the moment with minimum distance between the ships is taking as the critical moment and the start point to analyze the ship behavior patterns through the process. From this moment backward, the key feature points with behavior changes initiating the interaction can be identified. The proposed approach avoids the assumptions on the start of an encounter based on distance or risk level and aims to automatically analyze and identify the ship behavior during the encounters.

The remainder of this paper is organized as follows. Section 2 elaborates the research approach from data preprocessing to qualitatively and quantitatively analyzing the ship behavior under impacts during encounter processes, including the definition and classification of encounters. Section 3 introduces the research area and the overview of observed encounters from AIS data, while the detailed analysis results are illustrated in Section 4. Finally, Section 5 concludes the paper with discussion and recommendations for further research.

2. Research approach

The flow diagram in Fig. 1 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. The characteristics of relative movement status at the corresponding points during the encounter process are analyzed.

2.1. 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.

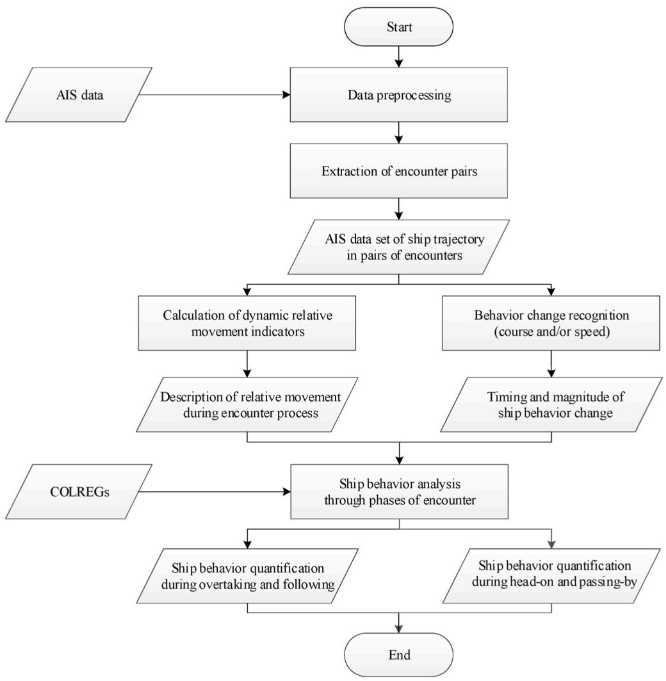

Fig. 1. Flow diagram of data pre-processing and data analysis. The ship behavior quantification refers to the empirical analysis to acquire the general characteristics of ship behavior pattern during encounters.

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 s, or at least the messages are transmitted at an interval of 10 s 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° (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 s.

2.2. Definition and extraction of encounters

In this section, the definition of encounter in this paper and the classification by COLREGs is introduced in Section 2.2.1, followed by the method of extracting encounter pairs of ship trajectories in AIS data in Section 2.2.2. Section 2.2.3 explains the calculation of dynamic relative movement status for each pair of extracted encounters.

2.2.1. 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 paper, 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 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 paper, 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 bidirectional 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 paper, 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 paper. 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 Fig. 2.

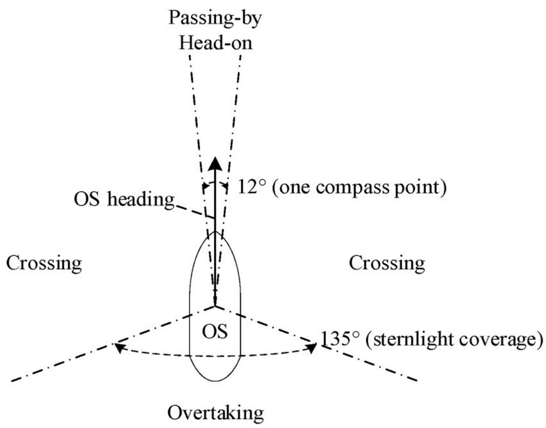

Fig. 2. Classification of encounter situations in ports and waterways.

2.2.2. *Extraction of encounters in AIS data*

According to the broader definition of encounter in Section 2.2.1, 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^i_{arr} and leaves at t^i_{dep}, and ship j enters the waterway segment at t^j_{arr} and leaves at t^j_{dep}. Ship i and ship j is considered as a pair of encounter candidates satisfying the following criterion

$$\left[t^i_{arr}, t^i_{dep}\right] \cap \left[t^j_{arr}, t^j_{dep}\right] \neq \varnothing \tag{1}$$

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.

2.2.3. *Calculation of dynamic relative movement during encounter process*

For each ship pair of the extracted encounters, the relative movement at each time stamp during the encounter process is calculated using the coordinate system shown in Fig. 3. The AIS data provides dynamic information in the space-fixed coordinate system $o_0 - x_0y_0$, 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.

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

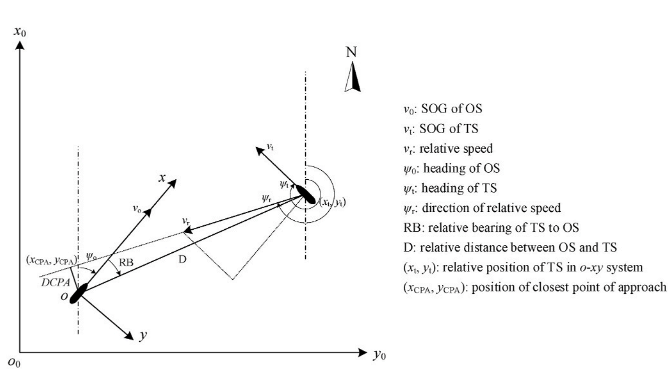

Fig. 3. Illustration of dynamic relative movement of TS (right) to OS (left) at one time stamp in the coordinate systems from the perspective of OS.

be directly calculated in the space-fixed coordinate system $o_0 - x_0y_0$.

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.

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

$$\psi_r = \psi_t - \arccos\frac{v_t^2 + v_r^2 - v_0^2}{2v_tv_r} \tag{3}$$

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.

$$\begin{cases} x_t = D\cos(RB) \\ y_t = D\sin(RB) \end{cases} \tag{4}$$

$$\begin{cases} x_{CPA} = \sin(\psi_r - \psi_0)(\sin(\psi_r - \psi_0)x_t - \cos(\psi_r - \psi_0)y_t) \\ y_{CPA} = \cos(\psi_r - \psi_0)(\cos(\psi_r - \psi_0)y_t - \sin(\psi_r - \psi_0)x_t) \end{cases} \tag{5}$$

$$DCPA = \sqrt{x_{CPA}^2 + y_{CPA}^2} \tag{6}$$

$$TCPA = \frac{\sqrt{(x_t - x_{CPA})^2 + (y_t - y_{CPA})^2}}{v_r} \tag{7}$$

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.

2.3. *Encounter situations in waterways*

In the waterways with physical or virtual boundaries on both sides, the crossing situations occur less than other situations due to the layout restrictions. Thus, in this paper, we focus on the common situations in the area of ports and waterways. 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.

2.3.1. *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 m 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). When the sailing status of the ship is back to her original tendency, the situation is deemed as phase 0 again.

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 Fig. 4. 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 Fig. 4) 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., 2019), 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.

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 Fig. 4. 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)).

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

As discussed in Section 2.2.1, for two ships sailing to the opposite direction, they are approaching on reciprocal or nearly reciprocal courses, which 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 Fig. 5. 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. When the sailing status of the ships follows their original sailing plan, it comes back to phase 0 again.

