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AIS data analysis for the impacts of wind and current on ship behavior in straight waterways

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ABSTRACT: Due to the increasing ship traffic flow in ports, maritime traffic safety has attracted much attention. In addition to traffic flow, the ship safety in restricted waters is influenced by external navigational factors (visibility, wind and current), encounter situations and human factors on board. In this paper, we investigate the effect of navigational factors on ship behavior. The raw AIS data and locally measured visibility, wind, and current data in the port of Rotterdam are collected to investigate the impacts of wind and current on ship speed and path (distance to the starboard bank). The results reveal that the wind mainly affects the paths of ships by the force of cross-wind, while the current impacts the speed over ground of ships when the current is with or against the heading of ship. The impacts on different sizes of ships are different as well. The port side wind has a larger impact on small ships than on large ships, while the impact of starboard side wind is larger for large ships than for small ships. The impact of current on the speed over ground is larger on small ships than large ships, and least on medium ships. The analysis results could assist the port authority in predicting ship traffic in different situations, and be used in the development of a new maritime traffic model to simulate ship behavior while considering the external navigational factors.

1 INTRODUCTION

Waterborne transport has been an important means of cargo transportation as the most economical method. More than 80% of world merchandised trade by volume are carried by sea (EuropeanCommission, 2013). The understanding and effective management of maritime traffic will benefit the overall performance of the sea ports and inland waterways. Due to the increasing ship traffic flow in hub ports, e.g. the port of Rotterdam, the maritime traffic safety is an important and sensitive issue. Unlike the large space for ship maneuvering at sea, ports and inland waterways are restricted areas. In such areas, the impacts of external navigational factors may lead to serious consequences, such as grounding or collision with vast loss of life and property. The understanding of ship behavior in real-life situations is of theoretical and practical significance.

In current studies of maritime traffic, various models are developed for risk assessment (Goerlandt and Kujala, 2011) (Montewka et al., 2011) (Park et al., 2016) (Fernandes et al., 2016) and capacity analysis (Özkan et al., 2016). However, most of these models include few external factors or make the external impacts as an assumption. This is partly due to a lack of insight into the relations between the observed ship behavior and the external conditions.

In order to investigate ship behavior, Automatic Identification System (AIS) data have proven to be a valuable source. AIS has been installed on all passenger ships and sea-going ships larger than 300 Gross Tonnage (GT), according to the requirement of International Maritime Organization (IMO). Many papers present analyses of ship behavior patterns based on AIS data (De Boer, 2010) (Shu et al., 2013) (Zhou et al., 2015) (Rong et al., 2015, Xiao et al., 2015). Combining AIS data with some meteorological data, the general impacts of visibility, wind and current on ship behavior are also presented (Shu et al., 2017). However, due to a lack of detailed hydrological information and ship behavioral attributes in the collected data, the impacts of other factors cannot be eliminated and the impact of wind and current from different directions is not fully investigated.

In this paper, the impacts of the wind and current on ship behavior are systematically analyzed based on raw AIS data and meteorological and hydrological data in a straight waterway in the port of Rotterdam for the whole year 2014. Using the actual ship heading, the direction of wind and current are defined into four directions relative to the ship movement. With a comparative analysis of ship behavior (indicated by path and speed over ground (SOG)) in different situations, the impacts of different wind and current conditions are revealed. The results will help researchers to simulate ship behavior in different external conditions and provide the port authority with an insight into relations between ship behavior and external factors.

In Section 2, the collected data set is introduced. Section 3 explains the proposed methodology for data analysis. The impact analysis results for wind and current are presented in Sections 4 and 5, respectively. Section 6 concludes the paper with discussion and recommendations for further research.

2 DATA DESCRIPTION

The research area is a nearly straight waterway, Nieuwe Waterweg, located at the entrance of the port, as shown in **Error! Reference source not found.**. The length of the research area is about 2.3 km. By choosing a straight waterway, the impact of waterway intersection on ship behavior is eliminated.

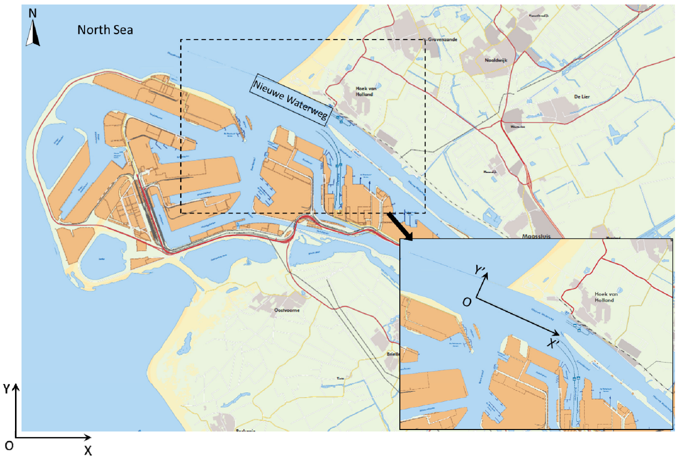


Figure 1. Layout and coordinate system of the research area in port of Rotterdam. (The X-Y coordinate system is the Dutch geographical coordinate system, Rijksdriehoeksmeting (RD system). In the cut out area, the transposed system is indicated, so the inbound ships sail in the X'-direction, while the lateral deviations from the straight path are visible in Y'-direction.)

