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1 Influence of external conditions and vessel encounters on vessel
2 behavior in ports and waterways using Automatic Identification

3 System data

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13 **Abstract**

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

26

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

29 **1. Introduction**

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

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

48 Initial studies qualitatively showed that the wind and current can effect vessel speed and course
49 in ports (de Boer, 2010). However, the influence of external factors, either wind or current, on vessel
50 behavior was investigated without eliminating the impact of other factors on vessel behavior in this
51 study and the influence of external factors on vessel behavior has not been quantified. A recent

52 maritime traffic simulation study showed that vessel characteristics (type and size) can also
53 significantly influence the vessel behavior in ports (Xiao et al., 2015). Notwithstanding these studies,
54 the influence of external conditions (including wind, visibility and current) and vessel encounters on
55 vessel behavior is not yet fully understood and quantified.

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

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

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

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

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

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

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

77 **2. Research area, data and approach**

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

80 ***2.1 Research area***

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

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

- 97 • Sea-Nieuwe Maas: vessels sail from Sea to the “Nieuwe Maas”
- 98 • Nieuwe Maas-Sea: vessels sail from the “Nieuwe Maas” to the Sea
- 99 • Sea-Oude Maas: vessels sail from the Sea to “Oude Maas”
- 100 • Oude Maas-Sea: vessels sail from the “Oude Maas” to the Sea

101 **2.2 Research data**

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

111 *2.2.1 AIS data and cross sections*

112 In the 1990s, the International Association of Maritime Aids to Navigation and Lighthouse
113 Authorities (IALA) presented to the International Maritime Organization (IMO) the first proposal
114 for AIS, in which the AIS system is designed to identify other vessels including their positions
115 (Eriksen et al., 2006). The purpose of the AIS system is “to contribute to improved situational
116 awareness for shore-side authorities and ships’ officers” (Bailey et al., 2008). The AIS system works

117 on Very High Frequency (VHF), so it is possible to detect other AIS-equipped vessels when the
118 radar detection is confined, such as under influence of strong rain or tall buildings. In the
119 International Convention for the Safety of Life at Sea (SOLAS), IMO made AIS mandatory for
120 vessels of 300 GT and more by 2004, and now it is mandatory for small vessels as well
121 (Organization, 2000).

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

129 The accuracy of AIS data has been improved a lot in the last decade. It was found that the
130 percentage of vessels that transmitted errors decreased from 10.4 % in 2004 to 3.5 % in 2007, and
131 most errors are about destination and draught, which includes misspelling, empty data fields,
132 incomprehensible abbreviations and references to the previous port (Bailey et al., 2008, Harati-
133 Mokhtari et al., 2007). It was also found that errors occur in Estimated Time of Arrival (ETA) (21.7
134 % of the observations were wrong), IMO number (14.1 %), Destination (11.0 %), Rate of turn (8.9
135 %), Heading (7.1 %), Dimensions (6.2 %), Draught (5.7 %), Course over ground (0.8 %), Speed
136 over ground (0.8 %) and a missing ship name (0.04%) (Solvsteen, 2009). It can be concluded that
137 dynamic vessel data are more accurate.

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

140 Nieuwe Maas and Nieuwe Maas-Sea and 68 cross sections in Sea-Oude Maas and Oude Maas-Sea
141 are defined (Shu et al., 2013). The systematic approach to make the cross sections perpendicular to
142 waterway centerline is preferable. When we analyzed the AIS data, we have drawn the cross
143 sections manually in “ShowRoute” in a more pragmatic manner. We have found that the results, in
144 terms of vessel speed, course and relative lateral position, are not sensitive to the precise choice of
145 the cross sections. Thus, these cross sections are not strictly perpendicular to waterway direction.
146 The interval between cross sections is approximately equal to 50 meters, which is similar to the
147 distance in which vessels send one AIS record, as the average speed of vessels in this area is around
148 10 knots (5.14 m/s) and the reporting interval for most vessels is 10 seconds. Each cross section is
149 formed by linking two points at the 5-meter depth contours on two sides of the waterway, which are
150 the dividing lines between light blue and dark blue area. The light blue indicates the area where the
151 water depth is larger than 5 meters, while the dark blue is corresponding to the area shallower than 5
152 meters. These two points are chosen such that the cross section is approximately perpendicular to the
153 waterway axis. The 5-meter depth contours are used because vessels normally do not pass the 5-
154 meter depth contour to avoid groundings. Therefore, the 5-meter depth contours are considered as
155 part of the bank in our research. It should be noted that there is no 5-meter depth contour in the
156 junction area and entrances to the basins on one side of the waterway, so there a smooth curve is
157 defined to link the adjacent 5-meter depth contours, as described previously (Shu et al., 2013).

158 Using these cross sections, AIS data in the time period from January 2009 to April 2011 are
159 extracted in the four aforementioned directions and will be used for the analyses. To calculate vessel
160 speed, course and position on a cross section, the data from the nearest point before and after the
161 cross section is used to extrapolate the values on the cross section, based on the function of time

162 using linear interpolation. In this way, each vessel path will have one data record on each cross
163 section.

164 2.2.2 *Wind, visibility and current data*

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

169 In order to investigate the influence of current on vessel behavior, it is important to have reliable
170 current data in the research area. In this study, the current data are available from the measuring
171 station “Botlekbrug” (Fig. 1), which is located in “Oude Maas”, and in the south of the research
172 area. Because the measured current data from one measuring station cannot represent the current in
173 the whole area, it is essential to identify the applicable area of the measured current data. These data
174 are recorded every 10 minutes and velocity is taken at 5 meters depth to the local datum -
175 Amsterdam Ordnance Datum (in Dutch “Normaal Amsterdams Peil”, NAP). As the current is
176 influenced by river discharge, the tidal condition and waterway geometry, the current may vary at
177 different locations as well as over the water depth. However, for most of the vessels that pass along
178 Oude Maas, the current speed at 5m below NAP represents the average conditions fairly well (for
179 which reason this depth has been chosen by the authorities). In order to link the recorded current
180 data to currents in other parts of the research area, a numerical simulation model called Delft3D
181 (Roelvink & Van Banning, 1995) has been applied by the Port of Rotterdam Authority to simulate
182 the currents along the stretch Sea-Oude Maas under different tidal conditions within one day. The
183 annual average discharge of 2300 m³/s is applied as input for this model and both the neap and

184 spring tide are simulated for tidal conditions. It is assumed that the variability of real current is
185 similar to the variability of simulated current along the waterways.