During the head-on process, according to the qualitative comparison

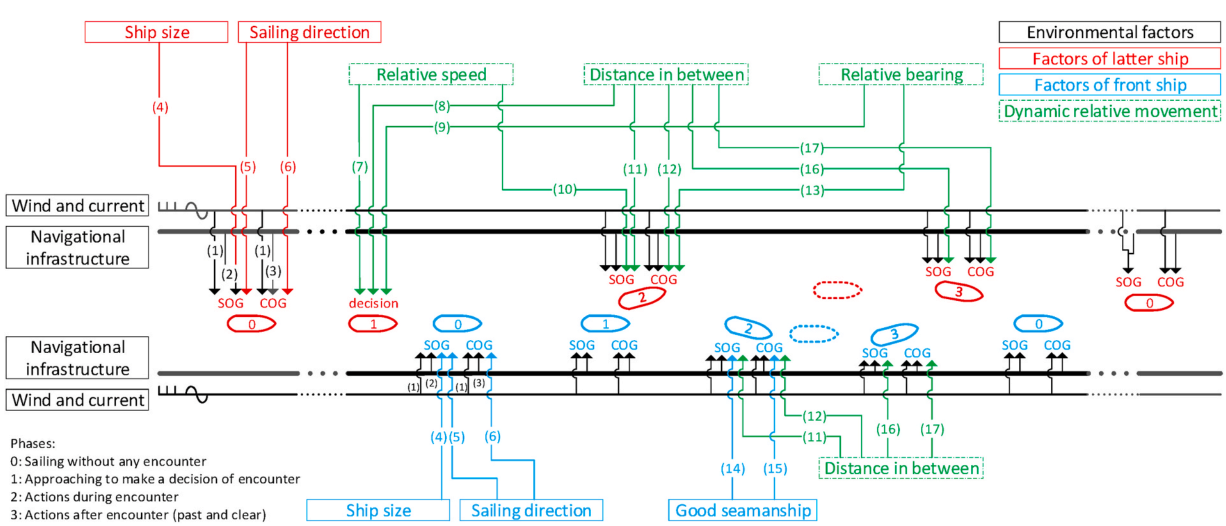

Fig. 4. Visualization of the impacts on both ship behavior during the overtaking process. The black thick lines refer to the waterway boundaries, while the black fine line refer to the existence of wind and current impacts throughout the voyage. The dashed position marks the moment when the latter ship (in red) overtakes the front one (in blue). The numbers inside both ships correspond to the phases of overtaking situation.

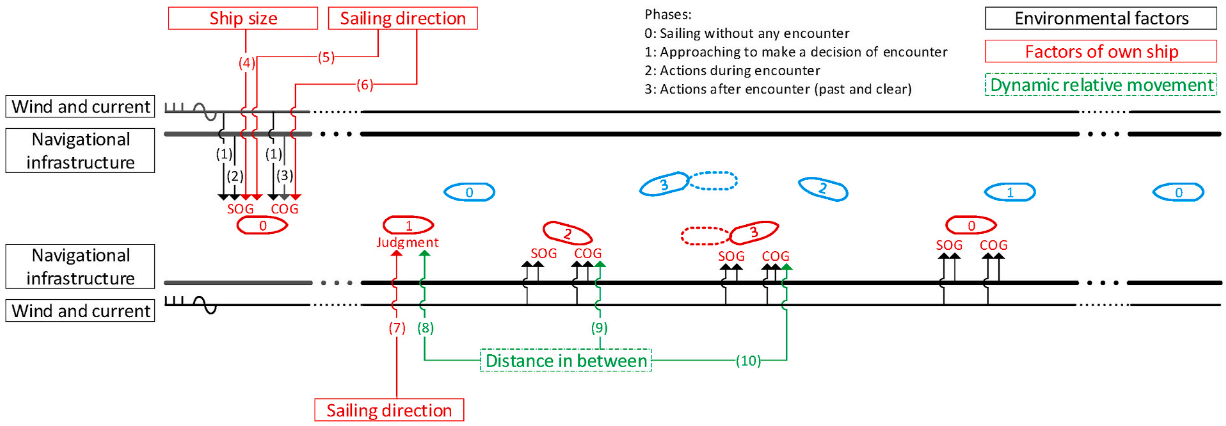

Fig. 5. Visualization of the impacts on either ship behavior during the head-on process. The black thick lines refer to the waterway boundaries, while the black fine line refer to the existence of wind and current impacts throughout the voyage. Both ships (in red and in blue) bear the same responsibility. 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.

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 Fig. 5. 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)).

2.4. Behavior changes recognition

In Section 2.3, 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.

2.4.1. 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 (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 2.3, 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 key feature points of 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 as shown in Fig. 6, 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), as presented in step (b) in Fig. 6. The iteration is repeated until the Euclidean distance of the last but one point (P_6 in Fig. 6) is judged. The last point is always retained as the key feature point. From the example in Fig. 6(e), it can be observed that P_3 is the point where a course change occurs, and the course fluctuation at point P_5 is discarded.

In this research, the initial points and threshold value to identify the key feature points with behavior changes can be determined according to the encounter phase, which will be explained in detail in Section 2.5 and Section 4.1.1.

2.4.2. 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

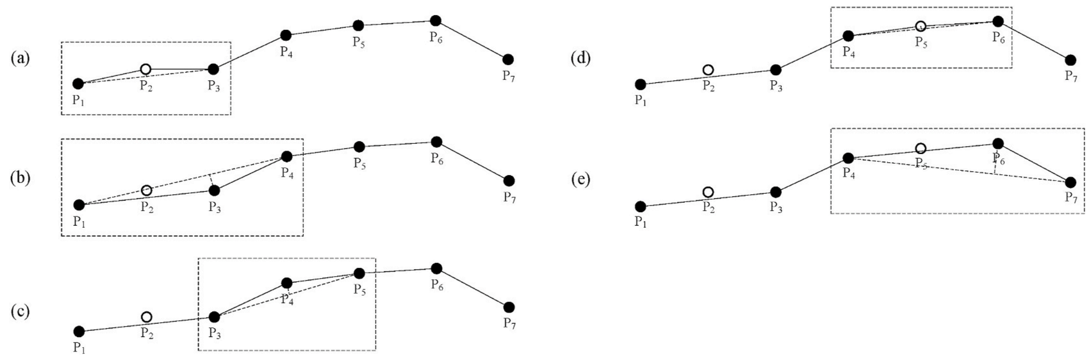

Fig. 6. Illustration of sliding window algorithm to recognize course alteration points.

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 calculated from speed change in AIS data 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 Section 4.1.2.

2.5. Ship behavior through phases of encounter

In Section 2.4, 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.

2.5.1. Sailing in the same direction

According to the encounter process in Fig. 4 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 Fig. 7, 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.

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) decelerates (accelerates) 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

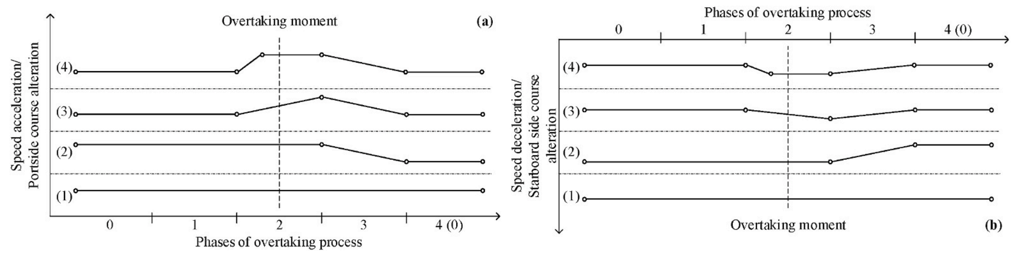

Fig. 7. Schematic diagram of ship behavior pattern through phases of overtaking process: (a) overtaking ship; (b) overtaken ship. The vertical dashed line refers to the overtaking moment in different patterns.

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 as analyzed in the behavior patterns 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 Fig. 4 and the dynamic relative movement factors calculated in Section 2.2.3.

2.5.2. 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 Fig. 7 (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 Fig. 7). 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 2.2.1.

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.

3. Research area and data description

The proposed research approach in Section 2 can be used to analyze AIS data in any ports and waterways. In this section, the research area for empirical analysis is introduced in detail in Section 3.1, followed by the collected AIS data providing information on ship behavior in Section 3.2.

3.1. Research area

The research area is located at the entrance of the port of Rotterdam, the Netherlands, as shown in Fig. 8. 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. When the environmental conditions allow, there are no additional sailing restrictions in the area by the local port authority (Port of Rotterdam, 2014). Overtaking is also permitted in the area. 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., 2019, 2020). The results show that the wind and current impacts are consistent in the area without sudden change leading to behavior change in a single voyage. Thus, the observed ship behavior changes during the process of encounter are not caused by the environmental factors. There are many navigational infrastructures (Aids to Navigation, e.g., buoys) along the waterway, while their impacts on ship speed is investigated in Zhou et al. (2022). The findings in the preliminary analyses are also incorporated in the investigation in this paper.

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. To investigate the ship behavior during the full process of encounters, 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 Fig. 8). The waterway stretch is about 10.2 km long, curved with a total direction change of about 20°.

