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Influence of external conditions and vessel encounters on vessel behavior in ports and waterways using Automatic Identification System data

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Abstract

The impact of many external factors, such as wind, visibility and current, on the behavior of vessels in ports and waterways has not been investigated systematically in existing maritime traffic models. In order to fill the current knowledge gap and provide a basis for developing a new model to effectively simulate maritime traffic, the influences of wind, visibility and current as well as vessel encounters on vessel behavior (vessel speed, course and relative distance to starboard bank) have been investigated in this study by analyzing Automatic Identification System data collected from the port of Rotterdam. It is found that wind, visibility, current and encounters have significant impact on the vessel speed and relative distance to starboard bank, while vessel course is mainly affected by current and encounters. The results also showed that the vessels would adapt their speed, course and relative distance to starboard bank during encounters. These findings showed the importance of considering external factors and encounters in simulating vessel behavior in restricted waterways and provide a starting point for building up more comprehensive maritime traffic models.

Keywords: Automatic Identification System data, uninfluenced and influenced vessel behavior, external condition, overtaking encounter, head-on encounter, ports and waterways

1. Introduction

As one of the important modes of international freight transportation, the scale of maritime transportation has been expanding sharply in recent decades. The increase of both vessel number and size draws more and more concerns for the balance between safety and capacity of maritime traffic: when measures are taken to increase capacity, usually the safety decreases, and vice versa. This holds even stronger for ports and inland waterways, where vessel encounters and external conditions can significantly influence vessel behavior, such as vessel speed and course. In those areas, vessel collisions and groundings occur more often because of the confined space (Darbra & Casal, 2004). As maritime traffic accidents may have serious consequences, such as personnel and property losses, traffic congestion and environmental impacts both in the water and in the surrounding area, it is desirable to properly address the safety and capacity of the maritime traffic system in restricted waterways.

Currently, various simulation models are available to investigate the maritime traffic system. Some of these models have been developed to assess risk of collisions and groundings (Montewka et al., 2010, Goerlandt & Kujala, 2011, Qu et al., 2011), while other models have been built to investigate the effect of vessel hydrodynamics and vessel maneuverability (Sutulo et al., 2002, Sariöz & Narli, 2003). However, most models focus on maritime traffic in open seas while only few investigate the traffic in ports and waterways (Xiao, 2014). And all these models consider only a limited number of external factors.

Initial studies qualitatively showed that the wind and current can effect vessel speed and course in ports (de Boer, 2010). However, the influence of external factors, either wind or current, on vessel behavior was investigated without eliminating the impact of other factors on vessel behavior in this study and the influence of external factors on vessel behavior has not been quantified. A recent maritime traffic simulation study showed that vessel characteristics (type and size) can also significantly influence the vessel behavior in ports (Xiao et al., 2015). Notwithstanding these studies, the influence of external conditions (including wind, visibility and current) and vessel encounters on vessel behavior is not yet fully understood and quantified.

The aim of this paper is to systematically investigate and quantify the influence of external conditions and vessel encounters on vessel speed, course and vessel path in ports and waterways. For vessels sailing in the confined waterways of the port, the vessel path is described by the relative distance to the starboard bank (the distance to starboard bank divided by waterway width). So, vessel speed, course and relative distance to starboard bank are three parameters considered in this paper. As currently no other research specifically focuses on this aspect, the results of this paper are seen as an essential basis for improvement of maritime traffic models and investigations on maritime traffic. In addition, this research also shows a method how to utilize Automatic Identification System (AIS) data and cross sections to extract useful information, such as vessel encounters.

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

Research question 1: How does wind influence vessel behavior (vessel speed, vessel course and relative distance to starboard bank)?

Research question 2: How does visibility influence vessel behavior (vessel speed, course and relative distance to starboard bank)?

Research question 3: How does current influence vessel behavior (vessel speed, course and relative distance to starboard bank)?

Research question 4: How do vessel encounters (head-on and overtaking) influence vessel behavior (vessel speed, course and relative distance to starboard bank)?

In this paper, the research data and approach are introduced in Section 2. Then, the influences of wind, visibility, current and vessel encounters on vessel behavior are presented, respectively, in Section 3 to 6. Finally, this paper ends with conclusion and discussions in Section 7.

2. Research area, data and approach

In this section, the research area is introduced, followed by the introduction of the research data and research approach. Then, the statistical analysis method used in this paper is described.

2.1 Research area

The research area used in this study is the Botlek area in the port of Rotterdam, as shown in Fig. 1. This area is chosen because of its high traffic density and the availability of historical data of wind, visibility and current from measuring stations located in this area. The research area comprises three navigation channels: “Nieuwe Waterweg”, “Nieuwe Maas” and “Oude Maas”. As the main waterways connecting the older port basins with the Sea, the “Nieuwe Maas” and the “Nieuwe Waterweg” have a width of around 400 meters and a minimum depth of 13.8 meters below Mean Lower Low Water (MLLW), which is the average height of the lowest tide recorded at a tide station in the port area. The vessel traffic in these two waterways mainly consists of commercial vessels including container vessels (59.6%) and General Dry Cargo (GDC) vessels (29.3%). 75% of these are small vessels less than 10,000 gross tonnage (GT). The “Oude Maas” joins the “Nieuwe Maas” from the south and forms the main connection for vessel traffic from the port of Rotterdam to the hinterland. The “Oude Maas” has a width of around 200 meters and a minimum depth of 9.6 meters MLLW. This condition in the “Oude Maas” restricts vessels, so 95% of the vessels in the “Oude Maas” are small vessels less than 10,000 GT. Among these vessels, 63.7% are GDC vessels and 26%

are tankers. In these analyses, the following four navigation directions are distinguished according to main vessel traffic flows:

- Sea-Nieuwe Maas: vessels sail from Sea to the “Nieuwe Maas”
- Nieuwe Maas-Sea: vessels sail from the “Nieuwe Maas” to the Sea
- Sea-Oude Maas: vessels sail from the Sea to “Oude Maas”
- Oude Maas-Sea: vessels sail from the “Oude Maas” to the Sea

2.2 Research data

The research data consists of two parts. Firstly, the vessel behavior is collected from the AIS data, which are provided by the Maritime Research Institute Netherlands (MARIN), using “ShowRoute”. The “ShowRoute” is a dedicated software developed by MARIN used for investigation of AIS data. AIS data have turned out to be a useful tool to investigate maritime traffic (Aarsæther & Moan, 2009, Mou et al., 2010, Hansen et al., 2013, Meng et al., 2014). Secondly, the wind, visibility and current data collected from two measuring stations in the research area are provided by the Port of Rotterdam Authority. In this section, AIS data and cross sections used to collect the AIS data are introduced firstly. Then, the available wind, visibility and current data are described.

2.2.1 AIS data and cross sections

In the 1990s, the International Association of Maritime Aids to Navigation and Lighthouse Authorities (IALA) presented to the International Maritime Organization (IMO) the first proposal for AIS, in which the AIS system is designed to identify other vessels including their positions (Eriksen et al., 2006). The purpose of the AIS system is “to contribute to improved situational awareness for shore-side authorities and ships’ officers” (Bailey et al., 2008). The AIS system works on Very High Frequency (VHF), so it is possible to detect other AIS-equipped vessels when the radar detection is confined, such as under influence of strong rain or tall buildings. In the International Convention for the Safety of Life at Sea (SOLAS), IMO made AIS mandatory for vessels of 300 GT and more by 2004, and now it is mandatory for small vessels as well (Organization, 2000).

The AIS system records the following types of data: static vessel data (Maritime Mobile Service Identity (MMSI) number, type of vessel, length, beam, etc.), dynamic vessel data (vessel position, time instant, speed, course, etc.) and voyage related information (draught, cargo, destination, etc.). The static vessel data are entered into the AIS system when the AIS unit is installed on vessels. It needs to be changed only if the ship type changes or if her name or MMSI changes. The dynamic information contains the vessel behavior information and serves as input for the analyses in this research. The voyage related data is entered manually by the vessel’s crew (Eriksen et al., 2006).

The accuracy of AIS data has been improved a lot in the last decade. It was found that the percentage of vessels that transmitted errors decreased from 10.4 % in 2004 to 3.5 % in 2007, and most errors are about destination and draught, which includes misspelling, empty data fields, incomprehensible abbreviations and references to the previous port (Bailey et al., 2008, Harati-Mokhtari et al., 2007). It was also found that errors occur in Estimated Time of Arrival (ETA) (21.7 % of the observations were wrong), IMO number (14.1 %), Destination (11.0 %), Rate of turn (8.9 %), Heading (7.1 %), Dimensions (6.2 %), Draught (5.7 %), Course over ground (0.8 %), Speed over ground (0.8 %) and a missing ship name (0.04%) (Solvsteen, 2009). It can be concluded that dynamic vessel data are more accurate.