186 The simulated current during the simulation period at the measuring station and at cross sections
187 2, 20, 38, 51, 63, 68 are presented as examples in Fig. 3. Here, cross sections 2, 20, 38, 51, 63 and
188 68 are chosen as representative situations, which are clearly distinct from each other. These cross
189 sections are selected from both straight stretches and the bend. Cross sections 2 and 20 represent the
190 situation in the straight stretch “Nieuwe Waterweg”; cross section 38 is selected because it is located
191 in the middle of the bend area; cross section 51, 63 and 68 represent the situation in the straight
192 stretch “Oude Maas”. It is shown that the simulated current at the measuring station and at the cross
193 sections 51, 63 and 68, which are all located in the “Oude Maas”, do not show substantial
194 differences. The absolute difference between the simulated current at the measuring station and the
195 values at cross sections 51, 63 68 is 0.21, 0.16 and 0.18 m/s for neap-average discharge and 0.19,
196 0.11 and 0.14 m/s for spring-average discharge, respectively. In comparison, the absolute difference
197 between the simulated current at the measuring station and the value on cross sections 2, 20, 38
198 (located on “Nieuwe Waterweg”) is much larger (0.62, 0.56 and 0.62 m/s for neap-average
199 discharge and 0.5, 0.49, 0.39 m/s for spring-average discharge, respectively). This result implies that
200 the current data collected from the measuring station in “Oude Maas” can be used to represent the
201 current on cross sections 51-68. This finding enables us to investigate the influence of current on
202 vessel behavior in this area.

203 ***2.3 Research approach***

204 In our research, the bridge team is considered as the “brain” of the vessel and covers the
205 intelligence and decision making for the vessel. Based on this assumption, the bridge team and the

206 vessel are considered as an integrated entity. The vessel behavior discussed in this paper is governed
207 by this entity and is defined by the vessel speed, course and path. The vessel behavior and potential
208 factors influencing vessel behavior are shown in Fig. 4. It can be seen that vessel behavior can be
209 affected by different factors, such as vessel characteristics and waterway geometry. In this paper,
210 external conditions (wind, visibility and current) and vessel encounters (head-on and overtaking) are
211 investigated, while specific vessel categories classified by vessel type and size (Shu et al., 2013) are
212 used to eliminate the influence of vessel characteristics.

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

225 In this research, the AIS data are combined with historical data of wind, visibility and current by
226 linearly interpolation based on time and coupling the time records of the individual AIS messages
227 and the data sets for wind, visibility and current. The combined data set is divided into two groups
228 corresponding to the uninfluenced and influenced vessel behavior according to the conditions listed

229 in Table 1. The thresholds for selecting uninfluenced vessel behavior are the same as we used in the
 230 previous paper: for wind < 8 m/s, for visibility $> 2,000$ meters and for encounters a distance to other
 231 vessels $< 1,000$ meters (Shu et al., 2013). The extra condition for uninfluenced vessel behavior is for
 232 current < 0.8 m/s. It should be noted that current is not considered when the influences of wind and
 233 visibility are investigated, because the current data only cover cross section 51-68.

234 **Table 1.** Conditions for uninfluenced and influenced vessel behavior.

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

235

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

243 To compare the influence of wind and visibility on vessel behavior, the vessel categories for
 244 container vessels with 5,100-12,000 GT and general dry cargo (GDC) vessels with gross tonnage
 245 less than 3,600 GT on all cross sections in Sea-Nieuwe Maas are investigated in this paper (Shu et

246 al., 2013). These two vessel categories in this direction are investigated since they are the most
247 common vessel categories in the research area and Sea-Nieuwe Maas is the direction with the main
248 vessel traffic flow. For current, GDC vessels with gross tonnage less than 3,600 GT on cross
249 sections 51-68 in Sea-Oude Maas and in Oude Maas-Sea are investigated, since GDC vessels are the
250 most common vessels in these two directions.

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

267 The influences of encounters on vessel behavior are investigated in Sea-Nieuwe Maas and
268 Nieuwe Maas-Sea, which are the waterways with the main vessel traffic flow. Using the algorithm

269 above, 948 head-on encounters are selected in Sea-Nieuwe Maas and Nieuwe Maas-Sea, while 146
270 and 106 overtaking encounters are selected respectively in Sea-Nieuwe Maas and in Nieuwe Maas-
271 Sea.

272 It should be noted here that vessel type and size is not considered when we investigate the
273 influence of vessel encounters on vessel behavior. To investigate average vessel behavior in
274 encounters, the cross section nearest to the Closest Point of Approach (CPA) is defined as the
275 relative cross section 0. Then, the cross sections located ahead and behind the relative cross section
276 0 are defined as the relative cross sections with negative ids and positive ids ranging in $[-68,68]$,
277 respectively. However, it is important to mention that the research area was divided into 69 cross
278 sections. If the relative cross section is located close to the border of the research area, some relative
279 cross sections would be located out of the research area, i.e. there is no data available. Therefore, the
280 data availability on the relative cross sections decreases with the increasing distance to the relative
281 cross section 0. To ensure that the average vessel behavior on each relative cross section is
282 supported by enough data, the minimum requirement for data number on each relative cross section
283 is 30 in these analyses. Then, the uninfluenced and influenced vessel behavior at each relative cross
284 section is calculated and compared for both vessels in encounters, and the uninfluenced behavior is
285 calculated according to the vessel categories in our previous research (Shu et al., 2013).

286 ***2.4 Statistical analysis method***

287 As it was found that vessel behavior is influenced by waterway geometry (Shu et al., 2013),
288 comparison between uninfluenced and influenced vessel behavior should be performed on each
289 cross section. In this paper, the Kolmogorov-Smirnov test (K-S test) is used to test if uninfluenced
290 and influenced vessel behavior come from the same distribution. The null hypothesis of the K-S test

291 is that “the uninfluenced and influenced vessel behavior are drawn from the same distribution”. In
292 this method, a threshold for the p-value, called the significance level of the test, is used as 5%. To
293 represent the results of K-S test, the parameter p_r is the percentage of cross sections, on which the
294 null hypothesis of K-S test is rejected.