3.2. 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

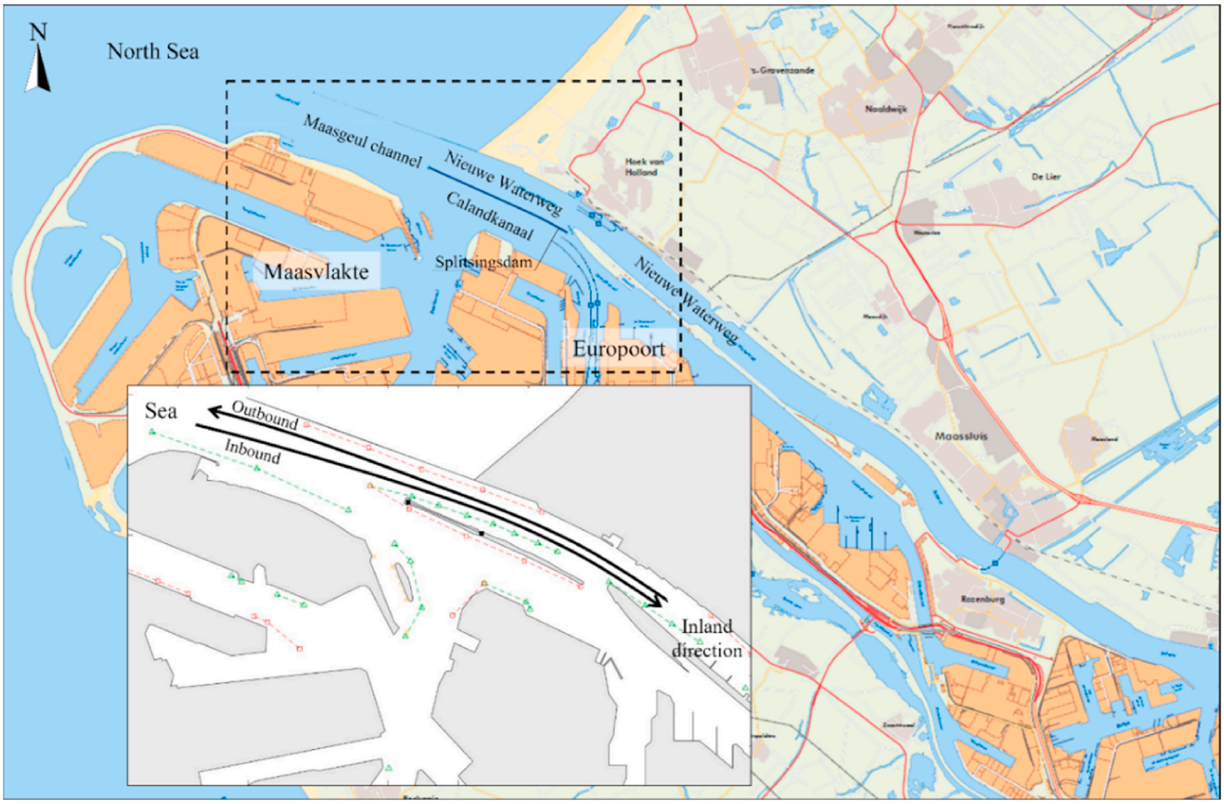

Fig. 8. Location of the research area in port of Rotterdam with specified ship traffic flow for analysis in the study.

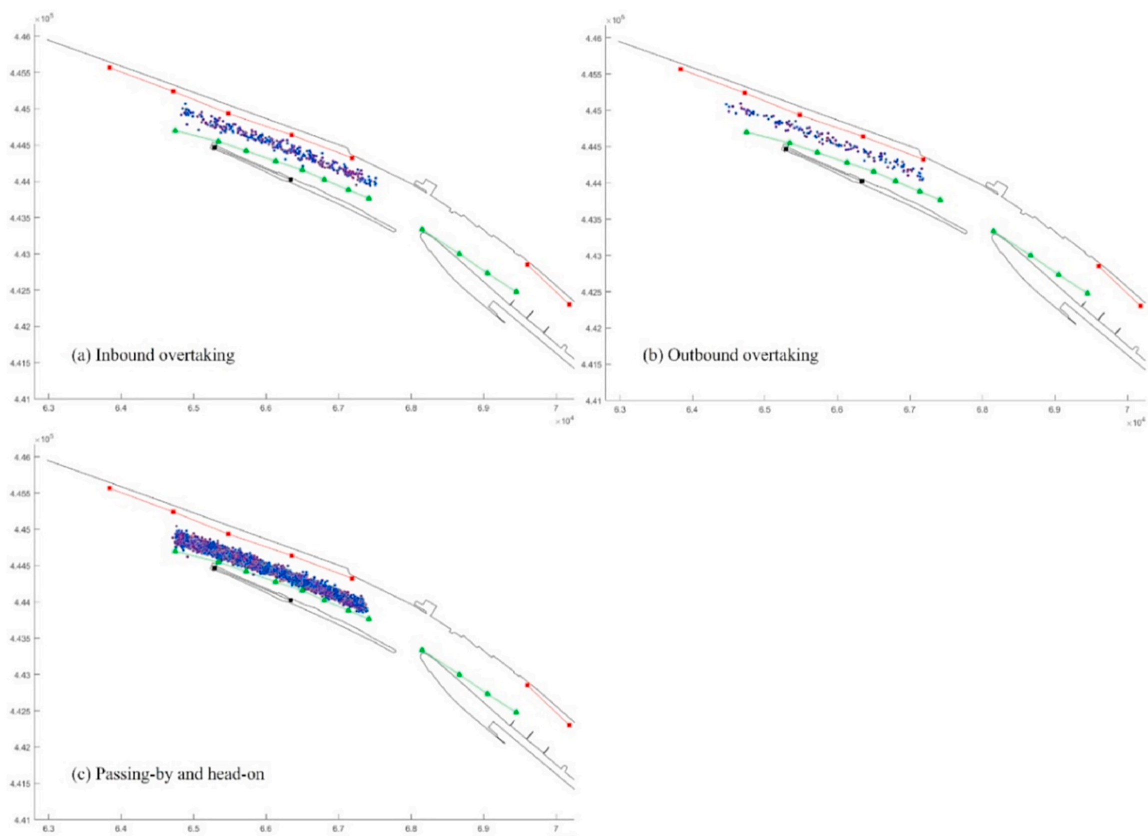

Fig. 9. Location of ships when the distance with the other ship is minimum during the encounter process: (a) location of inbound overtaking ship; (b) location of outbound overtaking ship; (c) location of inbound ship in passing-by and head-on situations.

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 s, or at least at an interval of 10 s 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 2.2.2, 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 Fig. 9). The number of the selected encounters extracted from the data set is listed in Table 1.

For the encounters of ships sailing into the same direction, all of them meet the definition of an overtaking situation as stated in Section 2.3.1. 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 2.2.1, 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 Fig. 9). 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.

4. 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 4.1. 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 4.2 and encounters with ships sailing in the opposite direction in Section 4.3.

4.1. Threshold determination for behavior change recognition

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

Table 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	

4.1.1. Course alteration

As introduced in Section 2.4.1, 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 Figs. 10 and 11. 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.

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 2.5.

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 2.5, for both encounter situations, the theoretical number of course alteration key feature points during the processes have been analyzed, which is 2–4. 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 Fig. 8). 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.

4.1.2. Speed change

Similar to the threshold determination for course alteration recognition, different threshold 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 Fig. 8), 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 2.5 considering individual behavior. The results of the recognized key feature points number are shown in Figs. 12 and 13.

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 Fig. 14. It can be found that in Fig. 14(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.