To reduce the data set size and to easily derive and compare the lateral position per ship, cross sections were defined and used to extract AIS data. As shown in Fig. 2, 69 cross sections in Sea-

Nieuwe Maas and Nieuwe Maas-Sea and 68 cross sections in Sea-Oude Maas and Oude Maas-Sea are defined (Shu et al., 2013). The systematic approach to make the cross sections perpendicular to waterway centerline is preferable. When we analyzed the AIS data, we have drawn the cross sections manually in “ShowRoute” in a more pragmatic manner. We have found that the results, in terms of vessel speed, course and relative lateral position, are not sensitive to the precise choice of the cross sections. Thus, these cross sections are not strictly perpendicular to waterway direction. The interval between cross sections is approximately equal to 50 meters, which is similar to the distance in which vessels send one AIS record, as the average speed of vessels in this area is around 10 knots (5.14 m/s) and the reporting interval for most vessels is 10 seconds. Each cross section is formed by linking two points at the 5-meter depth contours on two sides of the waterway, which are the dividing lines between light blue and dark blue area. The light blue indicates the area where the water depth is larger than 5 meters, while the dark blue is corresponding to the area shallower than 5 meters. These two points are chosen such that the cross section is approximately perpendicular to the waterway axis. The 5-meter depth contours are used because vessels normally do not pass the 5-meter depth contour to avoid groundings. Therefore, the 5-meter depth contours are considered as part of the bank in our research. It should be noted that there is no 5-meter depth contour in the junction area and entrances to the basins on one side of the waterway, so there a smooth curve is defined to link the adjacent 5-meter depth contours, as described previously (Shu et al., 2013).

Using these cross sections, AIS data in the time period from January 2009 to April 2011 are extracted in the four aforementioned directions and will be used for the analyses. To calculate vessel speed, course and position on a cross section, the data from the nearest point before and after the cross section is used to extrapolate the values on the cross section, based on the function of time using linear interpolation. In this way, each vessel path will have one data record on each cross section.

2.2.2 Wind, visibility and current data

The wind, visibility and current data are collected by two measuring stations in the research area. The wind and visibility data are recorded every 5 minutes by the measuring station “Geulhaven” (Fig. 1), which is located in the center of the research area. As the research area is relatively small and there are no obstructions, wind and visibility are considered to be homogeneous in this area.

In order to investigate the influence of current on vessel behavior, it is important to have reliable current data in the research area. In this study, the current data are available from the measuring station “Botlekbrug” (Fig. 1), which is located in “Oude Maas”, and in the south of the research area. Because the measured current data from one measuring station cannot represent the current in the whole area, it is essential to identify the applicable area of the measured current data. These data are recorded every 10 minutes and velocity is taken at 5 meters depth to the local datum - Amsterdam Ordnance Datum (in Dutch “Normaal Amsterdams Peil”, NAP). As the current is influenced by river discharge, the tidal condition and waterway geometry, the current may vary at different locations as well as over the water depth. However, for most of the vessels that pass along Oude Maas, the current speed at 5m below NAP represents the average conditions fairly well (for which reason this depth has been chosen by the authorities). In order to link the recorded current data to currents in other parts of the research area, a numerical simulation model called Delft3D (Roelvink & Van Banning, 1995) has been applied by the Port of Rotterdam Authority to simulate the currents along the stretch Sea-Oude Maas under different tidal conditions within one day. The annual average discharge of 2300 m^3/s is applied as input for this model and both the neap and spring tide are simulated for tidal conditions. It is assumed that the variability of real current is similar to the variability of simulated current along the waterways.

The simulated current during the simulation period at the measuring station and at cross sections 2, 20, 38, 51, 63, 68 are presented as examples in Fig. 3. Here, cross sections 2, 20, 38, 51, 63 and 68 are chosen as representative situations, which are clearly distinct from each other. These cross sections are selected from both straight stretches and the bend. Cross sections 2 and 20 represent the situation in the straight stretch “Nieuwe Waterweg”; cross section 38 is selected because it is located in the middle of the bend area; cross section 51, 63 and 68 represent the situation in the straight stretch “Oude Maas”. It is shown that the simulated current at the measuring station and at the cross sections 51, 63 and 68, which are all located in the “Oude Maas”, do not show substantial differences. The absolute difference between the simulated current at the measuring station and the values at cross sections 51, 63 68 is 0.21, 0.16 and 0.18 m/s for neap-average discharge and 0.19, 0.11 and 0.14 m/s for spring-average discharge, respectively. In comparison, the absolute difference between the simulated current at the measuring station and the value on cross sections 2, 20, 38 (located on “Nieuwe Waterweg”) is much larger (0.62, 0.56 and 0.62 m/s for neap-average discharge and 0.5, 0.49, 0.39 m/s for spring-average discharge, respectively). This result implies that the current data collected from the measuring station in “Oude Maas” can be used to represent the current on cross sections 51-68. This finding enables us to investigate the influence of current on vessel behavior in this area.

2.3 Research approach

In our research, the bridge team is considered as the “brain” of the vessel and covers the intelligence and decision making for the vessel. Based on this assumption, the bridge team and the vessel are considered as an integrated entity. The vessel behavior discussed in this paper is governed by this entity and is defined by the vessel speed, course and path. The vessel behavior and potential factors influencing vessel behavior are shown in Fig. 4. It can be seen that vessel behavior can be affected by different factors, such as vessel characteristics and waterway geometry. In this paper, external conditions (wind, visibility and current) and vessel encounters (head-on and overtaking) are investigated, while specific vessel categories classified by vessel type and size (Shu et al., 2013) are used to eliminate the influence of vessel characteristics.

It is hypothesized that vessel behavior changes in different external conditions and encounters. This hypothesis is tested by the comparison between different data sets with different thresholds, which are determined according to the local external conditions. On the one hand, these thresholds should be used to distinguish different vessel behavior. On the other hand, appropriate thresholds should be made to keep enough data for studying both influenced and uninfluenced vessel behavior. The research approach is to directly compare the vessel speed, course and relative distance without the influence of external conditions with the situations under which the vessel behavior is influenced by an individual factor. To this aim, the uninfluenced behavior, for vessels that are not influenced by external conditions (below or above certain threshold value) and by the presence of other vessels (the distance to other vessels is larger than a certain threshold) and the influenced behavior, where external conditions and/or vessel encounters play a substantial role to affect vessel behavior, were defined in a recent study (Shu et al., 2013).

In this research, the AIS data are combined with historical data of wind, visibility and current by linearly interpolation based on time and coupling the time records of the individual AIS messages and the data sets for wind, visibility and current. The combined data set is divided into two groups corresponding to the uninfluenced and influenced vessel behavior according to the conditions listed in Table 1. The thresholds for selecting uninfluenced vessel behavior are the same as we used in the previous paper: for wind < 8 m/s, for visibility > 2,000 meters and for encounters a distance to other vessels < 1,000 meters (Shu et al., 2013). The extra condition for uninfluenced vessel behavior is for current < 0.8 m/s. It should be noted that current is not considered when the influences of wind and visibility are investigated, because the current data only cover cross section 51-68.

Table 1. Conditions for uninfluenced and influenced vessel behavior.

	Conditions for uninfluenced behavior	**Conditions for influenced behavior**
Wind All cross sections	Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m	Wind > 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m
Visibility All cross sections	Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m	Wind < 8m/s Visibility < 2,000 m Distance to other vessels > 1,000 m
Current Cross sections 51-68	Current < 0.8 m/s Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m	Current > 0.8 m/s Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m

For the influenced behavior listed in Table 1, different categories for influenced behavior by wind and current are investigated. For wind, it is assumed that the wind has main influence on the side of the vessel where the wind comes from (bow, portside, stern or starboard), every side comprising directions within an arc of 90^o. As shown in Fig. 5, four wind categories are defined (Stern wind, Starboard wind, Bow wind and Portside wind) according to the angle between the wind and the course of vessels. For current, two categories “Against current” and “With current”, are chosen.

To compare the influence of wind and visibility on vessel behavior, the vessel categories for container vessels with 5,100-12,000 GT and general dry cargo (GDC) vessels with gross tonnage less than 3,600 GT on all cross sections in Sea-Nieuwe Maas are investigated in this paper (Shu et al., 2013). These two vessel categories in this direction are investigated since they are the most common vessel categories in the research area and Sea-Nieuwe Maas is the direction with the main vessel traffic flow. For current, GDC vessels with gross tonnage less than 3,600 GT on cross sections 51-68 in Sea-Oude Maas and in Oude Maas-Sea are investigated, since GDC vessels are the most common vessels in these two directions.

For encounters, three main types of vessel encounters have been distinguished according to the International Regulations for Preventing Collisions at Sea (COLREG): head-on, overtaking, and crossing encounters. Compared to head-on and overtaking encounters, cross encounters are more complicated for navigators to deal with and more difficult to be analyzed. In an early stage of this study, we have chosen to focus on head-on and overtaking encounters, which are more common in our research area, leaving crossing encounters as subject of future research. The AIS data on each cross section are used to select head-on and overtaking encounters according to the time in each AIS message. For head-on encounters, two vessels sail in different directions. These vessels are selected from the AIS data set according to the moment they pass adjacent cross sections. For vessel A sailing from cross sections *n* to cross section *n+1*. If vessel B appears between these two cross sections during this period, a head-on encounter occurs. In overtaking encounters, overtaking and overtaken vessels sail in the same direction. Similar to head-on encounters, these vessels are selected based on the moment they pass adjacent cross sections. For example, vessel A passes cross section *n* later than vessel B and it passes the next cross section *n+1* earlier than vessel B. Then, vessel A overtakes vessel B between these two cross sections. It should be noted that the influences of wind, visibility and current are not considered in these analyses.

The influences of encounters on vessel behavior are investigated in Sea-Nieuwe Maas and Nieuwe Maas-Sea, which are the waterways with the main vessel traffic flow. Using the algorithm above, 948 head-on encounters are selected in Sea-Nieuwe Maas and Nieuwe Maas-Sea, while 146 and 106 overtaking encounters are selected respectively in Sea-Nieuwe Maas and in Nieuwe Maas-Sea.