2.1 AIS data

The AIS data are collected from the port authority of Rotterdam, covering the whole year of 2014, including 2,299,842 messages. Every sea-going ship, even under the GT limit of IMO's regulation, has installed AIS and used it in all voyages. For the inland ships, both commercial and recreational ships, and sailing vessels longer than 20 meters are mandatory to use AIS since Dec. 1st, 2014 according to Central Commission for the Navigation of the Rhine. The regulation applies to most inland vessels in the Netherlands. The year 2014 is thus a transition year, during which more and more inland vessels are recorded by AIS. Thus, the majority of vessels in this research are seagoing ships.

In the collected AIS data, the cargo ships (993,566 messages, 43.2%), tankers (522,614 messages, 22.7%) and passenger ships (77,724 messages, 3.4%) are selected as the research objects. Other ships, such as pilot ship, tug, dredger, are not included in the analysis because the behavior of such ships in working and non-working status is different, while their working status is not indicated in the AIS messages. As for the cargo ships, since there is no secondary categorization of ship type in the collected AIS data, these ships cannot be identified as container, general cargo ship or bulker exactly. Thus, the impact of ship type on behavior is not specified.

To some extent, the ship size determines the windage area and the volume under water, which are relevant to the impacts of wind and current on ship behavior. In this paper, the ships are classified using beam as the criterion. In this research, the minimum beam in the data set is 6 meters, while the maximum beam is 79 meters. To make the proposed methodology generic, the beam intervals of four ship classes are determined as: (1) beam <10m, (2) 10m≤ beam < 23m, (3) 23m≤ beam <33m, (4) beam ≥33m.

The collected AIS data contain three types of information:

- Static information: Maritime Mobile Service Identity number, type, length, beam, sensor type.
- Dynamic information: utc time, X-position, Y-position, SOG, course over ground (COG), heading, navigation status, etc.
- Voyage-related information: draught.

The attributes to describe ship behavior (position, SOG, COG and heading) are illustrated in Figure 2.

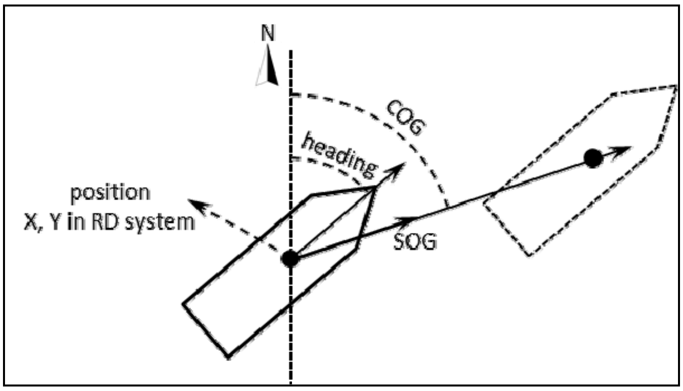


Figure 2. Illustration of behavioral attributes in AIS data.

The AIS messages describe the dynamic position of ship (X and Y) in the RD system. In order to explicitly compare the ship behavior, the coordinate system is transposed, as shown in **Error! Reference source not found.**. The origin lies at the west corner of research area. Thus, the ship position is described by the distance to the northwest boundary of research area (the Y'-axis) and the lateral distance to the dam (the X'-axis).

2.2 Meteorological and hydrological data

The meteorological condition refers to wind and visibility. This is locally measured data in 2014, collected from the port authority of Rotterdam. The wind velocity data are at an interval of 5 minutes, while the visibility is measured every minute.

The hydrological condition refers to the current velocity. The data are also from the port authority. Unlike wind, the locally measured current velocity is not representative for the whole area, due to the propagation of flow and the difference through the water-depth . Thus, the data of current velocity are calculated using the SIMONA model (Vollebregt et al., 2003) with the measured water level from eight stations around the port as input. The collected data describe the current in 41×7 orthogonal curvilinear grids with a resolution about 85 meters. The current velocity in each grid cell is presented by 10 layers with an average depth at an interval of 15 minutes.

3 DATA ANALYSIS METHODOLOGY

Since the research area is a nearly straight waterway, the observed COG of the ships are always parallel to the bank. Thus, only the impacts of wind and current on ship path and SOG are analyzed. To compare the ship behavior when passing the same location, a set of cross-sections are developed parallel to Y'-axis. The ship behavior data are interpolated to the cross-sections by the last message before and the first message after the cross-section. By calculating the proceeded distance of ships between two adjacent AIS messages in data set, the interval distance between cross-sections is determined as 65 meters, with 35 cross-sections in total. This value guarantees that there is at least one AIS message in between two adjacent cross-sections for 75 percent of the data.