4.2. Encounter of ships sailing to the same direction

Due to the limited size of the research area, the full voyages of both

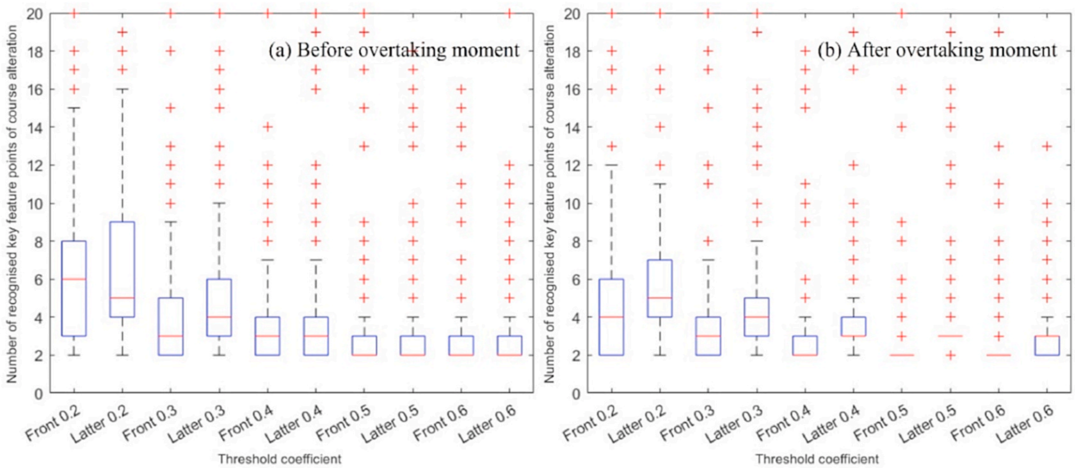

Fig. 10. Number of recognized key feature points of course alteration during the overtaking process using different threshold coefficients: (a) before overtaking moment; (b) after overtaking moment.

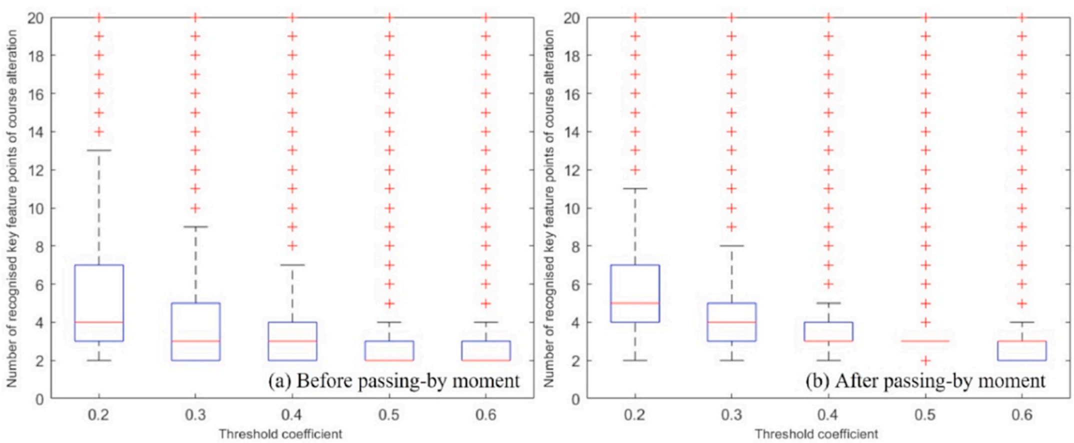

Fig. 11. Number of recognized key feature points of course alteration during the passing-by and head-on process using different threshold coefficients: (a) before passing-by moment; (b) after passing-by moment.

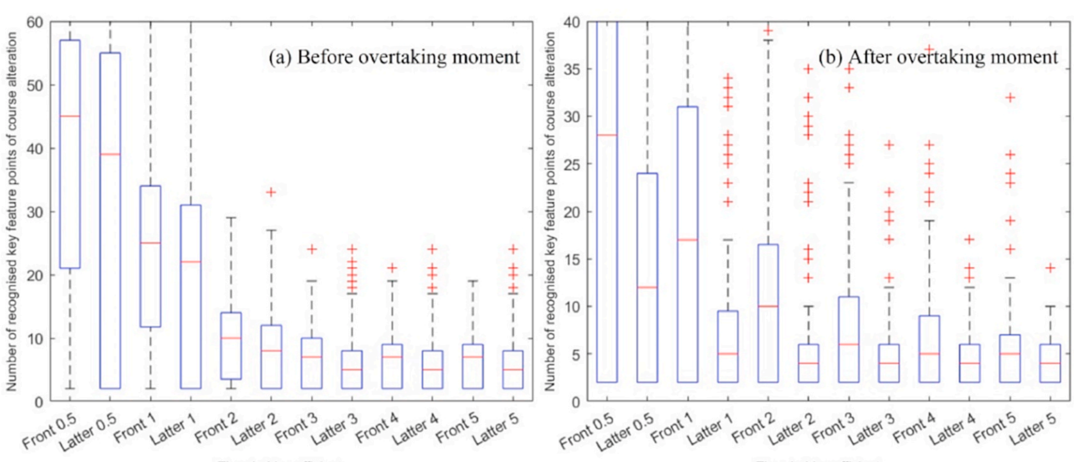

Fig. 12. Number of recognized key feature points of speed change during the overtaking process using different threshold coefficients: (a) before overtaking moment; (b) after overtaking moment.

ships heading to their destinations after overtaking are not included in the dataset. Thus, the impacts and ship behavior in phase 3 (see Fig. 4) cannot be fully elaborated in this paper. 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

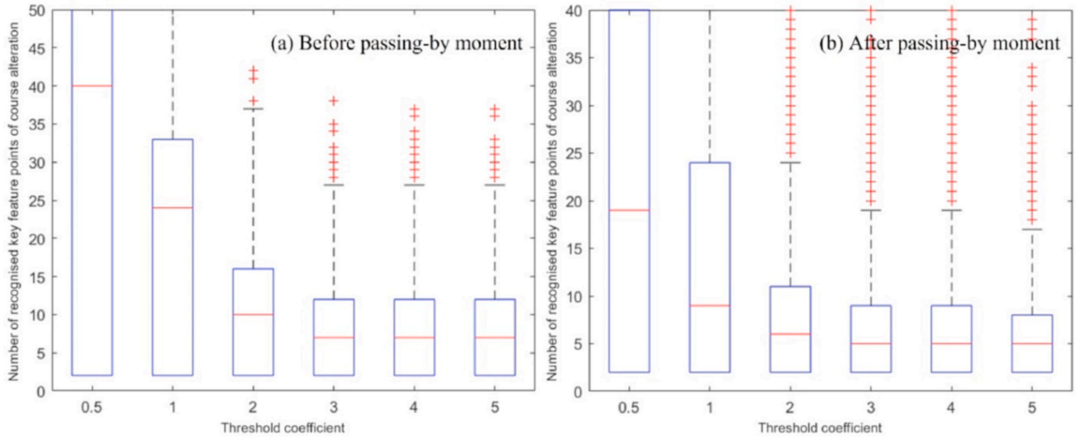

Fig. 13. Number of recognized key feature points of speed change during the passing-by and head-on process using different threshold coefficients: (a) before passing-by moment; (b) after passing-by moment.