It should be noted here that vessel type and size is not considered when we investigate the influence of vessel encounters on vessel behavior. To investigate average vessel behavior in encounters, the cross section nearest to the Closest Point of Approach (CPA) is defined as the relative cross section 0. Then, the cross sections located ahead and behind the relative cross section 0 are defined as the relative cross sections with negative ids and positive ids ranging in [-68,68], respectively. However, it is important to mention that the research area was divided into 69 cross sections. If the relative cross section is located close to the border of the research area, some relative cross sections would be located out of the research area, i.e. there is no data available. Therefore, the data availability on the relative cross sections decreases with the increasing distance to the relative cross section 0. To ensure that the average vessel behavior on each relative cross section is supported by enough data, the minimum requirement for data number on each relative cross section is 30 in these analyses. Then, the uninfluenced and influenced vessel behavior at each relative cross section is calculated and compared for both vessels in encounters, and the uninfluenced behavior is calculated according to the vessel categories in our previous research (Shu et al., 2013).

2.4 Statistical analysis method

As it was found that vessel behavior is influenced by waterway geometry (Shu et al., 2013), comparison between uninfluenced and influenced vessel behavior should be performed on each cross section. In this paper, the Kolmogorov-Smirnov test (K-S test) is used to test if uninfluenced and influenced vessel behavior come from the same distribution. The null hypothesis of the K-S test is that “the uninfluenced and influenced vessel behavior are drawn from the same distribution”. In this method, a threshold for the p-value, called the significance level of the test, is used as 5%. To represent the results of K-S test, the parameter p_r is the percentage of cross sections, on which the null hypothesis of K-S test is rejected.

In addition, *Mean Absolute Percentage Error (MAPE)* is used to represent the average of percentage errors by which influenced behavior differs from the uninfluenced behavior. The *MAPE* in this paper is defined as:

$$MAPE = 1/n \sum_{i=1}^{n} |\mu_i - \mu_i^*| / \mu_i^* \qquad \text{Eq. (1)}$$

where *n* is the number of cross sections, and μ_i and μ_i^* denote the average influenced and uninfluenced behavior on cross section *i*, respectively. If *n* equals to 1, the *MAPE* will become *Absolute Percentage Error (APE),* which will be used to investigate the vessel behavior at the relative cross section 0 during encounters in Section 6.1 and Section 6.2.

3. Influence of strong wind on vessel behavior (Research question 1)

Fig. 6 shows the average uninfluenced and influenced vessel behavior by stern wind, starboard wind, bow wind and portside wind for the two vessel categories. Here, the x-axis “distance to the first cross section” represents the longitudinal distance along the centerline of the waterway.

As shown in Fig. 6 (a) and Fig. 6 (b), vessel speed is influenced by strong wind for both container and GDC vessels, especially under stern wind and bow wind. It is in line with our expectations that vessel speed increased under stern wind and decreased under bow wind, which is caused by the wind force added on the vessels. For starboard wind and portside wind, a small drop is observed on most cross sections and can be explained by the anticipation of dangerous situations by the bridge team. In addition, it is found that strong wind has stronger influence on GDC vessels than on container vessels, which may be due to the fact that GDC vessels are much smaller than container vessels, and thus smaller vessels are easier to be influenced by wind. In Fig. 6 (c) and Fig. 6 (d), it is shown that the influenced vessel course is similar to uninfluenced vessel course for both container and GDC vessels. However, the larger fluctuations of vessel course for GDC vessels than for container vessels also indicate that GDC vessels are more easily affected by wind than container vessels. Fig. 6 (e) and Fig. 6 (f) show that the relative distance to starboard bank under stern wind and bow wind are comparable with uninfluenced behavior, while the relative distance is decreased under portside wind and it is increased under starboard wind. It also can be found that the deviation of relative distance under portside wind and starboard wind from the uninfluenced behavior is larger for GDC vessels than for container vessels. In addition, the deviation between uninfluenced and influenced relative distance is larger in the eastern part of the waterway than in the western part. This might be caused by the influence of the waterway geometry.

To compare the average difference between uninfluenced and influenced behavior along the waterway, the values of p_r and *MAPE* for different wind categories are shown in Table 2.

Table 2. Statistical results of p_r and *MAPE* between uninfluenced and influenced vessel behavior by wind in Sea-Nieuwe Maas.

		Speed		**Course**		**Relative distance**	
		$\boldsymbol{p_r}$(%)	$\boldsymbol{MAPE}$(%)	$\boldsymbol{p_r}$(%)	$\boldsymbol{MAPE}$(%)	$\boldsymbol{p_r}$(%)	$\boldsymbol{MAPE}$(%)
Container 5,100-12,000 GT	Stern	39.1	2.3	7.2	0.3	2.9	1.6
	Starboard	1.4	1.4	30.4	0.6	37.7	4.2
	Bow	11.6	2.5	4.3	0.4	1.4	3
	Portside	2.9	2.1	2.9	0.3	11.6	4.9
GDC <3,600 GT	Stern	10.1	3.4	10.1	0.6	17.4	3.3
	Starboard	0	2.2	30.4	0.9	30.4	7.3
	Bow	97.1	9.6	0	0.5	0	4.5
	Portside	13	4.3	13	0.7	20.3	9.4

As shown in Table 2, the null hypothesis of the K-S test for container vessel speed is rejected at 39.1% and 11.6% of cross sections for stern wind and bow wind, respectively. The values of *MAPE* indicate that the speed is increased by 2.3% and decreased by 2.5% under stern wind and bow wind, respectively. For GDC vessels, stronger influence is observed for bow wind and the null hypothesis is rejected on 97.1% of cross sections, where vessel speed is decreased by 9.6%. Although vessel speed is only influenced by stern wind at 10.1% of cross sections, the value of *MAPE* shows vessel speed is increased by 3.4%. The null hypothesis of the K-S test is accepted for starboard and portside wind at most cross sections for both container and GDC vessels. This means that the starboard and portside wind do not influence vessel speed.

For vessel course, the null hypothesis of K-S test is accepted in most cases, except for starboard wind, under which the null hypothesis is rejected at around 30% of cross sections for both vessel categories. Such results imply that only starboard wind has influence on vessel course.

Similarly, the strongest influence on the relative distance to starboard bank is also observed for starboard wind, under which the null hypothesis is rejected for more than 30% of cross sections for both vessel categories, and the relative distance is increased by 4.2% and by 7.3% percent, respectively. The strong influence is also observed for portside wind, under which the relative distance is decreased by 4.9% and by 9.4% for both vessel categories. This indicates that starboard and portside wind lead to lateral deviation to portside and starboard bank, respectively.

It can be concluded that stern wind and bow wind influence vessel speed, starboard wind affect vessel course, and starboard and portside wind has influence on the relative distance to starboard bank. Furthermore, the influence of wind on GDC vessels is stronger than the influence on container vessels. This might be caused by the different superstructure and different size of these two vessel types.

4. Influence of bad visibility on vessel behavior (Research question 2)

The results of visibility for the two vessel categories in Sea-Nieuwe Maas are presented in Fig. 7. In Fig. 7 (a), it can be found that vessel speed is decreased under bad visibility for container vessels. Compared to Fig. 7 (b), the difference between uninfluenced and influenced vessel speed for container vessels is much larger than for GDC vessels. This might be caused by the different perception of danger for different vessel categories. Fig. 7 (c) and Fig. 7 (d) show strong resemblance of uninfluenced and influenced vessel course, which means the vessel course is barely influenced by bad visibility. In Fig. 7 (e) and Fig. 7 (f), the relative distance for influenced behavior is observed to be smaller than for uninfluenced behavior on most cross sections. This means that vessels sail closer to the bank in bad visibility, although they may have radar system onboard.

The statistical results of p_r and *MAPE* are presented in Table 3.

Table 3. Statistical results of p_r and *MAPE* between uninfluenced and influenced vessel behavior by visibility in Sea-Nieuwe Maas.

	Speed		**Course**		**Relative distance**	
	$\boldsymbol{p_r}$(%)	$\boldsymbol{MPE}$(%)	$\boldsymbol{p_r}$(%)	$\boldsymbol{MPE}$(%)	$\boldsymbol{p_r}$(%)	$\boldsymbol{MPE}$(%)
Container 5,100-12,000 GT	58	4.9	11.6	0.5	24.6	3.6
GDC <3,600 GT	0	1.7	0	0.5	11.6	5.1

The statistical results show different influence on vessel speed for container and GDC vessels. For container vessels, the null hypothesis is rejected on most cross sections (58%) and the *MAPE* shows that vessel speed is decreased by 4.9%. However, p_r shows that the null hypothesis is accepted for GDC vessels on all cross sections and the value of *MAPE* is very small (1.7%). For vessel course, it is found that bad visibility almost does not influence vessel course for both container and GDC vessels. Although the null hypothesis is rejected for relative distance on 24.6% and 11.6% of cross sections for container and GDC vessels, the values of *MAPE* are 3.6% and 5.1%. This means that vessels will deviate to starboard bank under bad visibility and the influence for GDC vessels is stronger than for container vessels. This can be explained by the perception of danger for the bridge team and thus they sail closer to the bank.

To conclude, bad visibility has a negative influence on container vessel speed, but it does not influence GDC vessel speed. It is also found that vessel course is barely influenced by visibility. For the relative distance, both container and GDC vessels will deviate to starboard bank under bad visibility, where the GDC vessels will deviate more than container vessels, which could be explained by the different draught of these two vessel types.