The proposed research methodology is illustrated in Figure 4. To eliminate the impact of ship encounters, the processed data set excludes ships with an encounter to other ships during the voyage in the research area. According to the International Regulations for Preventing Collisions at Sea, the conducts of ships at sea are regulated in two situations, being in sight of another ship and in restricted visibility. Preliminary analyses of ship behavior in the port of Rotterdam show that the ships behave differently when the locally measured visibility range is less than 2000 meters. To eliminate the impact of visibility, the situation with visibility larger than 2000 meters are chosen.

Based on a preliminary analysis of ship behavior in different external conditions, some thresholds are used to set up the situations for impact analysis. For both wind and current, there are three situations, being weak, average, and strong. When the wind speed is less than 8 m/s, it is deemed as weak wind with little impact on ship behavior. Wind speed larger than 13.7 m/s is classified as strong wind. The impact of such wind on ship behavior is not analyzed, due to a lack of data in these rare conditions. As for current velocity, only the surface velocity and the depth-averaged velocity are known in a real-life situation. In the research area, the depth-average current speed is smaller than the surface current speed due to the reverse flow near the bottom. Thus, the surface current is identified as the indicator to represent the current condition. The current speed less than 0.37 m/s is deemed as weak current, while the current speed larger than 1.45 m/s is strong. The impact of strong current is not investigated either.

To analyze the impacts of wind and current on ship behavior, four relative directions to ship behavior are defined as secondary situations rather than the original wind/ current directions. The four relative directions are with the wind/ current, against the wind/ current, wind/ current from the port side and wind/ current from the starboard side, as shown in Figure 3. The directions are determined by the angle between wind/ current direction and heading of the ship. In this way, the wind and current situation is linked to the dynamic ship motion, which would better reveal the impacts than using the original geographical directions. The ship behavior in each secondary situation for both wind and current are compared to the ship behavior in the unhindered situation using five descriptive statistics, being 1st, 25th, 50th, 75th, 99th percentile. The statistical test of t-test is also performed to each pair of comparison. In this paper, p-value at 0.05 is taken as the criterion to decide the significance level. The null hypothesis of the t-test is that 'the unhindered and hindered ship behavior are from the same distribution'. In the result of t-test, if H is equal to 1, it means the null hypothesis is rejected. In this way, the situation with an impact on ship behavior is recognized.

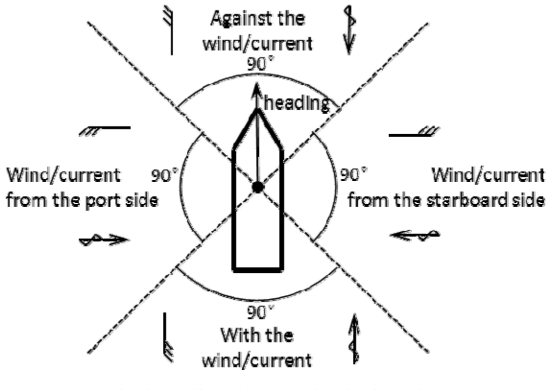


Figure 3. Four relative directions of wind and current.

4 IMPACT OF WIND

The impact of wind on ship path and SOG is discussed in this section. The data set of both inbound and outbound ships are analyzed. As an example, the results of inbound ships (North Sea-Nieuwe Waterweg) with medium beam (10m≤ beam < 23m) are presented in details. The results of outbound ships (Nieuwe Waterweg-North Sea) are similar. When the impacts on different size of ships are different, a comparison between different classes of ships is also given.