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

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

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

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

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

306 As shown in Fig. 6 (a) and Fig. 6 (b), vessel speed is influenced by strong wind for both
307 container and GDC vessels, especially under stern wind and bow wind. It is in line with our
308 expectations that vessel speed increased under stern wind and decreased under bow wind, which is
309 caused by the wind force added on the vessels. For starboard wind and portside wind, a small drop is
310 observed on most cross sections and can be explained by the anticipation of dangerous situations by
311 the bridge team. In addition, it is found that strong wind has stronger influence on GDC vessels than

312 on container vessels, which may be due to the fact that GDC vessels are much smaller than container
313 vessels, and thus smaller vessels are easier to be influenced by wind. In Fig. 6 (c) and Fig. 6 (d), it is
314 shown that the influenced vessel course is similar to uninfluenced vessel course for both container
315 and GDC vessels. However, the larger fluctuations of vessel course for GDC vessels than for
316 container vessels also indicate that GDC vessels are more easily affected by wind than container
317 vessels. Fig. 6 (e) and Fig. 6 (f) show that the relative distance to starboard bank under stern wind
318 and bow wind are comparable with uninfluenced behavior, while the relative distance is decreased
319 under portside wind and it is increased under starboard wind. It also can be found that the deviation
320 of relative distance under portside wind and starboard wind from the uninfluenced behavior is larger
321 for GDC vessels than for container vessels. In addition, the deviation between uninfluenced and
322 influenced relative distance is larger in the eastern part of the waterway than in the western part.
323 This might be caused by the influence of the waterway geometry.

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

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

		Speed		Course		Relative distance	
		p_r (%)	$MAPE$ (%)	p_r (%)	$MAPE$ (%)	p_r (%)	$MAPE$ (%)
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

328

329 As shown in Table 2, the null hypothesis of the K-S test for container vessel speed is rejected at
330 39.1% and 11.6% of cross sections for stern wind and bow wind, respectively. The values of *MAPE*
331 indicate that the speed is increased by 2.3% and decreased by 2.5% under stern wind and bow wind,
332 respectively. For GDC vessels, stronger influence is observed for bow wind and the null hypothesis
333 is rejected on 97.1% of cross sections, where vessel speed is decreased by 9.6%. Although vessel
334 speed is only influenced by stern wind at 10.1% of cross sections, the value of *MAPE* shows vessel
335 speed is increased by 3.4%. The null hypothesis of the K-S test is accepted for starboard and
336 portside wind at most cross sections for both container and GDC vessels. This means that the
337 starboard and portside wind do not influence vessel speed.

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

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

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

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

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

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

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

	Speed		Course		Relative distance	
	p_r (%)	$MAPE$ (%)	p_r (%)	$MAPE$ (%)	p_r (%)	$MAPE$ (%)
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

365
 366 The statistical results show different influence on vessel speed for container and GDC vessels.
 367 For container vessels, the null hypothesis is rejected on most cross sections (58%) and the $MAPE$
 368 shows that vessel speed is decreased by 4.9%. However, p_r shows that the null hypothesis is
 369 accepted for GDC vessels on all cross sections and the value of $MAPE$ is very small (1.7%). For
 370 vessel course, it is found that bad visibility almost does not influence vessel course for both

371 container and GDC vessels. Although the null hypothesis is rejected for relative distance on 24.6%
372 and 11.6% of cross sections for container and GDC vessels, the values of *MAPE* are 3.6% and 5.1%.
373 This means that vessels will deviate to starboard bank under bad visibility and the influence for
374 GDC vessels is stronger than for container vessels. This can be explained by the perception of
375 danger for the bridge team and thus they sail closer to the bank.

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

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

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

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

389

390 **Table 4.** Statistical results of p_r and $MAPE$ between uninfluenced and influenced vessel behavior by
 391 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

392
 393 It can be found that vessel speed is decreased under “Against current” by 11.6% in Sea-Oude
 394 Maas and by 5.3% in Oude Maas-Sea, and is increased under “With current” by 6.1% in Sea-Oude
 395 Maas and by 12.9% in Oude Maas-Sea. Although the values of $MAPE$ for vessel course are very
 396 small, the values of p_r show that the uninfluenced and influenced vessel course are different at most
 397 cross sections. Finally, two strong influences on relative distance are observed for “Against current”
 398 in Sea-Nieuwe Maas and “With current” in Oude Maas-Sea, but values of $MAPE$ are all more than
 399 5%, which means relative distance is influenced by bad visibility.

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

404 **6. Influence of encounters (Research question 4)**

405 In this section, the results of comparison between uninfluenced and influenced vessel behavior
 406 on the relative cross sections for head-on and overtaking encounters are shown, respectively. Since it
 407 is assumed that vessel behavior differs most for both vessels in encounters, the K-S test will only be
 408 applied for the relative cross section 0 to test if the uninfluenced and influenced vessel behavior are

409 equal. The result of K-S test equals to 0 (accepted) or 1 (rejected). Similarly, the *Absolute*
410 *Percentage Error (APE)* will be applied at the relative cross section 0 as well. As the relative cross
411 section 0 can be at different locations in the research area, the difference attributed to the location is
412 not considered in this paper.

413 *6.1 Head-on encounters*

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

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

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

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

433
 434 It is found that vessel speed and relative distance are considered to be different for uninfluenced
 435 and influenced behavior at the relative cross section 0. The values of *APE* for relative distance in
 436 two directions are 13.3% and 9.7%, which imply the strong deviation to starboard bank at the
 437 relative cross section 0 for vessels in head-on encounters. The vessel course at the relative cross
 438 section 0 is considered to be uninfluenced, but it should be noted that vessels adapt their course
 439 before and after the relative cross section 0.

440 *6.2 Overtaking encounters*

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

451 of vessels overtake other vessels on their starboard in the opposite direction. Then, the analysis will
452 focus on portside overtaking in Sea-Nieuwe Maas, and both portside and starboard overtaking in
453 Nieuwe Maas-Sea.