5. Influence of strong current on vessel behavior (Research question 3)

Fig. 8 shows the average uninfluenced and influenced vessel behavior for GDC vessels in Sea-Oude Maas and Oude Maas-Sea. Fig. 8 (a) and Fig. 8 (b) show both that vessel speed is decreased under “Against current” and is increased under “With current” in two directions, which means the vessel speed is influenced by current. Fig. 8 (c) and Fig. 8 (d) show that vessel course under strong current deviates from uninfluenced behavior. In Fig. 8 (e) and Fig. 8 (f), the relative distance to starboard bank changes along the waterway depending on current direction.

The statistical results of p_r and *MAPE* are presented in Table 4.

Table 4. Statistical results of p_r and *MAPE* between uninfluenced and influenced vessel behavior by current in Sea-Oude Maas and in Oude Maas-Sea.

		Speed		**Course**		**Relative distance**	
		p_r	$MAPE$	p_r	$MAPE$	p_r	$MAPE$
Sea-Oude Maas	Against current	100	11.6	61.1	0.3	94.2	6.2
	With current	0	6.1	33.3	0.5	22.2	5.3
Oude Maas-Sea	Against current	0	5.3	61.1	0.3	27.8	8.4
	With current	100	12.9	88.9	0.3	100	9.7

It can be found that vessel speed is decreased under “Against current” by 11.6% in Sea-Oude Maas and by 5.3% in Oude Maas-Sea, and is increased under “With current” by 6.1% in Sea-Oude Maas and by 12.9% in Oude Maas-Sea. Although the values of *MAPE* for vessel course are very small, the values of p_r show that the uninfluenced and influenced vessel course are different at most cross sections. Finally, two strong influences on relative distance are observed for “Against current” in Sea-Nieuwe Maas and “With current” in Oude Maas-Sea, but values of *MAPE* are all more than 5%, which means relative distance is influenced by bad visibility.

To sum up, vessel speed is decreased by “Against current” and increased by “With current”. Vessel course and relative distance to starboard bank are also influenced by strong current, but the pattern of the influence needs further research using the real time data and considering the influence of waterway geometry.

6. Influence of encounters (Research question 4)

In this section, the results of comparison between uninfluenced and influenced vessel behavior on the relative cross sections for head-on and overtaking encounters are shown, respectively. Since it is assumed that vessel behavior differs most for both vessels in encounters, the K-S test will only be applied for the relative cross section 0 to test if the uninfluenced and influenced vessel behavior are equal. The result of K-S test equals to 0 (accepted) or 1 (rejected). Similarly, the *Absolute Percentage Error* (*APE)* will be applied at the relative cross section 0 as well. As the relative cross section 0 can be at different locations in the research area, the difference attributed to the location is not considered in this paper.

6.1 Head-on encounters

Fig. 9 shows the comparison between uninfluenced and influenced vessel behavior for 948 head-on encounters in Sea-Nieuwe Maas and in Nieuwe Maas-Sea. Fig. 9 (a) and Fig. 9 (b) show that vessel speed in Sea-Nieuwe Maas is decreased and vessel speed in Nieuwe Maas-Sea does not strongly change in head-on encounters. This might be caused by the fact that incoming vessels are more likely to decrease their speed than outgoing vessels. In Fig. 9 (c) and Fig. 9 (d), vessel course is observed to be changed during the encounters between relative cross sections -20 and 20, although the difference at the relative cross section 0 is very small. This is the course change related to the maneuver during encounters. For relative distance to starboard bank, Fig. 9 (e) and Fig. 9 (f) show the similar phenomenon that vessels will deviate to starboard bank during head-on encounters, especially between relative cross sections -20 and 20. It can be concluded that the entire maneuver is completed within about 40 cross sections, which means that our investigation area is sufficient to analyze vessel head-on encounters. This finding indicates that the influence distance is around 2 km, in which the bridge team should start the maneuvering for head-on encounter. Furthermore, it can be concluded that the safe lateral distance between head-on vessels (on cross section 0) is around 0.35 times the width of the waterway.

The statistical results of K-S test and *APE* between uninfluenced and influenced vessel behavior at the relative cross section 0 are shown in Table 5.

Table 5. Statistical results of K-S test and *APE* between uninfluenced and influenced vessel behavior at the relative cross section 0.

		Speed	**Course**	**Relative distance**
Sea-Nieuwe Maas	K-S test result	1	0	1
	APE (%)	5.3	0.2	13.3
Nieuwe Maas-Sea	K-S test result	1	0	1
	APE (%)	1.2	0.2	9.7

It is found that vessel speed and relative distance are considered to be different for uninfluenced and influenced behavior at the relative cross section 0. The values of *APE* for relative distance in two directions are 13.3% and 9.7%, which imply the strong deviation to starboard bank at the relative cross section 0 for vessels in head-on encounters. The vessel course at the relative cross section 0 is considered to be uninfluenced, but it should be noted that vessels adapt their course before and after the relative cross section 0.

6.2 Overtaking encounters

In this section, 146 and 106 overtaking encounters respectively in Sea-Nieuwe Maas and in Nieuwe Maas-Sea are investigated. Since there is no regulation on which side vessels shall overtake each other, the bridge team can choose which side is the best for two vessels according to their experience, waterway geometry, on-coming traffic, etc. Before investigating the vessel behavior at the relative cross section 0, it is important to know on which side vessels overtake each other in the research area. In Fig. 10, histograms of relative lateral position difference of overtaken and overtaking vessels at the relative cross section 0 in Sea-Nieuwe Maas and Nieuwe Maas-Sea are shown. The positive and negative value of relative lateral position difference represents the portside and starboard overtaking, respectively. It can be found that most vessels overtake other vessels on their portside in Sea-Nieuwe Maas in Fig. 10 (a). However, Fig. 10 (b) shows that around one third of vessels overtake other vessels on their starboard in the opposite direction. Then, the analysis will focus on portside overtaking in Sea-Nieuwe Maas, and both portside and starboard overtaking in Nieuwe Maas-Sea.

The average uninfluenced and influenced vessel behavior in Sea-Nieuwe Maas and in Nieuwe Maas-Sea is shown in Fig. 11. Fig. 11 (a) and Fig. 11 (b) show that overtaking vessels increase their speed and overtaken vessels decrease their speed in overtaking encounters. This cooperative procedure could shorten the encounter period and thus increase the safety. Fig. 11 (c) and Fig. 11 (d) show that both overtaking and overtaken vessels will deviate from uninfluenced vessel course between relative cross section [-40, 40], which also show the cooperation between overtaking and overtaken vessels. Fig. 11 (e) and Fig. 11 (f) show the changes of relative distance for overtaking and overtaken vessels, which implies that during the overtaking the vessel on portside moves away from the bank and the vessel on starboard towards the bank. And the deviation of overtaken vessels in lateral direction is less than that of overtaking vessels. The safe lateral distance between overtaking vessels equals to 0.28 times the width of the waterway, which is smaller than between head-on vessels.

It also can be seen that the overtaking maneuver is not completed within the research area. Since both vessels sail in the same direction, overtaking encounters take more time and a longer distance than head-on encounters. This finding indicates the distance, in which the bridge team starts the maneuvering for overtaking, is larger than 2 km.

Then, the statistical results of the K-S test and *APE* between uninfluenced and influenced vessel behavior at the relative cross section 0 for overtaking encounters in Sea-Nieuwe Maas and in Nieuwe Maas-Sea are shown in Table 6 and Table 7, respectively.

Table 6. Statistical results of K-S test and *APE* between uninfluenced and influenced vessel behavior at the relative cross section 0 for overtaking encounters in Sea-Nieuwe Maas.

	Speed	**Course**	**Relative distance**
K-S test - overtaken	1	0	1
APE (%) - overtaken	23.2	0.8	23.1
K-S test - overtaking	1	0	1
APE (%) - overtaking	11.6	0.5	45.6

Table 7. Statistical results of the K-S test and *APE* between uninfluenced and influenced vessel behavior at the relative cross section 0 for overtaking encounters in Nieuwe Maas-Sea.

	Starboard overtaking			**Portside overtaking**		
	Speed	**Course**	**Relative distance**	**Speed**	**Course**	**Relative distance**
K-S test - overtaken	1	0	1	1	0	1
APE (%) - overtaken	29.3	0.8	37	14.8	0.8	28.4
K-S test- overtaking	1	0	1	1	0	1
APE (%) - overtaking	1.9	0.9	33	14.4	0.3	55.8

It is found that vessel speed and relative distance are significantly different than the uninfluenced behavior at the relative cross section 0 for both starboard overtaking and portside overtaking. Vessel speed is decreased by around 20% for overtaken vessels and is increased for around 10% for overtaking vessels. The relative distance is significantly changed between 23% - 37% for overtaken vessels and changed between 33% - 55% for overtaking vessels during encounters. However, vessel course is not influenced at the relative cross section 0, although it was found that vessel course changes before and after cross section 0. All these changes of vessel behavior can be considered as the cooperative behavior of the vessels in overtaking encounters. The overtaking vessels increase their speed and deviate from their original course, while the overtaken vessels will decrease the speed and deviate to the opposite direction. These maneuvers are performed by both vessels to shorten the overtaking period and increase the safety during encounters.

To conclude, vessel speed and relative distance to starboard bank are decreased during head-on encounters, but vessel course is influenced before and after CPA (relative cross section 0). In overtaking encounters, speed of overtaken vessels is decreased and speed of overtaking vessels is increased. In both starboard overtaking and portside overtaking, vessels will deviate to keep a larger lateral distance between overtaking and overtaken vessels. These behavior changes are performed by the bridge team to shorten the overtaking period and increase the safety during encounters.