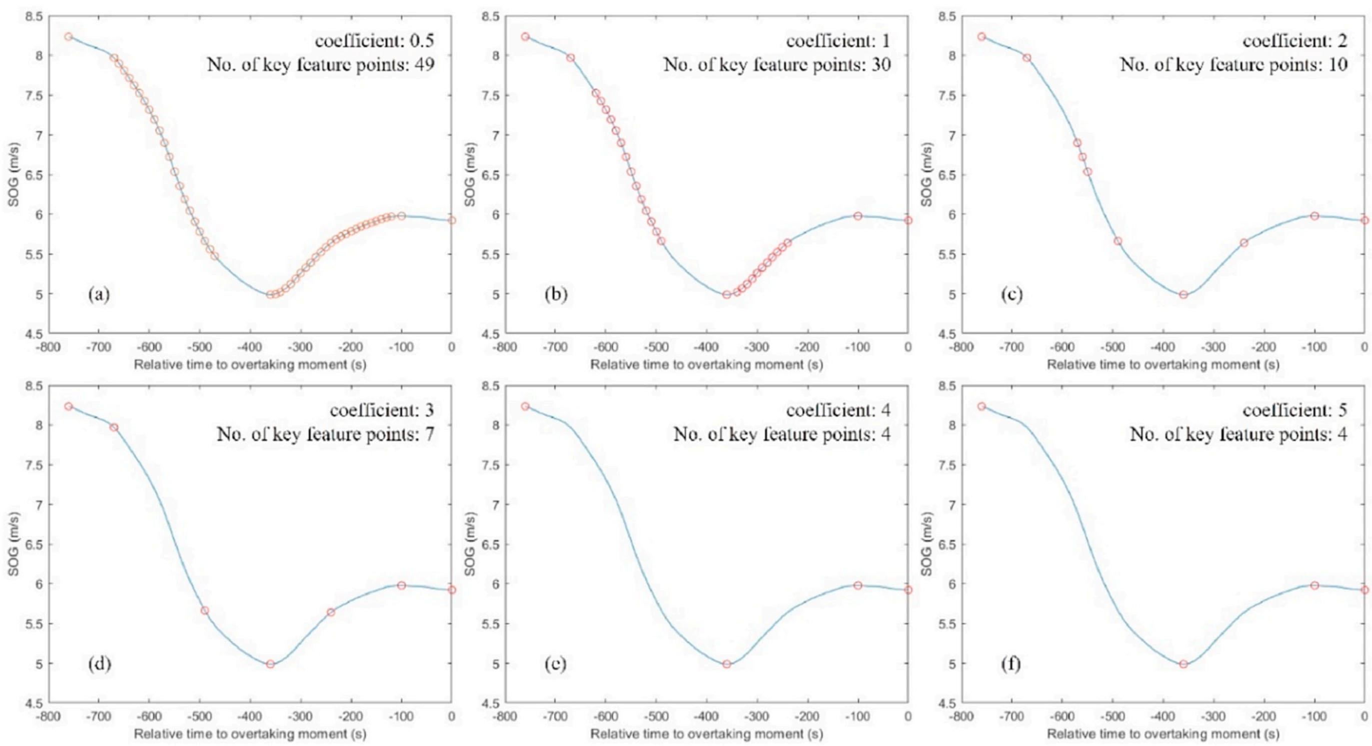

Fig. 14. Process of threshold determination for speed change key feature point recognition taking one trajectory as an example: (a)–(e) with an increase of coefficient adopted.

relative movement conditions before the critical overtaking moment are discussed in phases.

4.2.1. 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 2.4, 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 2.

The number in round brackets () indicates starboard side overtaking. The number in square brackets [] refers to the occurrences that the overtaking ship reaches the intended highest speed before the overtaking moment. The number in braces {} indicates the occurrences 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,

Table 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

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.

4.2.2. Decision of overtaking (phase 1)

According to the overtaking process shown in Fig. 4, 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. Even though the encounter with two ships sailing to the same direction is overtaking situation according to the definition in Section 2.2.1, the behavior of the latter ship can be following or overtaking. Thus, the distance between the ships when entering the research area and leaving the area are compared. Based on the comparison result, 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 3. In this paper, we focus on the full following and overtaking behavior during the encounter process.

As shown in Fig. 4, for a ship with a certain sailing direction (inbound

Table 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

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., 2019). The initial status of distance and relative speed, the starting point of approaching in phase 0 in Fig. 4, for complete overtaking encounters, incomplete overtaking encounters, and following encounters are presented in Fig. 15.

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 1 km, 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.

4.2.3. 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 Fig. 2. It is due to the bending of the waterway (see Fig. 8). 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 (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

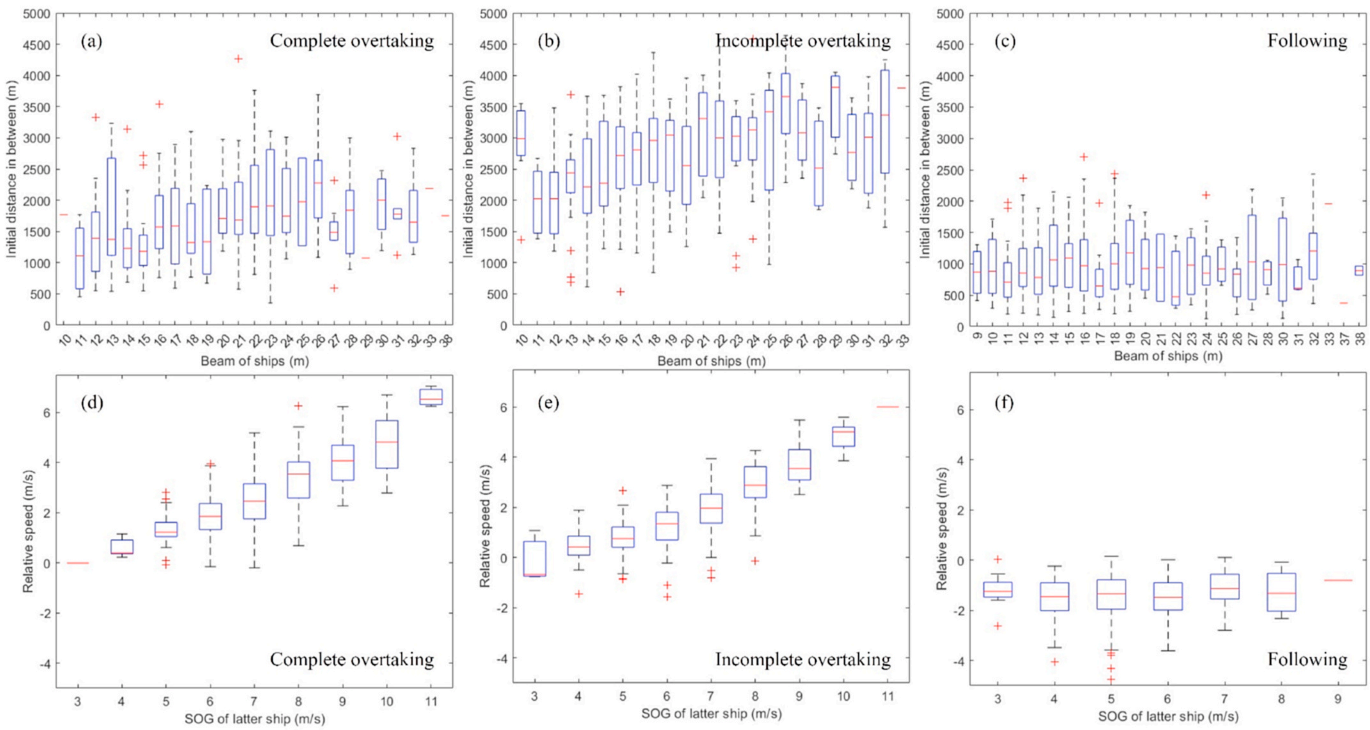

Fig. 15. Initial status of distance (upper row) and relative speed (lower row) between the two ships in different encounters: (a, d) complete overtaking; (b, e) incomplete overtaking; (c, f) following.

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 Fig. 16.

When the latter ship starts evasive actions, the visual distance in between is around 0.8–1.5 km (see left in Fig. 16), while the time is about 10 min for course alteration (see Fig. 16(b),(d)) and 5–10 min for speed change (see Fig. 16(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 2.4, 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. Considering the variances among the original ship behavior in the collected data, the generic behavior change magnitude can hardly be directly investigated for all encounters. However, 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. This way, the behavior objectives at the critical moment describe their changing tendency. 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 Fig. 17, and the relative speed status in Fig. 18.

It can be observed in Fig. 17(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 Fig. 17(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 Fig. 18(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 Fig. 7, 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 Fig. 19. 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