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

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

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

473 **Table 6.** Statistical results of K-S test and *APE* between uninfluenced and influenced vessel
 474 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
<i>APE</i> (%) - overtaken	23.2	0.8	23.1
K-S test - overtaking	1	0	1
<i>APE</i> (%) - overtaking	11.6	0.5	45.6

475

476 **Table 7.** Statistical results of the K-S test and *APE* between uninfluenced and influenced vessel
 477 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
<i>APE</i> (%) - overtaken	29.3	0.8	37	14.8	0.8	28.4
K-S test- overtaking	1	0	1	1	0	1
<i>APE</i> (%) - overtaking	1.9	0.9	33	14.4	0.3	55.8

478

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

488 speed and deviate to the opposite direction. These maneuvers are performed by both vessels to
489 shorten the overtaking period and increase the safety during encounters.

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

496 **7. Conclusion and discussions**

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

501 Stern wind and bow wind mainly influence vessel speed, while starboard wind and portside wind
502 can affect the relative distance to starboard bank. It was found that vessel speed is on average
503 increased by 2.3% for container vessels and by 3.4% for GDC vessels under stern wind, but it is
504 decreased by 2.5% and 9.6%, respectively by bow wind. Vessel course is barely influenced by wind,
505 except for starboard wind. The relative distance to starboard is increased by 4.2% and 7.3% and is
506 decreased by 4.9% and 9.4% respectively for the two vessel types. It is also can be seen that GDC
507 vessels are easier to be influenced by wind than container vessels. Bad visibility has negative
508 influence on vessel speed for container vessels (4.9%), but is does not influence GDC vessels.
509 Vessel course is not influenced by visibility. The relative distance to starboard bank is decreased by

510 bad visibility by 3.6% and 5.1% for container vessels and GDC vessels, respectively. For current, it
511 is clear that GDC vessel speed is decreased by 11.6% and 5.3% under “Against current” and is
512 increased by 6.1% and 12.9% under “With current”. That means current has significant influence on
513 vessel speed. In addition, the influences of current on vessel course and relative distance to starboard
514 are observed to be significant. But further research on the influence of current and waterway
515 geometry is required.

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

532 original path, and vessel speed for overtaking vessel is increased and speed of overtaken vessels is
533 decreased. This cooperative behavior should be considered when vessel encounters are simulated.

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

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

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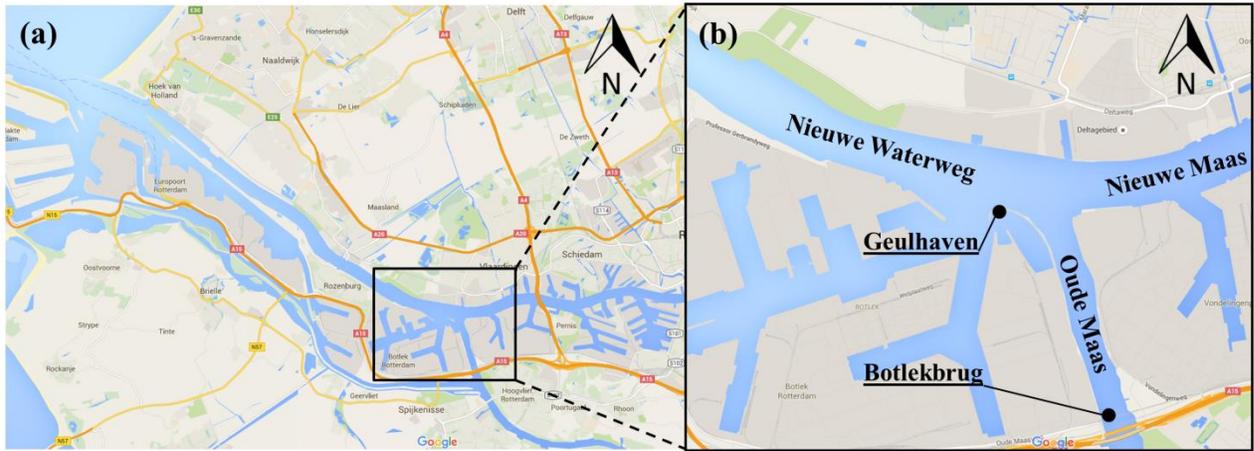
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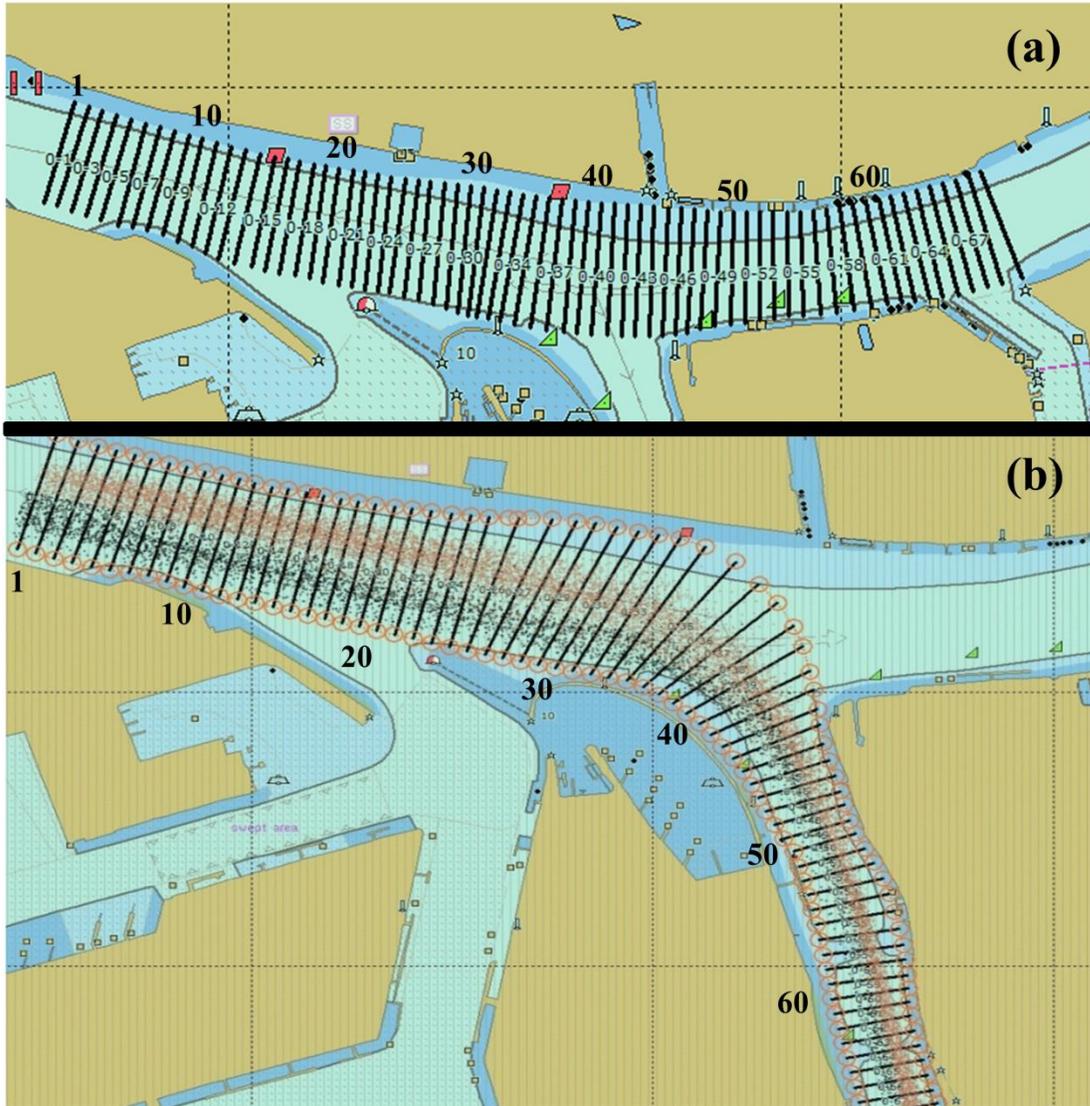
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604 **Figures**