7. Conclusion and discussions

In this paper, the influences of external conditions (wind, visibility and current) and vessel encounters (head-on and overtaking) on vessel speed, course and relative distance to starboard bank are analyzed by comparing uninfluenced and influenced vessel behavior using AIS data and historical data of wind, visibility and current.

Stern wind and bow wind mainly influence vessel speed, while starboard wind and portside wind can affect the relative distance to starboard bank. It was found that vessel speed is on average increased by 2.3% for container vessels and by 3.4% for GDC vessels under stern wind, but it is decreased by 2.5% and 9.6%, respectively by bow wind. Vessel course is barely influenced by wind, except for starboard wind. The relative distance to starboard is increased by 4.2% and 7.3% and is decreased by 4.9% and 9.4% respectively for the two vessel types. It is also can be seen that GDC vessels are easier to be influenced by wind than container vessels. Bad visibility has negative influence on vessel speed for container vessels (4.9%), but is does not influence GDC vessels. Vessel course is not influenced by visibility. The relative distance to starboard bank is decreased by bad visibility by 3.6% and 5.1% for container vessels and GDC vessels, respectively. For current, it is clear that GDC vessel speed is decreased by 11.6% and 5.3% under “Against current” and is increased by 6.1% and 12.9% under “With current”. That means current has significant influence on vessel speed. In addition, the influences of current on vessel course and relative distance to starboard are observed to be significant. But further research on the influence of current and waterway geometry is required.

For head-on encounters, it was found that vessel speed is decreased by 5.3% and 1.2%, and relative distance to starboard bank is decreased by 13.3% and 9.7% at the relative cross section 0 in two directions, respectively. Although vessel course at the relative cross section 0 is observed to be uninfluenced, it changes before and after CPA (relative cross section 0). It was also found that the research area is sufficient to cover the head-on encounters, which are approximately completed between relative cross sections -20 and 20. In overtaking encounters, it was firstly found that vessels can overtake each other either by portside or starboard side. Furthermore, vessel speed and relative distance to starboard bank are influenced during overtaking encounters. Vessel speed is decreased around 20% for overtaken vessels and is increased around 10% for overtaking vessels. The relative distance is decreased by around 25% for overtaken vessels and is increased by 50% for overtaking vessels in portside overtaking, while 37% and 33% in starboard overtaking. In addition, it was found that overtaking maneuver is not completed within the research area. It can be concluded that overtaking encounters take more time and a longer distance than head-on encounters since both vessels sail in the same direction, and the safe lateral distance between overtaking vessels is smaller than between head-on vessels. For both head-on and overtaking encounters, two vessels show the cooperative behavior during the encounters. For example, both vessels will deviate from their original path, and vessel speed for overtaking vessel is increased and speed of overtaken vessels is decreased. This cooperative behavior should be considered when vessel encounters are simulated.

The results of these analyses could benefit both port authority and the bridge team. For port authority, these results could be used to improve the maritime traffic management and risk assessment in ports and waterways, such as the risk grading for different external conditions and encounters or waterway expansion. For the bridge team, the results could serve as the guidance for vessel maneuvering. On the other hand, the analysis results also provide direction for the new maritime traffic model (Hoogendoorn et al., 2013) or risk assessment model development.

Although the influence of each individual factor is investigated in this paper, the combined influence of these factors needs to be further investigated. In addition, vessel behavior is only investigated on part of the waterway due to the limit of available current data. A real-time measured current data in different locations could provide more insight into the influence of current on vessel course and relative distance to starboard bank. Furthermore, it is recommended to investigate the relation between safe lateral distance and vessel dimensions, which is more practicable for the bridge team. The future research will also focus on developing a new maritime traffic model, which will consider the influence of external conditions and vessel encounters presented in this paper.

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Figures

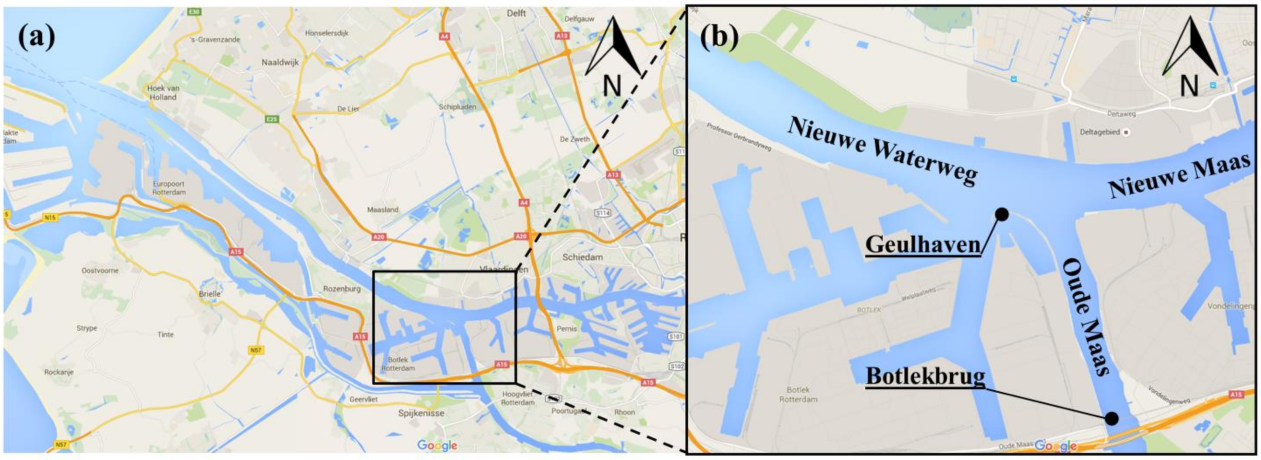

Fig. 1. (a) Location of research area: the Botlek area in the port of Rotterdam; (b) the zoom-in view of the Botlek area, comprising three parts: “Nieuwe Waterweg”, “Nieuwe Maas” and “Oude Maas”. The locations of the measuring station “Geulhaven” for wind and visibility and the measuring station “Botlekbrug” for current are also specified.

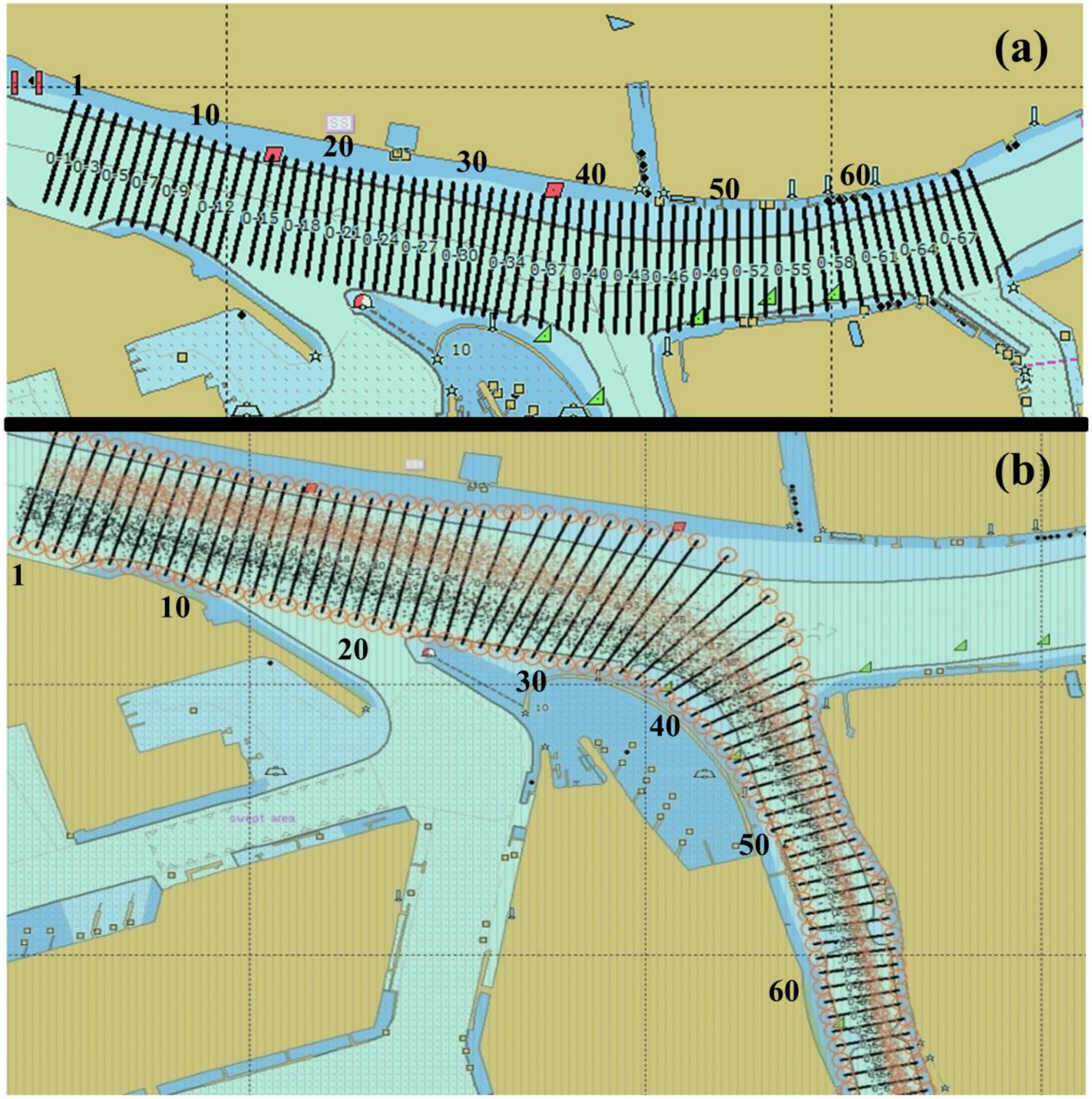

Fig. 2. (a) 69 cross sections in Sea-Nieuwe Maas and Nieuwe Maas-Sea, the cross sections are numbered from the west to the east as cross section 1 to 69; (b) 68 cross sections in Sea-Oude Maas and Oude Maas-Sea, the cross sections are numbered from the west to the southeast as cross section 1 to 68 (Shu et al., 2013).