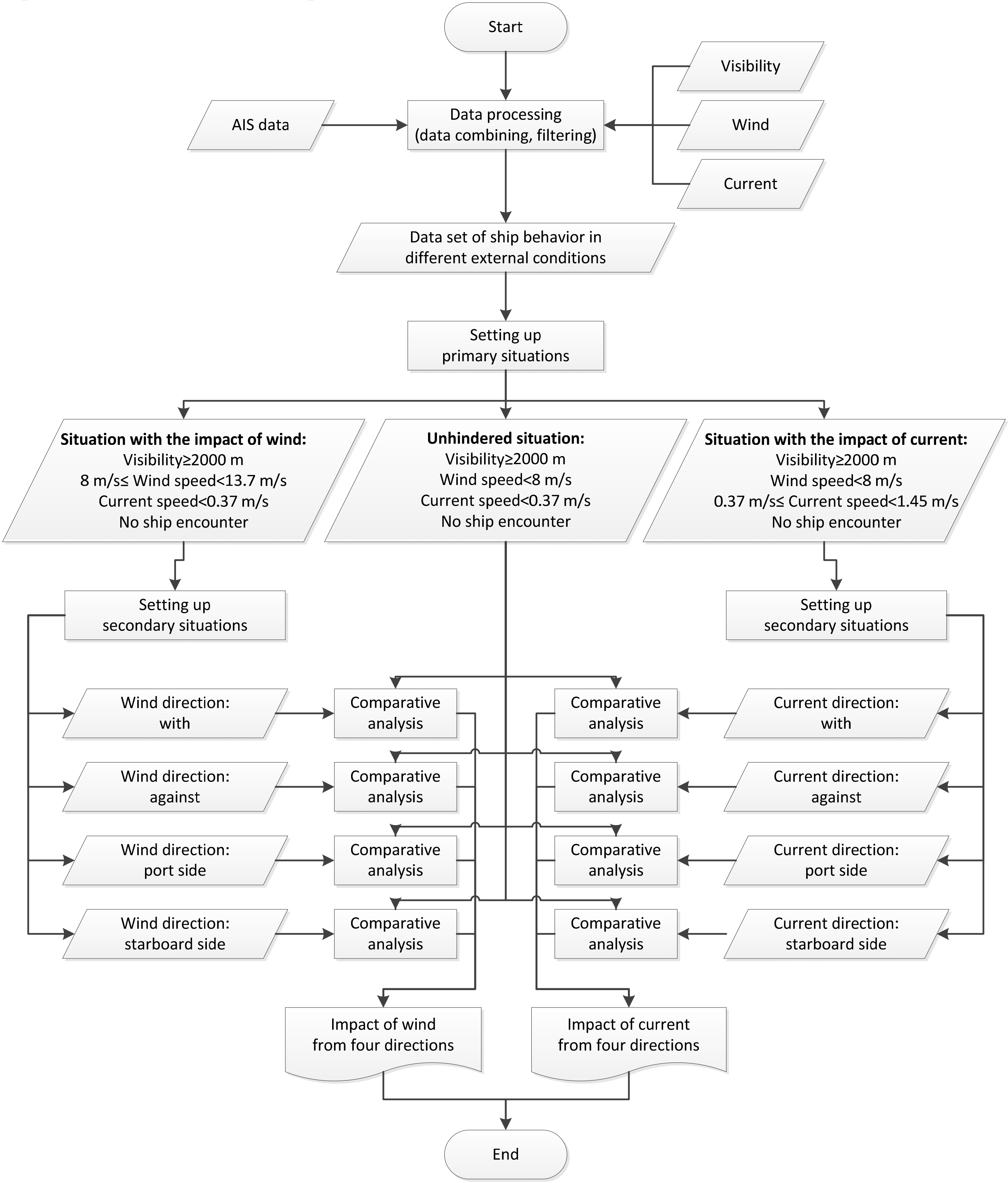


Figure 4. Flow diagram of the impact analysis based on AIS data. (The secondary situations are determined by the angle between wind/current direction and heading of ship. With the wind/current means the direction of wind/current is in the range from right ahead to 45 degrees on either side of the ship, while against means the direction is in the range from right aft to 45 degrees abaft the beam. Port side means the direction is in the range from 45 degrees afore to 45 degrees abaft the beam on the port side, while starboard side means the same range on the starboard side of ship.)

4.1 Path

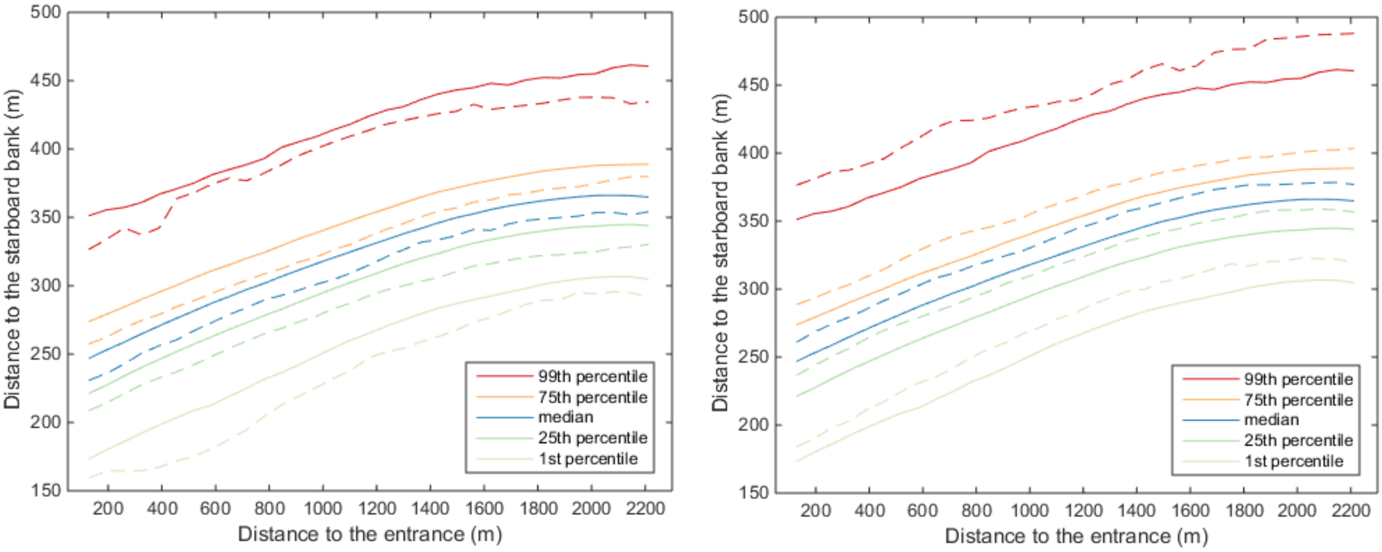
In the situations ‘with the wind’ and ‘against the wind’, the paths of ships are similar to the paths in the unhindered situation. The statistical test result also proves that the lateral distances to the starboard bank in these two situations are not significantly different to the unhindered paths. The statistical analysis result is presented in Table 1.