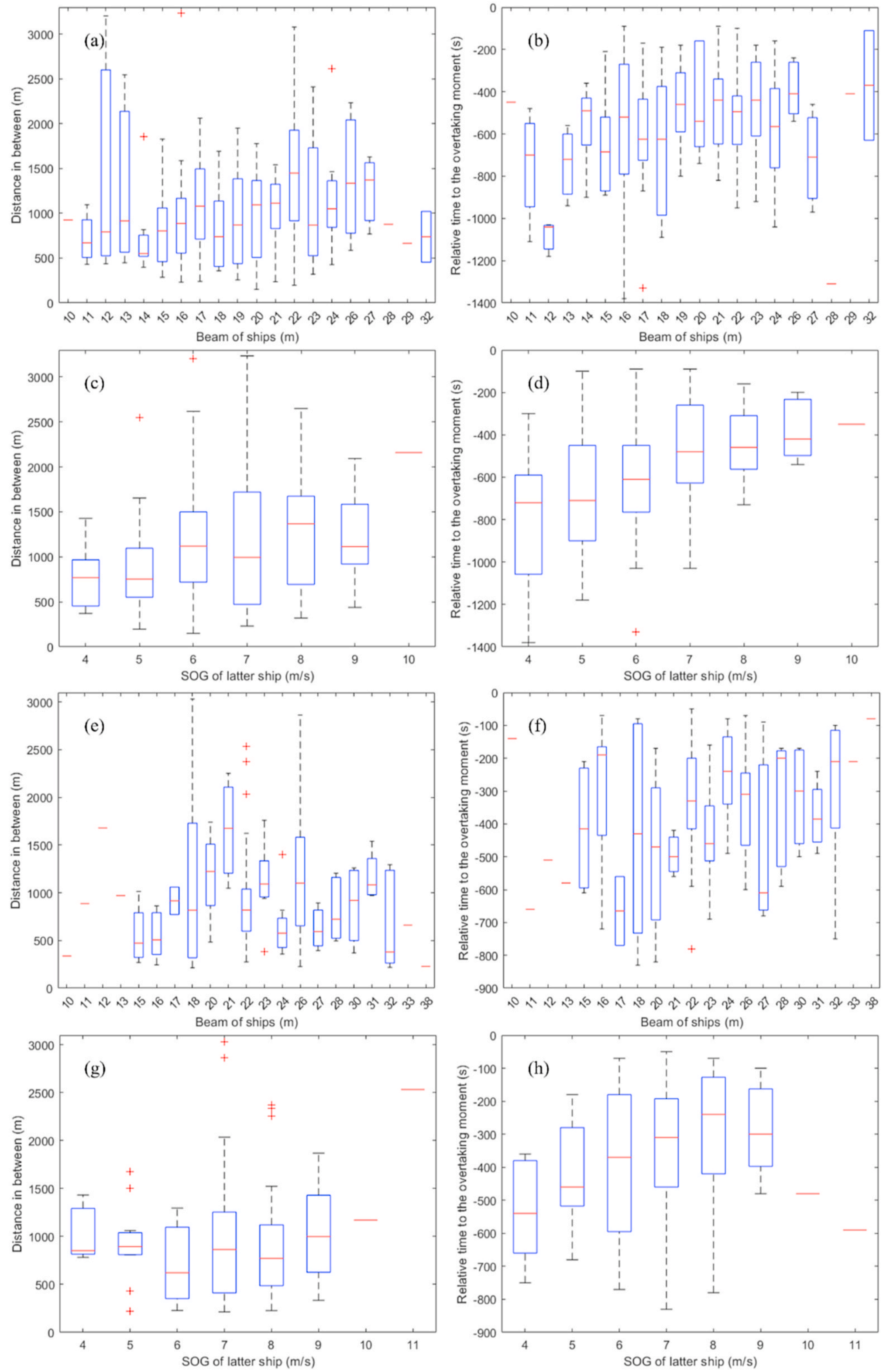

Fig. 16. The distance in between (left) and relative time to the overtaking moment (right) at the first course alteration point (upper four figures) and the first speed change point (lower four figures) considering the intrinsic characteristics of latter ship.

investigation.

4.2.4. 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 s 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

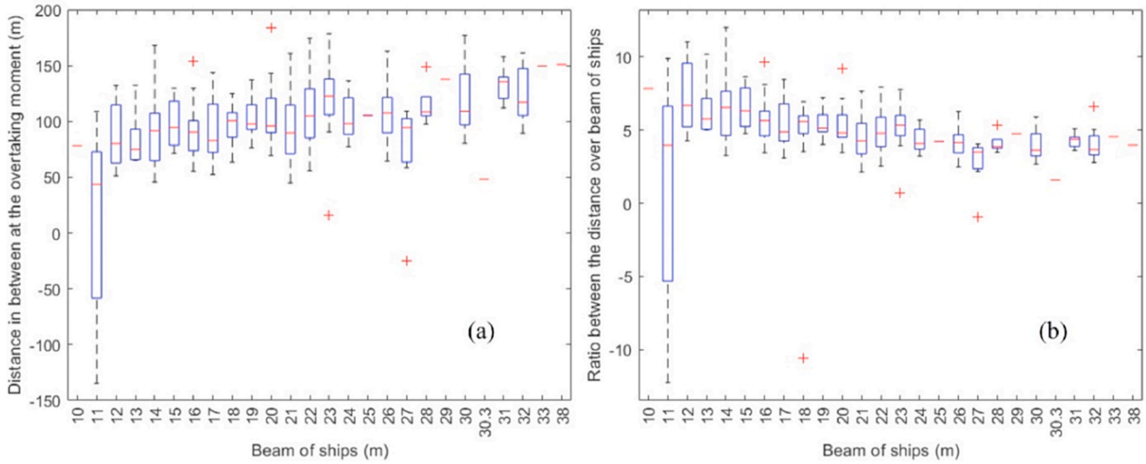

Fig. 17. The distance status at the overtaking moment (the negative value refers to the overtaking on the starboard side of the front ship): (a) the distance between ships; (b) the ratio between the distance over beam of the latter ship.

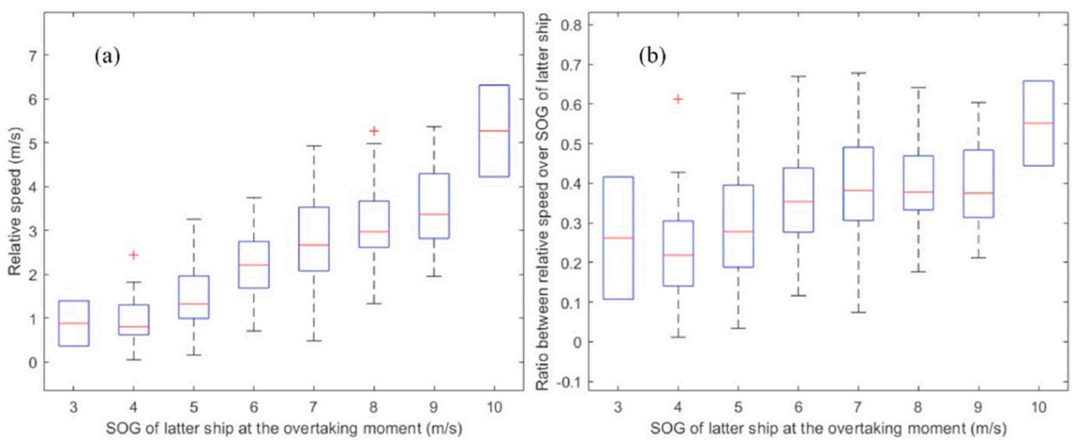

Fig. 18. The relative speed status at the overtaking moment: (a) the relative speed; (b) the ratio between the relative speed over the instant SOG of the latter ship.

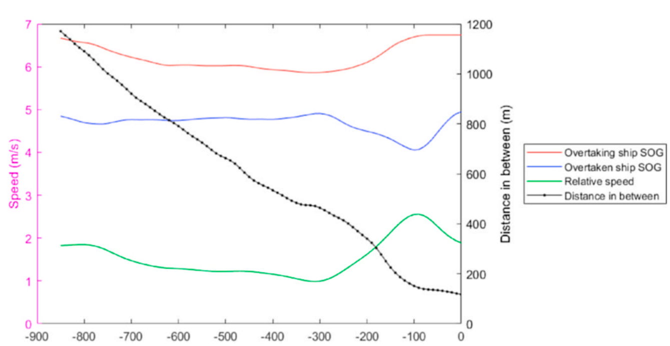

Fig. 19. An example of overtaking ship reaching her objective speed before the overtaking moment.

change, their behavior before the overtaking moment requires more attention.

From the statistical results in Table 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 Fig. 20. The last key feature point refers to the overtaking moment.

Comparing the timing of course alteration (Fig. 20(a, c)) and speed change (Fig. 20(b, d)), the relative distance is similar, which is about 0.5–1 km. 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 Fig. 21. 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 Figs. 17(a) and Figure 21(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.

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 paper.