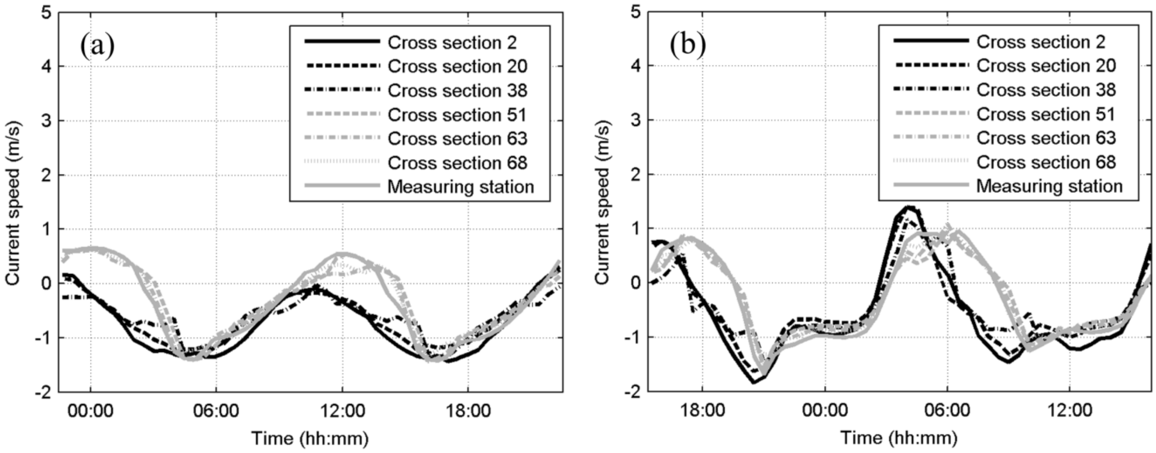

Fig. 3. The simulated current speed at the condition of (a) neap-average discharge and (b) spring-average discharge, at different cross sections and at the measuring station over one day, simulated by the model Delft3D.

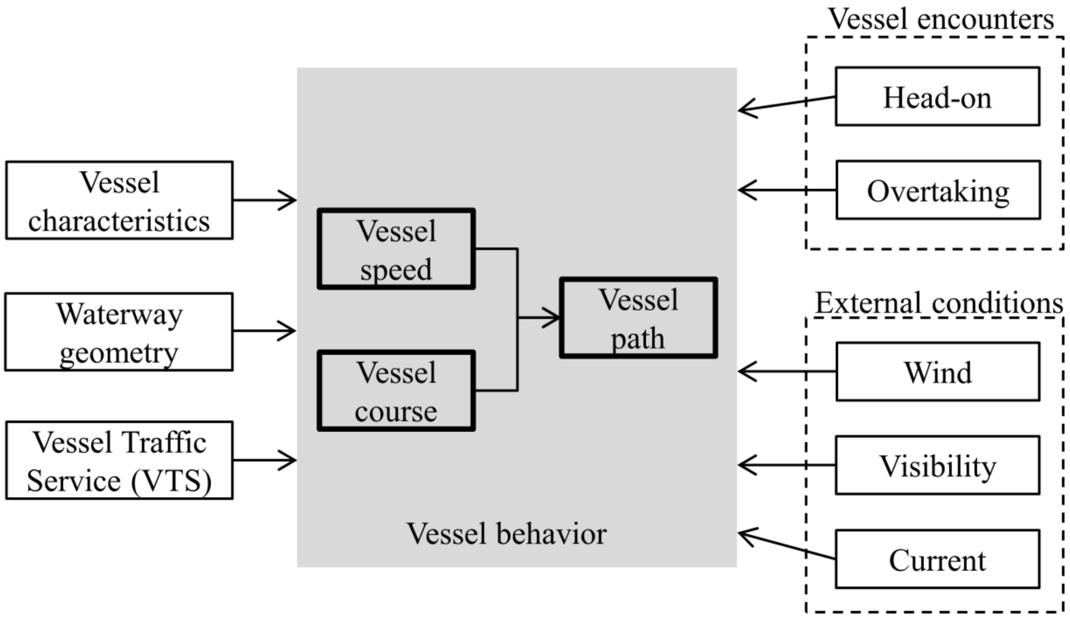

Fig. 4. Vessel behavior and potential factors influencing vessel behavior.

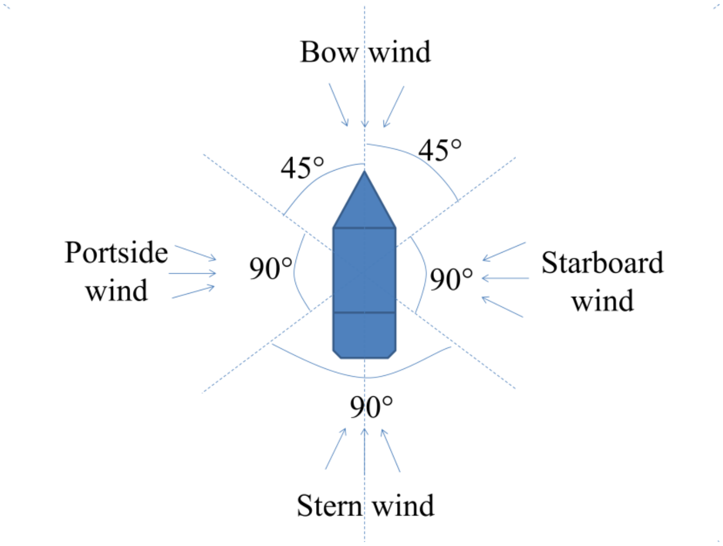

Fig. 5. Four wind categories based on the angle between vessel course and wind direction.

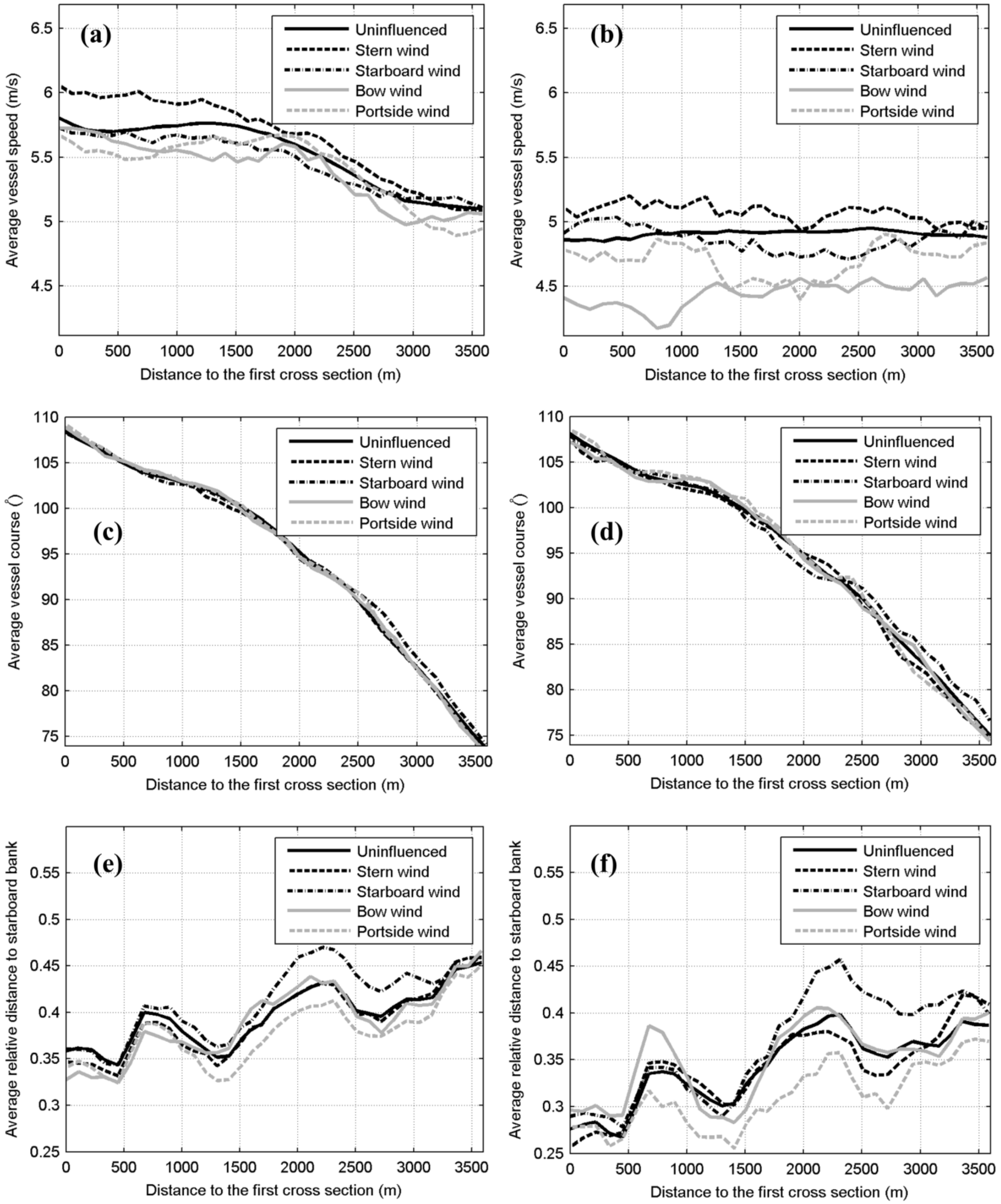
(a)
(b)
(c)
(d)
(e)
(f)
Uninfluenced
Stern wind
Starboard wind
Bow wind
Portside wind
Average vessel speed (m/s)
Average vessel course (°)
Average relative distance to starboard bank
Distance to the first cross section (m)
0
500
1000
1500
2000
2500
3000
3500
4.5
5
5.5
6
6.5
75
80
85
90
95
100
105
110
0.25
0.3
0.35
0.4
0.45
0.5
0.55

Fig. 6. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by wind for container vessels in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by wind for GDC vessels in Sea-Nieuwe Maas.