Table 1. T-test results between paths in wind-hindered and unhindered situations.

Situation	No. of cross-sections with H = 1*	Average p-value
With the wind	2	0.2917
Against the wind	0	0.6668
Wind from the port side	35	5.1172×10^{-4}
Wind from the starboard side	35	4.9795×10^{-7}

* The total number of cross-sections is 35.

However, the cross-wind does influence the paths of the ships, as shown in Figure 5. Since the transposed coordinate system is orthogonal while the dam (the starboard bank) is with a slight bend, the lateral distance to the starboard bank increases with larger distance to the entrance. With the wind from the port side, the paths are closer to the starboard bank. On the contrary, the paths are closer to the port bank when the wind is from the starboard side. Both results show that the wind force will push the ship to the other side, which is as we expected. The statistical results also indicate that the hypothesis is rejected that ship paths in cross-wind situations are equal to the unhindered paths.

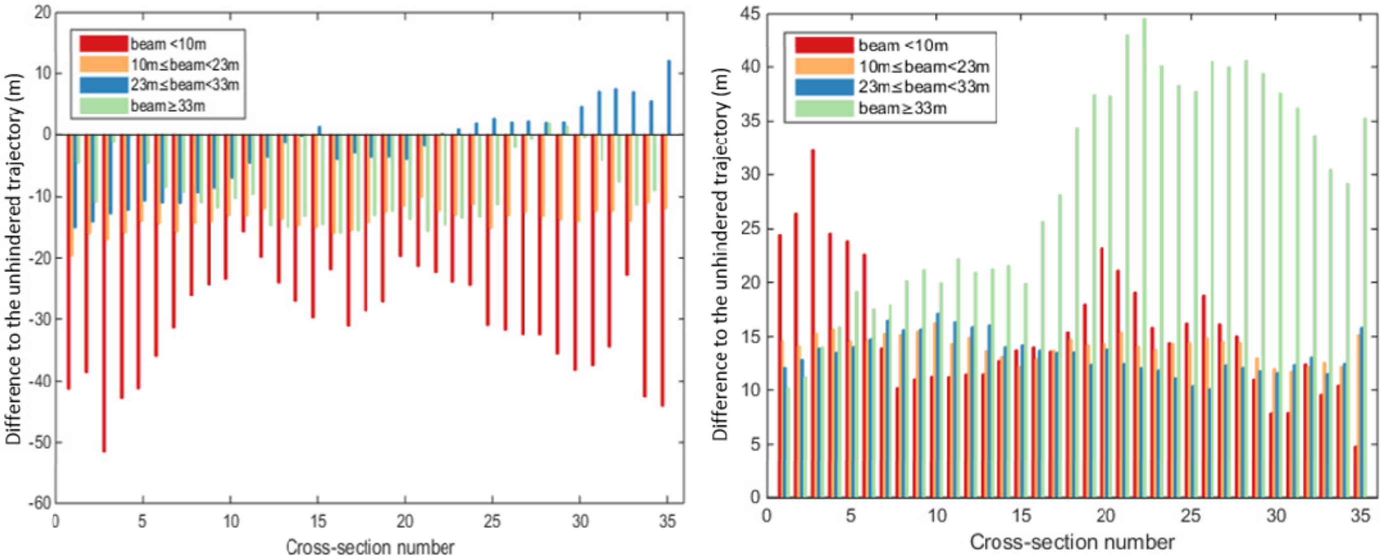


(a) Situation: wind from the port side (dashed lines) and unhindered situation (solid lines).

(b) Situation: wind from the starboard side (dashed lines) and unhindered situation (solid lines).

Figure 5. Ship path as a function of wind conditions.

The deviation direction of all the ships in the same crosswind situation are the same. However, the extent of the impacts varies among different ship sizes. The differences between the mean values on each cross-section compared to the unhindered situation is shown in Figure 6. It reveals that with port wind, small ships (beam < 10m) sail closer to the starboard bank than large ships (beam ≥ 10m). With the wind force to the starboard bank, large ships appear to keep more distance to the bank to prevent collision due to their large inertia and possible shallow water near the bank. Meanwhile, starboard-wind impacts is larger for large ships than for small ships. In both crosswind situations, large ships bear larger wind force than small ships. However, the wind from the starboard side pushes ships to the portside bank, which also implies that they sail closer to the centerline of the waterway with sufficient water-depth and room for ship maneuvering.



(a) Situation: wind from the port side.