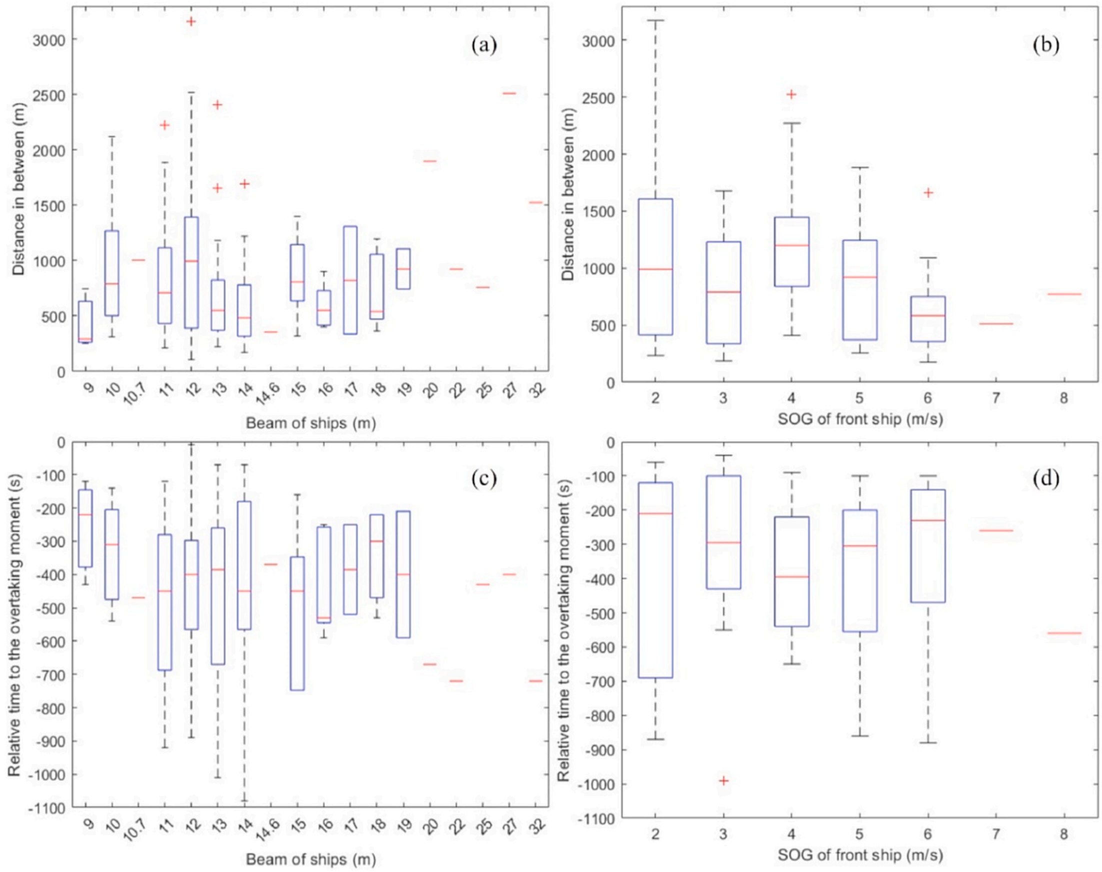

Fig. 20. The relative movement status (upper row for distance in between; lower row for relative time to overtaking moment) at the last behavior changing point of front ship: (a,c) course alteration; (b,d) speed change.

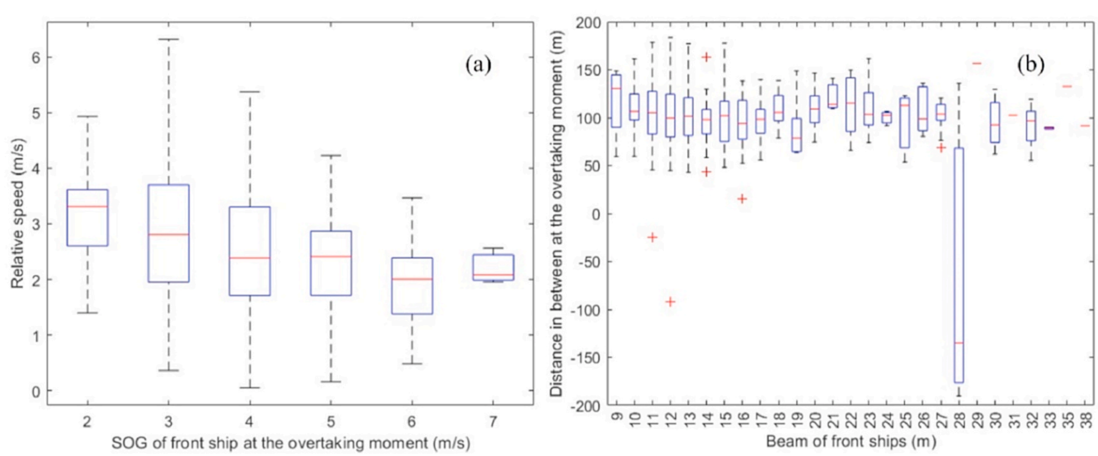

Fig. 21. The distance (a) and relative speed (b) status at the overtaking moment from the perspective of overtaken ship (the negative value refers to the overtaking on the starboard side of the front ship).

4.3. 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 4.3.1, followed by the ship behavior and the corresponding dynamic relative movement conditions in phases of passing-by and head-on situations in Section 4.3.2.

4.3.1. Overview of ship behavior when approaching from the opposite direction

Similar to the analysis of ship behavior preferences during overtaking encounters in Section 4.2.1, the behavior of both ships when approaching from the opposite directions is generalized. As shown in Fig. 9(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 paper, 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 Fig. 22.

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 2.2.1, 4565 out of 5976 inbound ships do not present behavior change within the last 2 km 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 2 km 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 paper, to eliminate the impacts of sailing directions on substantial speed change, we focus on the behavior analysis before the passing-by moment.

4.3.2. Ship behavior during the encountering process

Based on the findings in Section 4.2, 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 encounter time is short, the KS test is used to statistically compare whether the lateral distances at the different moments (the key feature point of behavior change and the critical passing-by 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. 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. Thus, 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 before approaching 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. 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 Fig. 23.

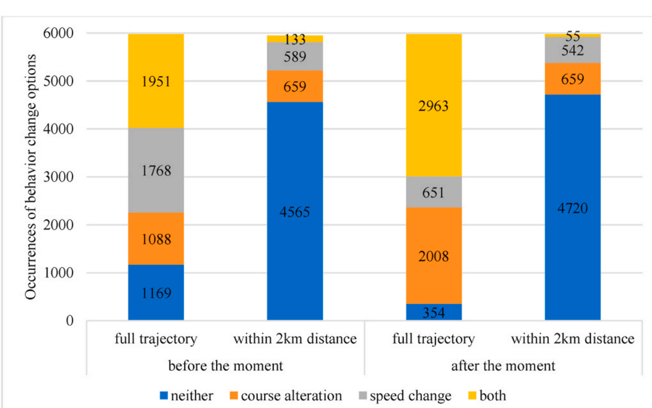

Fig. 22. Occurrences of behavior change options of ships when approaching from the opposite direction.

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 Fig. 24.

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 1–1.6 km. However, in the temporal respect, taking the passing-by moment as time reference, the time for these two actions is both around 1.5–2min before the critical moment, in which speed change (in Fig. 24(d)) is slightly earlier than course alteration (in Fig. 24(c)). 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.

5. Discussions and conclusions

Starting from the definition of encounters based on the spatial-temporal co-existence of ships in ports and waterways, this paper 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. The proposed method analyzes the ship behavior in AIS data starting from the critical moment when the distance between two ships is minimum. By the sliding window algorithm backward from the moment, the key feature points with behavior change can be recognized. For the ships with such evasive behavior during encounters, the timing and magnitude of ship behavior change before ships passing by each other can be generically revealed. The proposed approach can be applied in other area using the local historical AIS data. In this paper, The empirical findings in the port of Rotterdam, the Netherlands are discussed in Section 5.1, followed by the conclusions in Section 5.2.