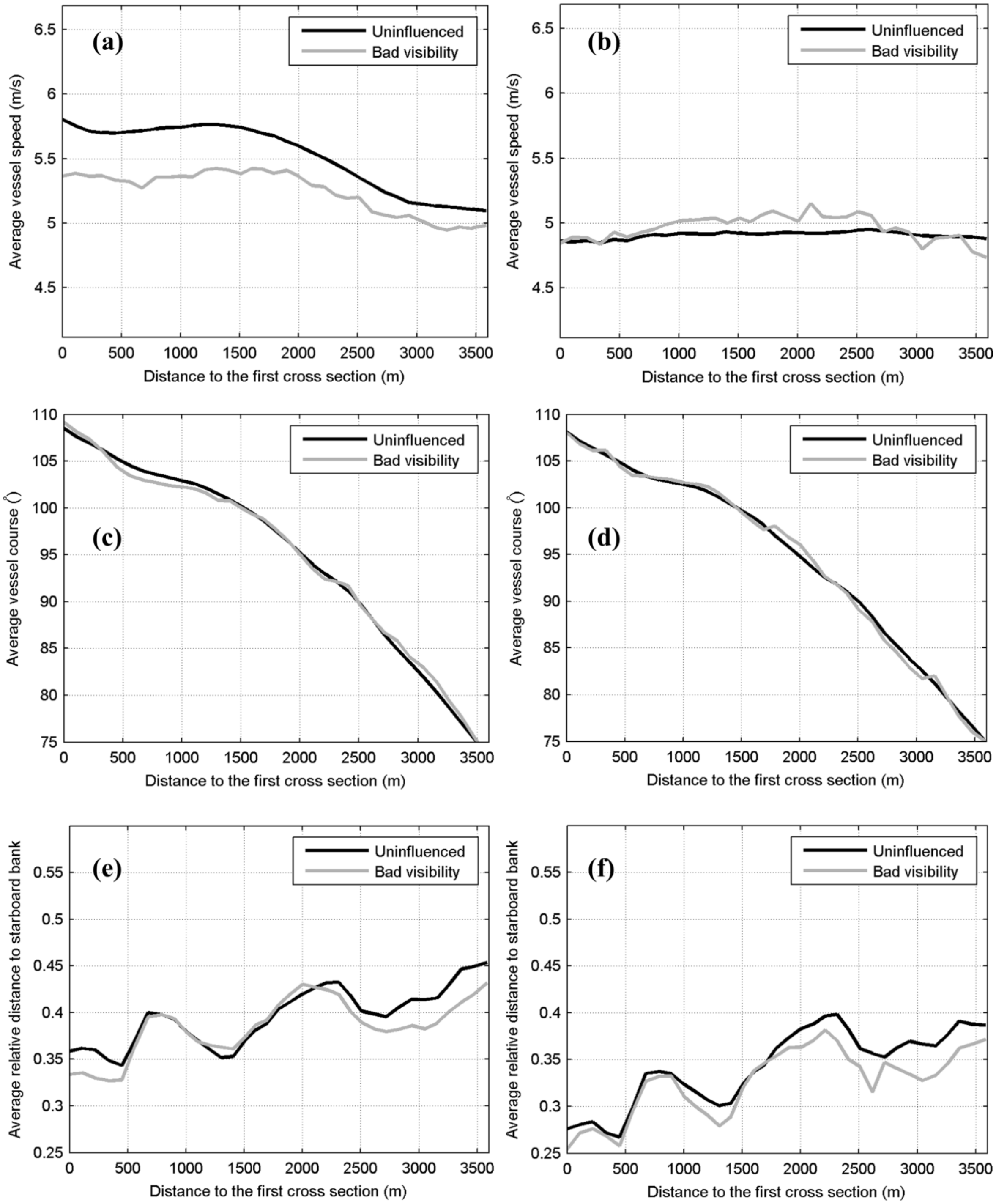

Fig. 7. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by visibility for container vessels in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by visibility for GDC vessels in Sea-Nieuwe Maas.

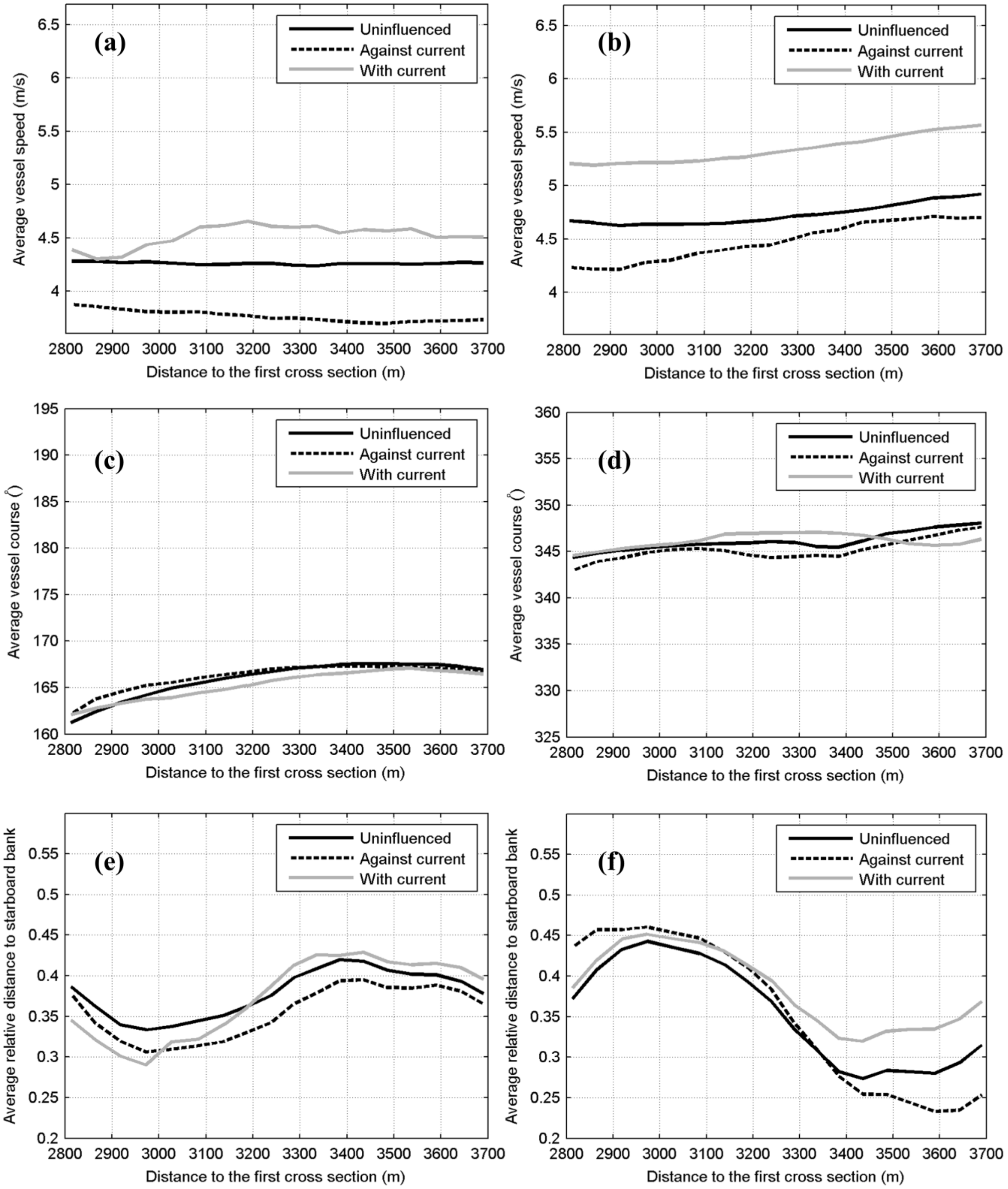

Fig. 8. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by current for GDC vessels at cross section 51-68 in Sea-Oude Maas; uninfluenced and influenced

vessel speed (b), course (d) and distance to starboard bank (f) by current for GDC vessels at cross section 51-68 in Oude Maas-Sea.