(b) Situation: wind from the starboard side.

Figure 6. Difference to the unhindered paths in cross-wind situations (positive value means hindered path closer to the port bank, while negative value means hindered path closer to the starboard bank).

4.2 SOG

The differences of SOG in the situations ‘with the wind’, ‘wind from the port side’, and ‘wind from the starboard side’ are quite small. The t-test results also show that in these three situations, ship’s SOGs are not significantly different from the unhindered situation. However, when ships sail against the wind, there is a decrease in SOG of ships, as shown in **Error! Reference source not found.**. The t-test results also indicate the difference of SOG between the situation ‘against the wind’ and the unhindered situation. For all the ships, it will increase the fuel consumption to maintain a same SOG as in the unhindered situation, when the wind is from ahead. It is neither economical for the ship owner, nor environment-friendly for the port. It is observed that the impacts of wind on SOG are similar to different size of ships. The reason is that even the wind force is large, the ships would increase the level of engine operation to maintain a speed avoiding maneuvering failure of rudder effect in any circumstances.

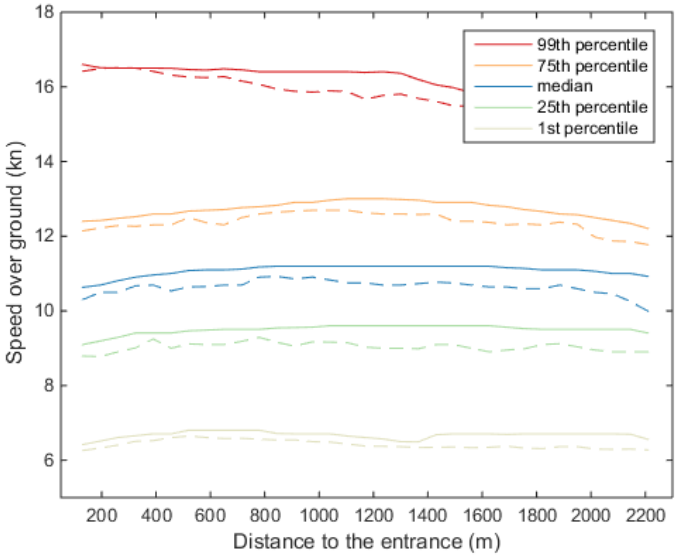
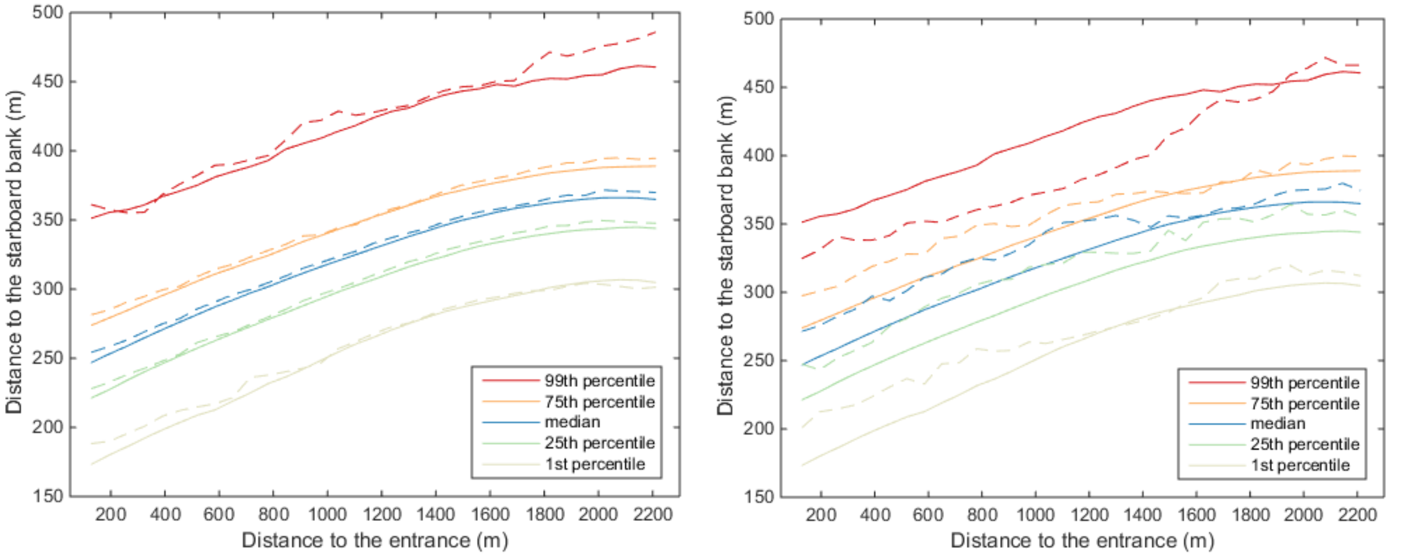


Figure 7. Ship SOG in the situation ‘against the wind’.