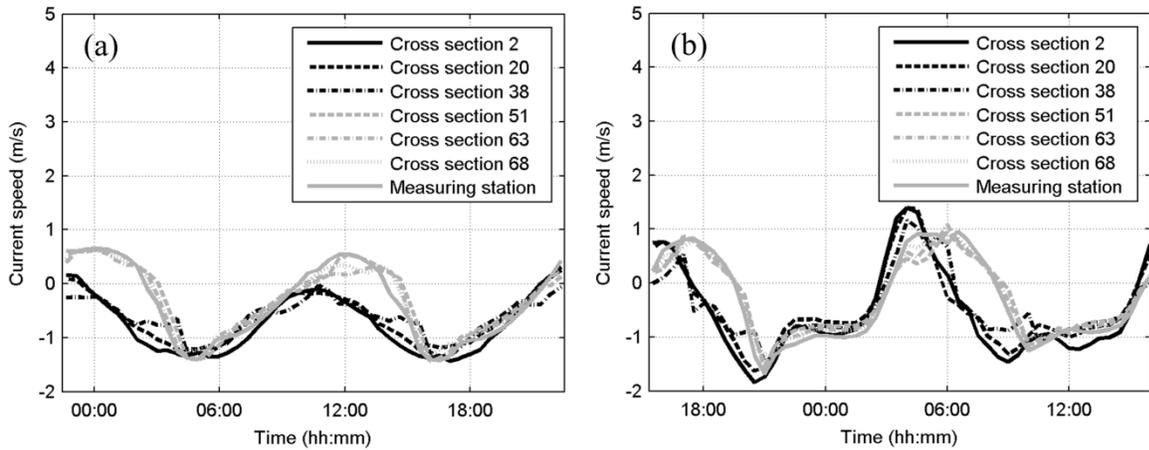
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606 Fig. 1. (a) Location of research area: the Botlek area in the port of Rotterdam; (b) the zoom-in view
607 of the Botlek area, comprising three parts: “Nieuwe Waterweg”, “Nieuwe Maas” and “Oude Maas”.
608 The locations of the measuring station “Geulhaven”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

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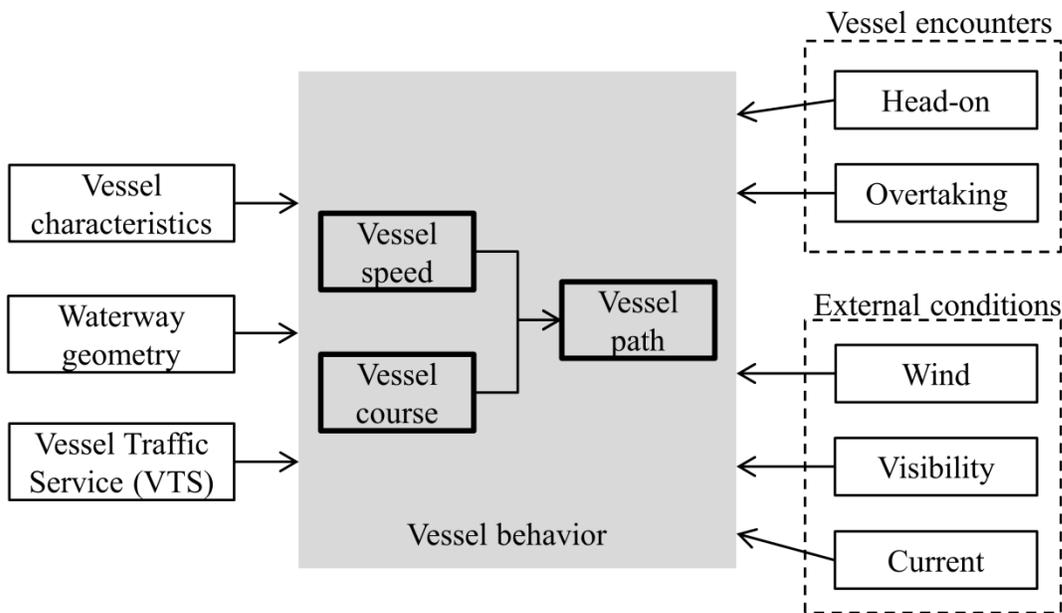
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 612 Fig. 2. (a) 69 cross sections in Sea-Nieuwe Maas and Nieuwe Maas-Sea, the cross sections are
 613 numbered from the west to the east as cross section 1 to 69; (b) 68 cross sections in Sea-Oude Maas
 614 and Oude Maas-Sea, the cross sections are numbered from the west to the southeast as cross section
 615 1 to 68 (Shu et al., 2013).