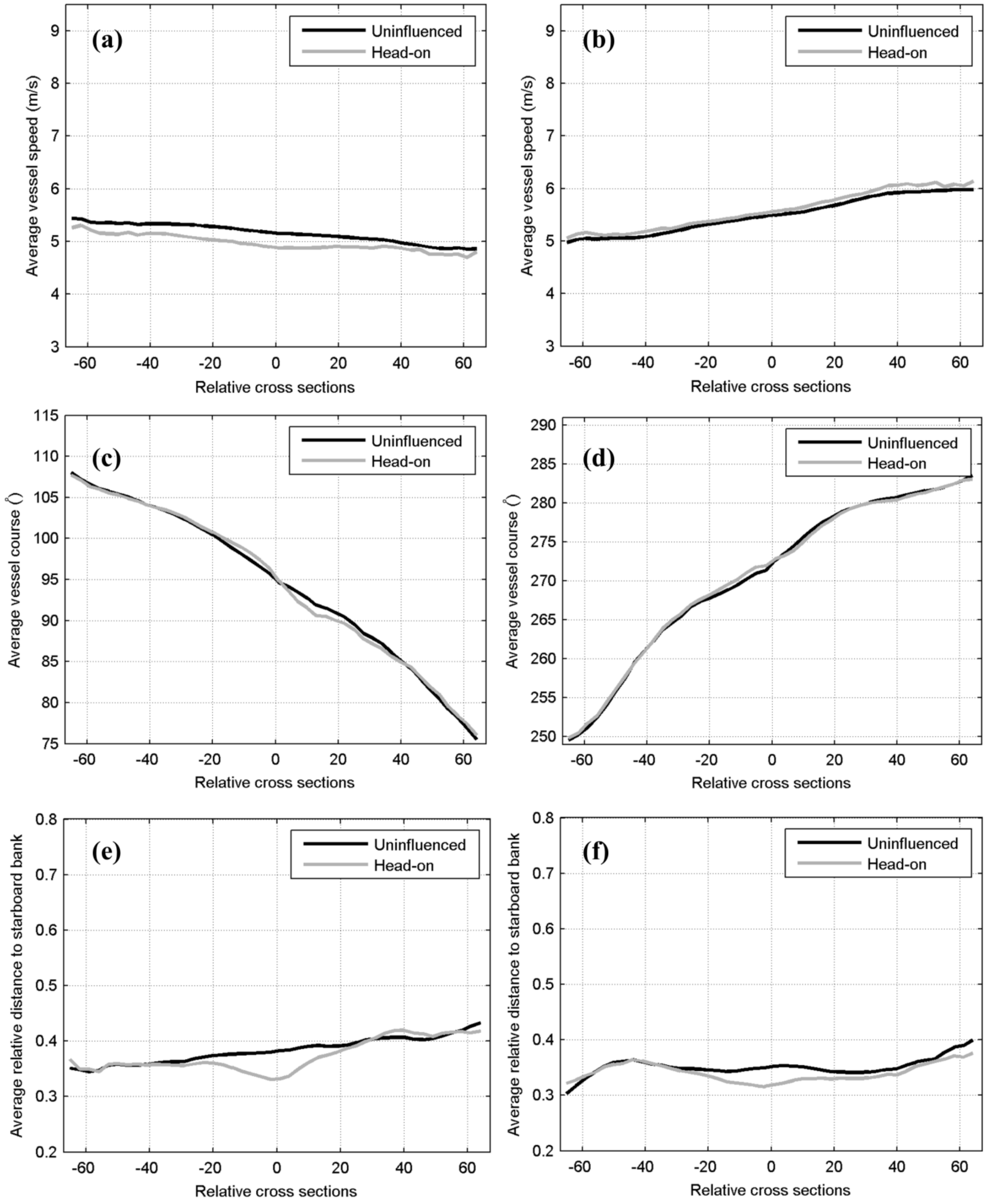

Fig. 9. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by head-on encounters in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by head-on encounters in Nieuwe Maas-Sea.

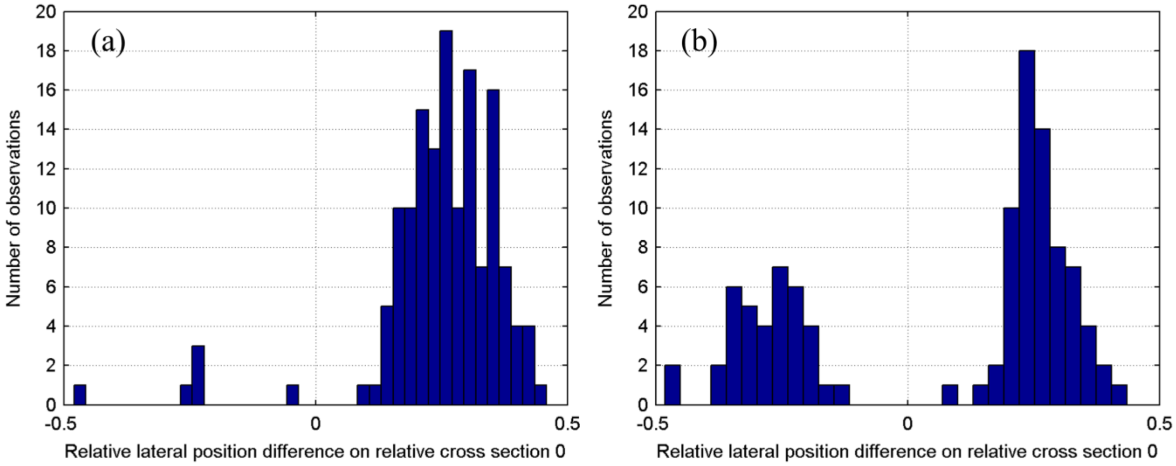

Fig. 10. Histograms of relative lateral position difference of overtaken and overtaking vessels at relative cross section 0 in Sea-Nieuwe Maas (a) and Nieuwe Maas-Sea (b).

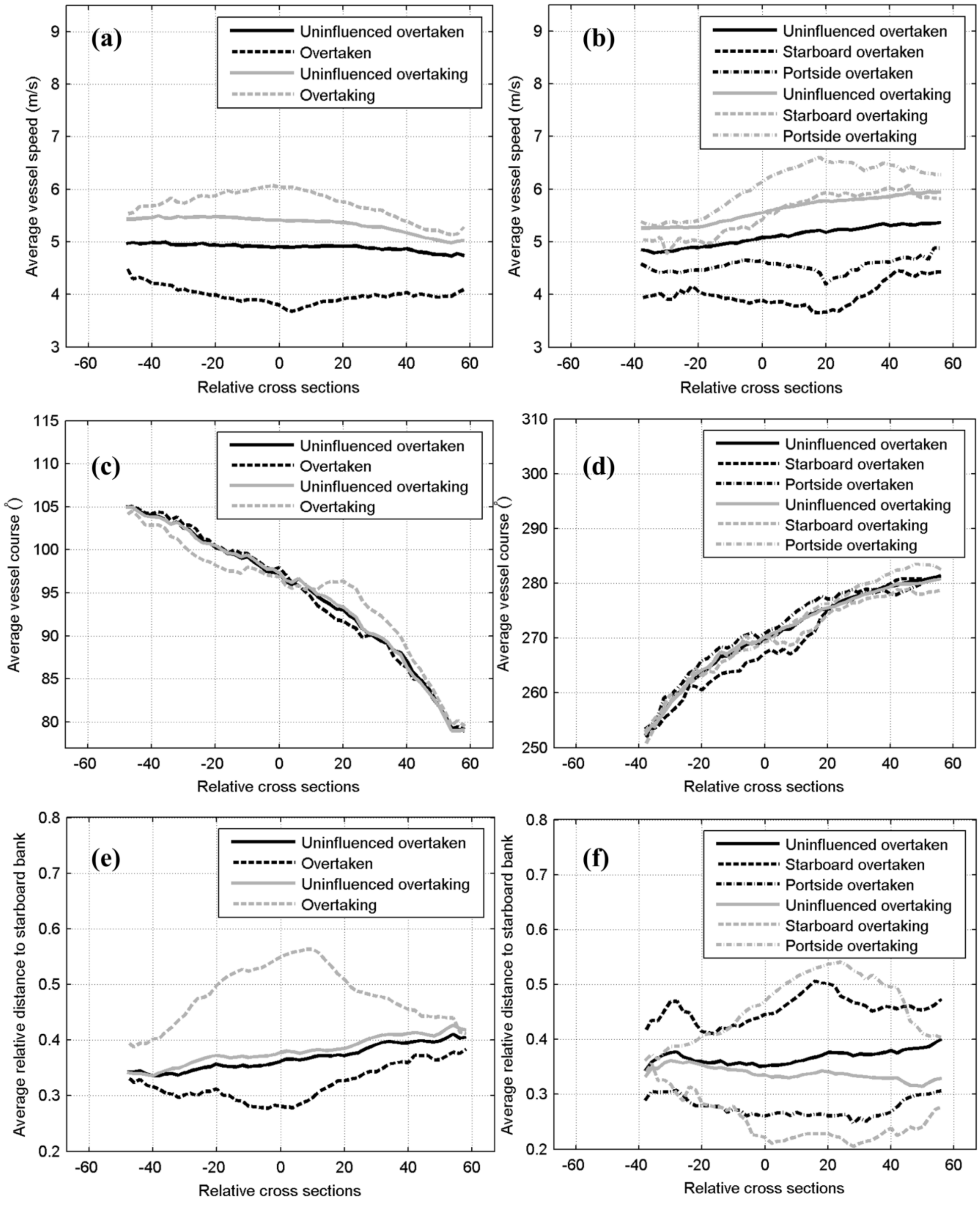

Fig. 11. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by overtaking encounters in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by overtaking encounters in Nieuwe Maas-Sea.