5 IMPACT OF CURRENT

5.1 Path

There is no significant difference between paths in the situations ‘against current’ and ‘current from port side’, which is supported by the t-test results. However, in the situations ‘with current’ and ‘current from the starboard side’, ships sail further to the starboard bank, as shown in Figure 8. In the t-test results, for 24 cross-sections the hypothesis that the paths in the situation ‘with current’ are equal to the unhindered paths is rejected, with an average p-value of 0.0488, which is close to the acceptance value 0.05. It means the ships sail further to the starboard bank when the current pushes them forward, but the distance difference is small as can be seen from Figure 8. In the situation ‘current from starboard side’, a significant difference is observed in all cross-sections. The ships sail further to the starboard bank, but the distance deviation varies a lot. The reason of such behavior variation in the starboard-current needs to be further investigated.



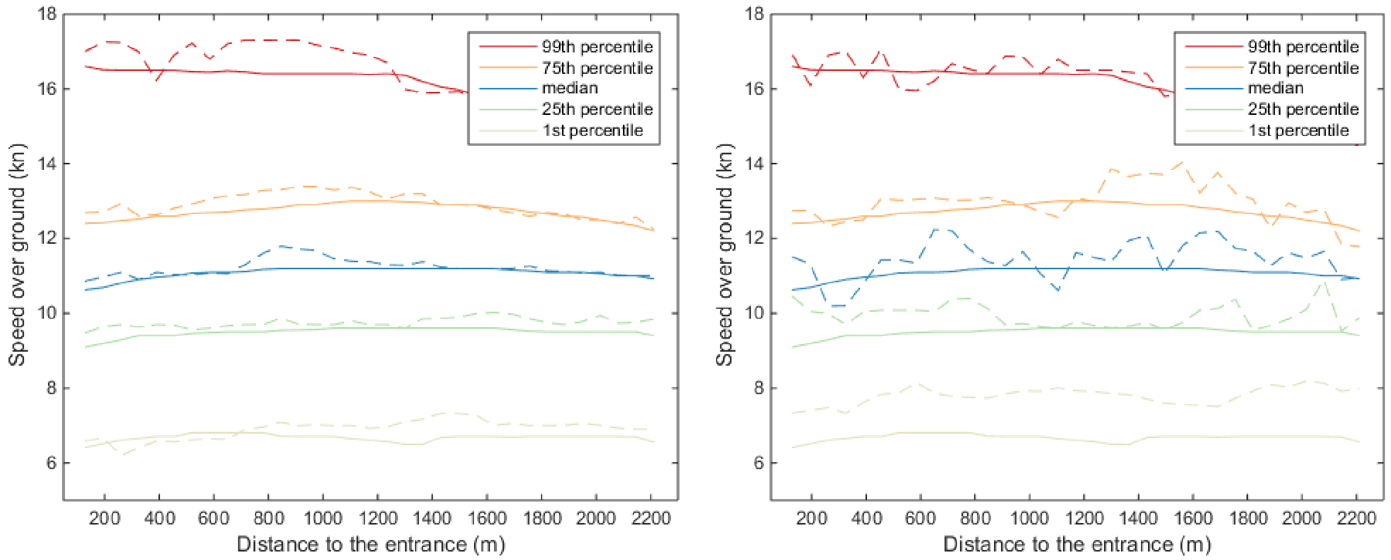
(a) Situation: with the current (dashed lines) and unhindered situation (solid lines).

(b) Situation: current from the starboard side (dashed lines) and unhindered situation (solid lines).

Figure 8. Ship path as a function of current conditions.

5.2 *SOG*

Figure 9 presents the impacts of current on the SOG of ships. The current from the port side does not have a significant impact on SOG, as also indicated by the t-test results. The t-test result also indicates that the hypothesis that SOG in the situation 'current from the starboard side' is equal to the unhindered situation is not accepted, which suggests this direction of current does impact SOG. However, the hindered SOG fluctuates a lot. For most ships, the SOG increases, especially for 1st percentile value. The ships maneuver frequently under the bank effect when the current is from the starboard side.