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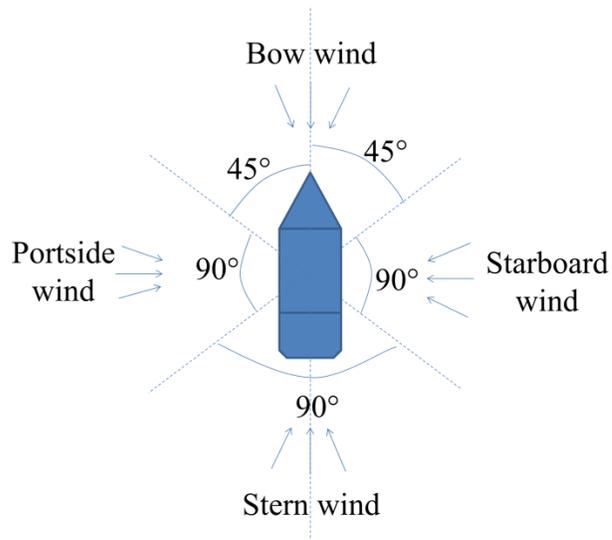
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Fig. 3. The simulated current speed at the condition of (a) neap-average discharge and (b) spring-average discharge, at different cross sections and at the measuring station over one day, simulated by the model Delft3D.



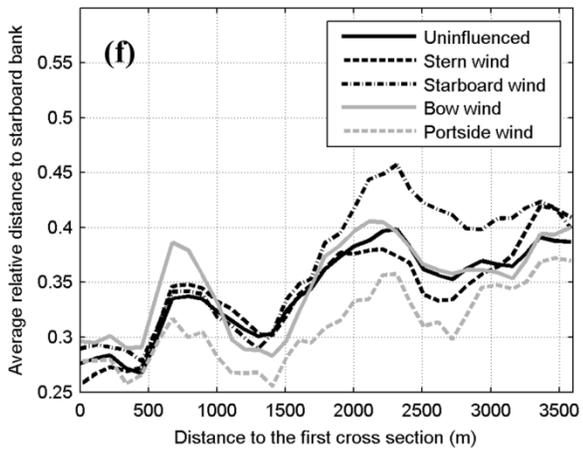
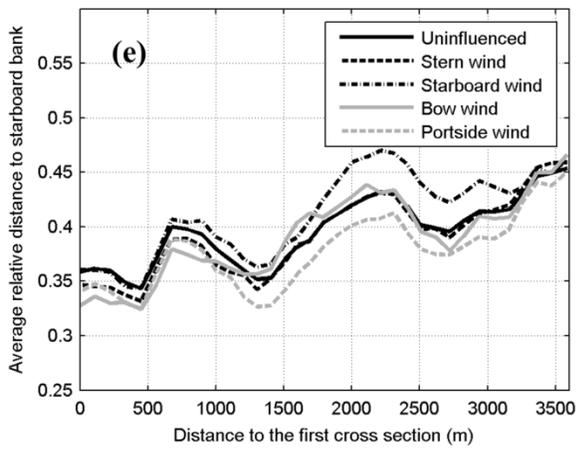
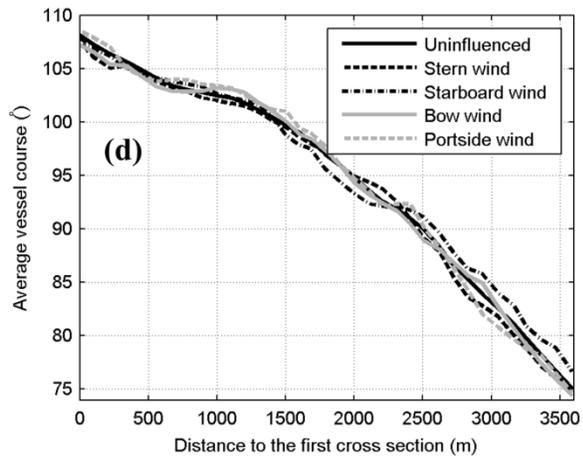
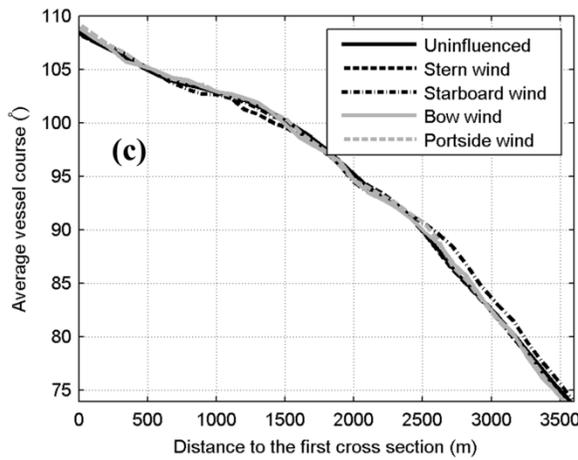
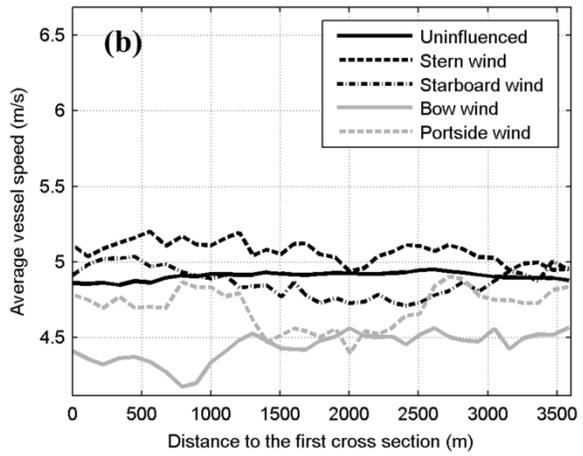
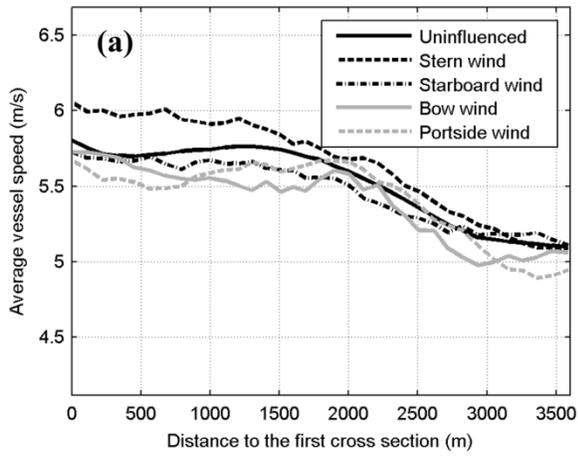
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Fig. 4. Vessel behavior and potential factors influencing vessel behavior.