5.1. Discussions on the empirical findings

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 1 km 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

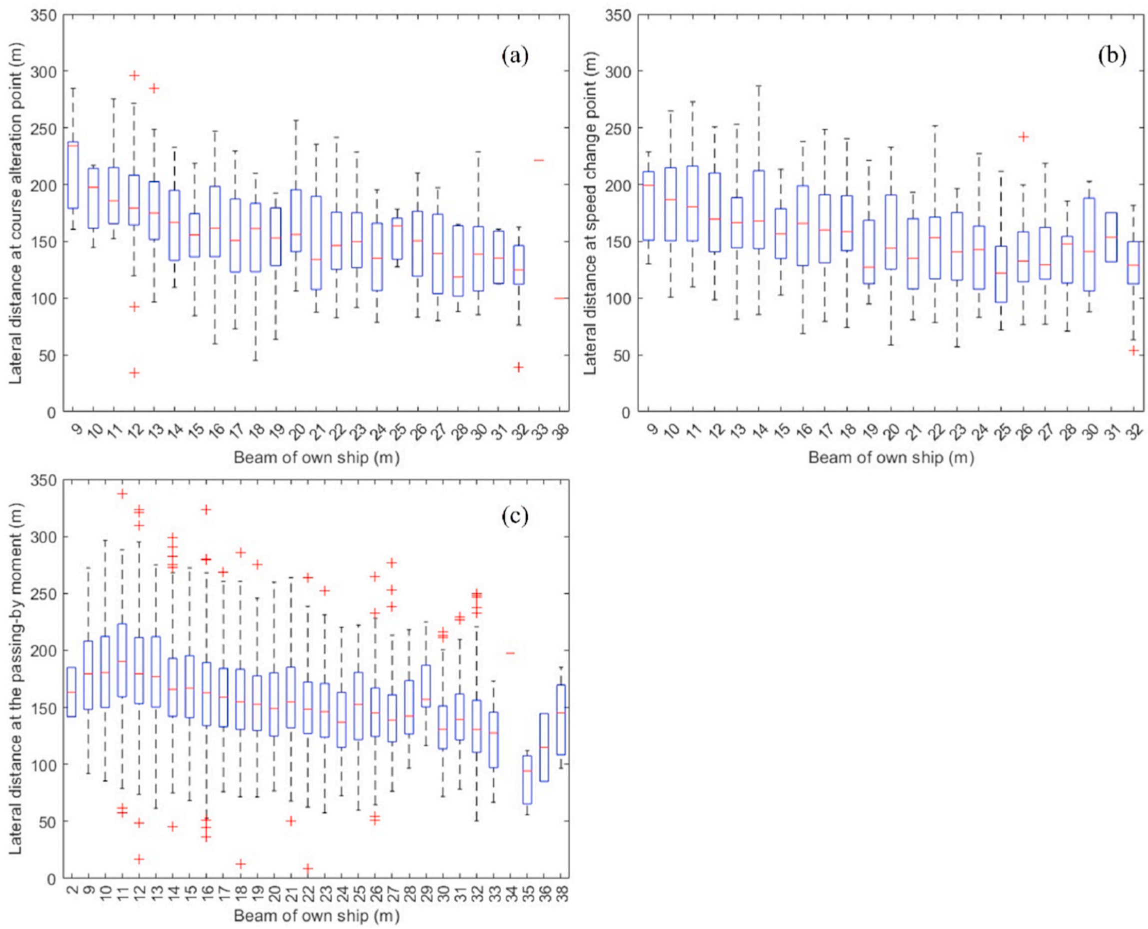

Fig. 23. Comparison of lateral distance between ships: (a) at point of course alteration; (b) at point of speed change; (c) at the passing-by moment.

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 0.5–1 km, 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 1–1.6 km. From the

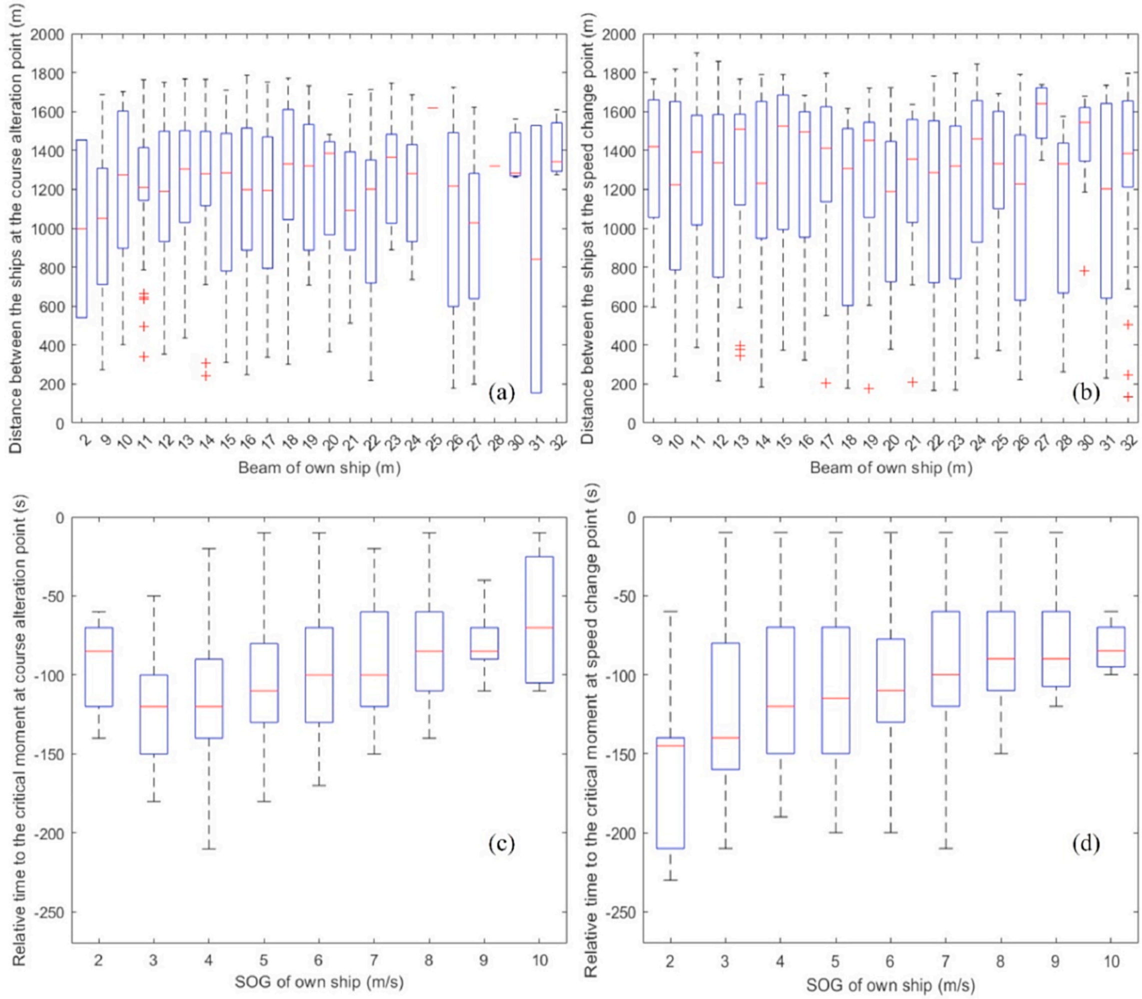

Fig. 24. The relative movement status (upper row for distance in between; lower row for relative time to the passing-by moment) at the behavior change point: (a,c) course alteration; (b,d) speed change.

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.

Currently, the extensive analysis of ship behavior in all encounters in ports and waterways is limited. Compared to the findings by Shu et al. (2017) in port of Rotterdam, the average distance when ships taking action also falls in the range found in this research. Compared to the maritime simulator results by Kang et al. (2019) in the head-on situations the confined waterways, the dynamic relative movement status is described by DCPA and TCPA. All officers take evasive actions in the experiments, and the average condition to take action is when DCPA is about 0.1 km and TCPA of 10 min. Since DCPA and TCPA are calculated based on the speed and relative position of both ships, the triggering conditions to take evasive actions cannot be directly compared to the findings in this research. Besides, due to the waterway width, the change of course is about 10–19°, which is larger than the observation in this research area. It also implies that the physical conditions of navigable waters play an important role in the empirical findings in different layout. Thus, to obtain the characteristics of the ship behavior in ports and waterways, the empirical analysis should be performed using the local historical AIS data.

5.2. Conclusions and future work

The proposed methodology systematically identifies the ship behavior during the encounter processes in different situations 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 different 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.

The proposed approach can be applied in other ports and waterways analyzing the local ship behavior in AIS data. Due to the limitation of the research area in this research, 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. Besides, this research only provides the empirical findings from historical AIS data analysis, the mathematical models based on the findings to quantitatively describe and predict the behavior still needs to be developed. Since the method aims to analyze the ship behavior during any encounter irrespective of their behavior change, the results show large variances due to the differences among individual ships. To further develop the mathematical model, the ships can be first classified into groups to obtain more specific results. 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.

CRediT authorship contribution statement

Yang Zhou: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Winnie Daamen:** Methodology, Writing – review & editing. **Tiedo Vellinga:** Supervision, Funding acquisition. **Serge P. Hoogendoorn:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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