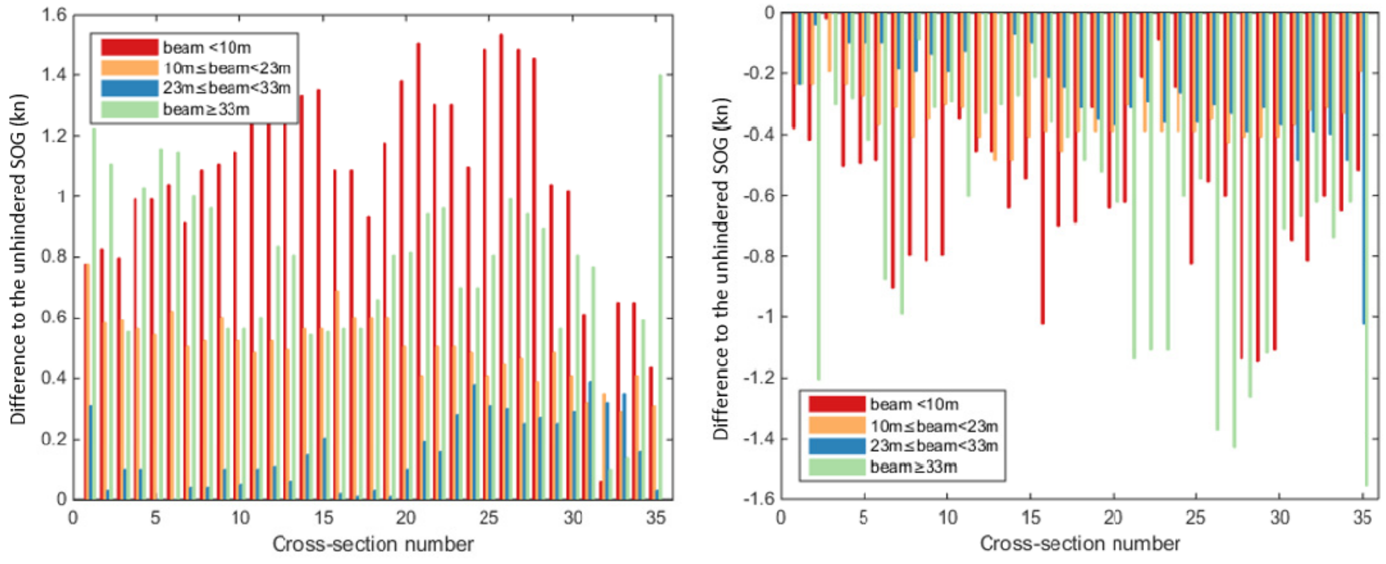


(a) Situation: current from the port side (dashed lines) and unhindered situation (solid lines).

(b) Situation: current from the starboard side (dashed lines) and unhindered situation (solid lines).

Figure 9. Ship SOG as a function of current conditions.

It can also be observed that the SOG of ships increases in the situation of 'with current' and decreases in the situation of 'against current', which follows our expectations. In the statistical results for both situations, the hypothesis that the SOG of ships is equal to the unhindered SOG is rejected for all cross-sections. However, the impacts of current among different ship sizes are different, as shown in Figure 10. The impact of current on small ships (beam < 10m) is the largest. Then, the impact decreases with an increase of the size of the ships (10m ≤ beam <33m). However, the impact on large ships (beam ≥ 33m) increases again. When the ship size increases, the gravity of ships also increases. Thus the frictional resistance effect of current on ships decreases. However for large ships (beam ≥ 33m), the draught is bigger than smaller ships, which means the ship is impacted by more layers of current. The current force on large ships is also larger. Furthermore, the extent of SOG increase in the situation 'with current' is larger than the impact of SOG decrease in the situation 'against current'. It is because the ships would increase the level of engine operation to maintain a proper speed for ship maneuvering.



(a) Situation: with the current

(b) Situation: against the current

Figure 10. Difference to the unhindered SOG in situations 'with the current' and 'against the current' (positive value means an increase of SOG, while negative value means a decrease of SOG).

6 CONCLUSIONS AND DISCUSSION

This paper investigates the impacts of wind and current on ship behavior (indicated by path and SOG) using AIS data from a straight waterway in the port of Rotterdam, the Netherlands.

It is shown that the cross-wind influences the paths of ships, while the paths present no significant difference in the situations 'with the wind' or 'against the wind' compared to unhindered situation. The wind from the port side appears to 'push' the ships towards the starboard side of the bank, and vice versa. The port side wind has a larger impact on small ships than on large ships. On the contrary, the impact of wind from the starboard side is larger for large ships than for small ships. The reason is the insufficient water-depth and room for maneuvering on the starboard side of ships. The impact of wind of SOG is only observed in the situation 'against the wind' with a decrease of SOG for all ship sizes.

In the situations 'against current' and 'port side current', no impact on the path of ships is revealed. However, the paths in the situations 'with the current' and 'starboard side current' showed a larger distance to the starboard bank compared to the unhindered situation. In the situation 'with current' and 'against current', SOG of ships increases and decreases respectively. The impact is larger for small ships than large ships, and least on medium ships. The impact in the situation 'with current' is larger than 'against current'. The port-side current does not influence SOG, while the starboard current influences SOG, due to the bank effect.

It can be concluded that paths of ships are easier to be impacted by wind than current, especially by cross-winds. The SOG of ships will decrease when sailing against either wind or current, but increase only when sailing with current. In addition, the impact of current from starboard side is possibly due to the bank effect. But further research on the impact of bank effect on ship behavior is required.

The analysis result could benefit both researchers and port authority. For the researcher, a detailed insight into the impact of wind and current helps to predict ship behavior in different external conditions. For the port authority, the revealed impact pattern of wind and current can be used to predict ship behavior in forecasted external factors, which helps the ship traffic management and risk control in port.

Within this paper, only a straight waterway is investigated. In a later stage, a port area with more complex layout will be analyzed to identify the impact on all ship behavioral attributes, being path, SOG, COG and heading, in particular for cases where the course does not correspond to the heading.

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