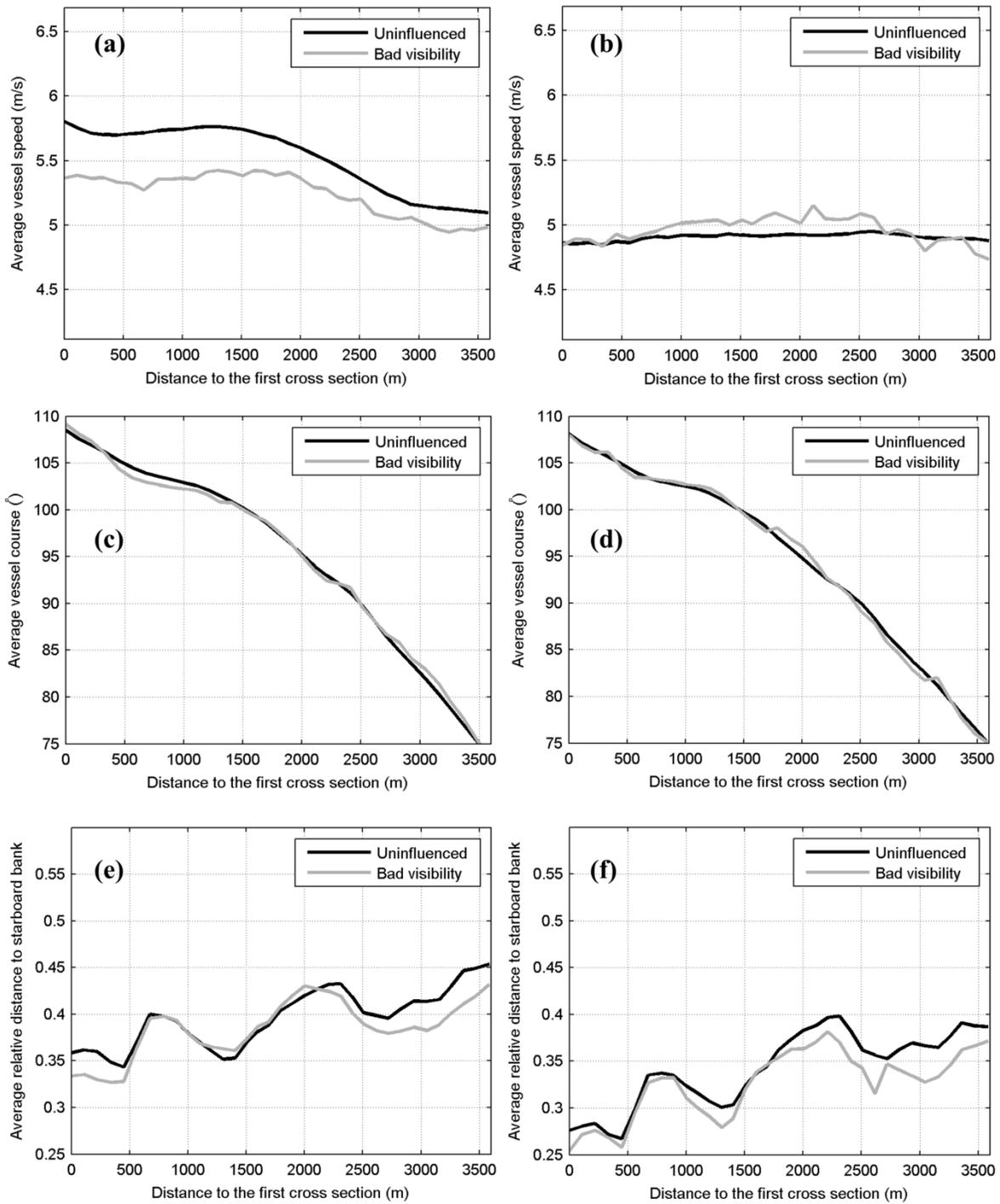
625

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

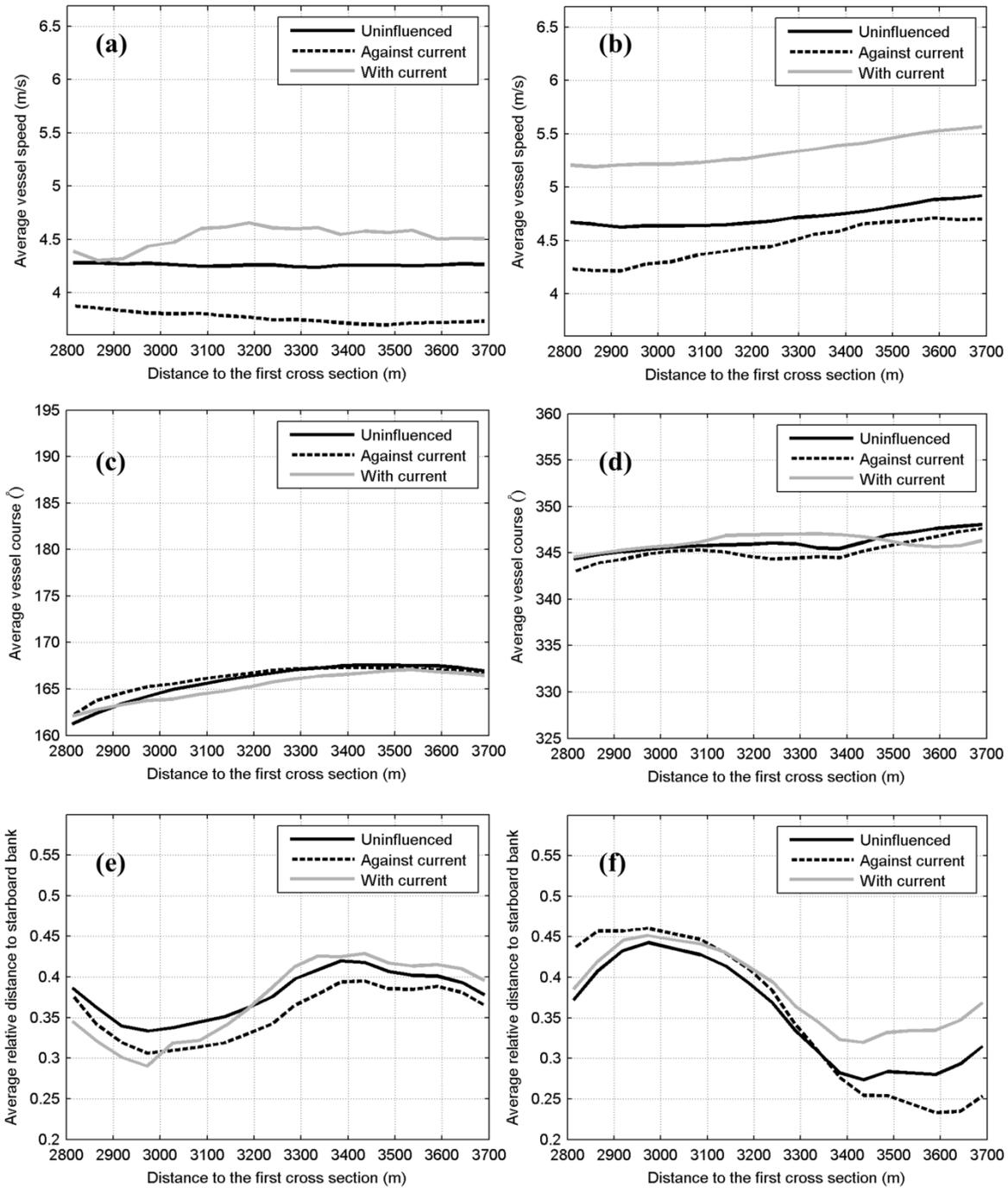


629 Fig. 6. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)
630 by wind for container vessels in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b),
631 course (d) and distance to starboard bank (f) by wind for GDC vessels in Sea-Nieuwe Maas.

632



633
 634 Fig. 7. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)
 635 by visibility for container vessels in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed
 636 (b), course (d) and distance to starboard bank (f) by visibility for GDC vessels in Sea-Nieuwe Maas.

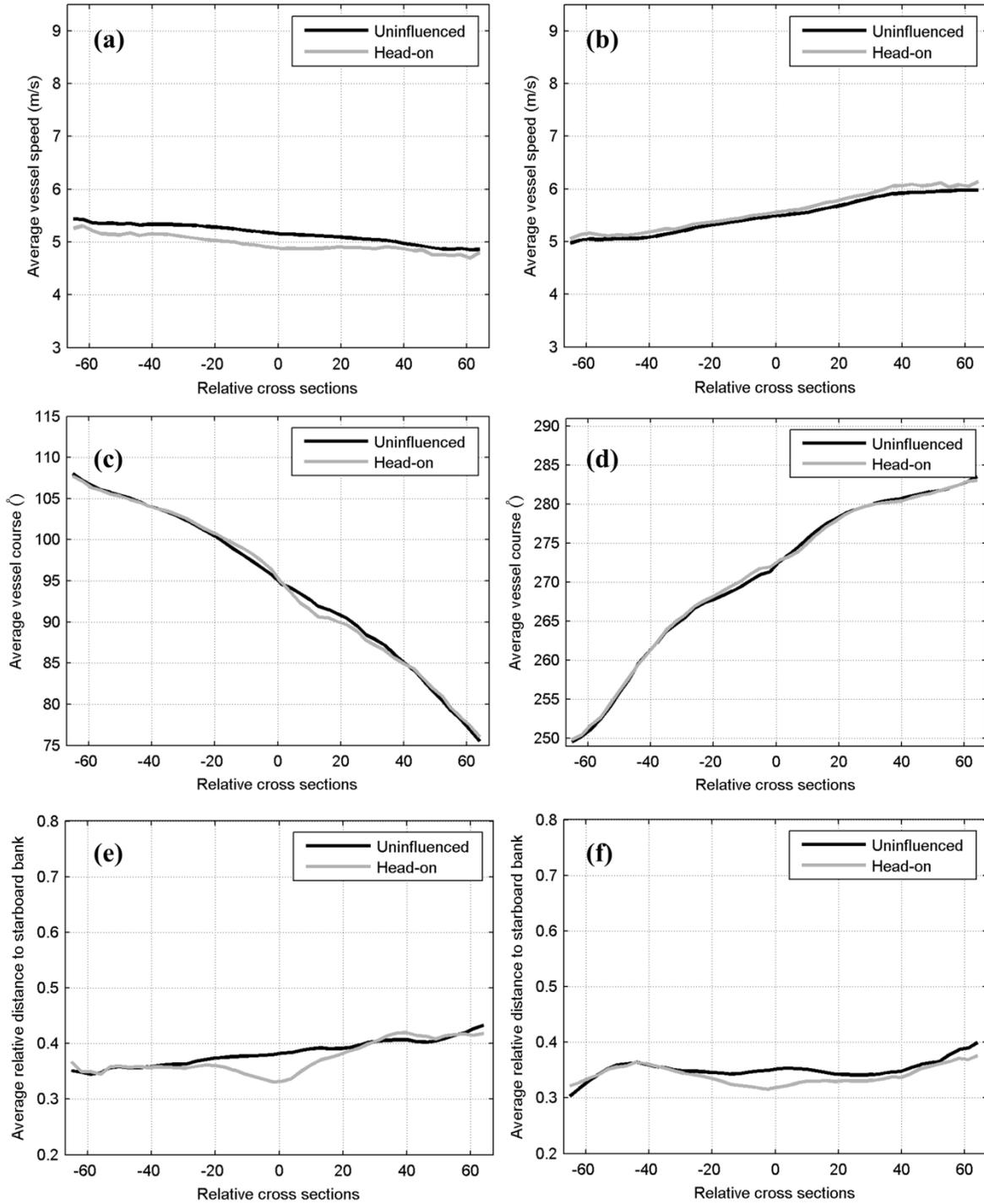


639 Fig. 8. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)

640 by current for GDC vessels at cross section 51-68 in Sea-Oude Maas; uninfluenced and influenced

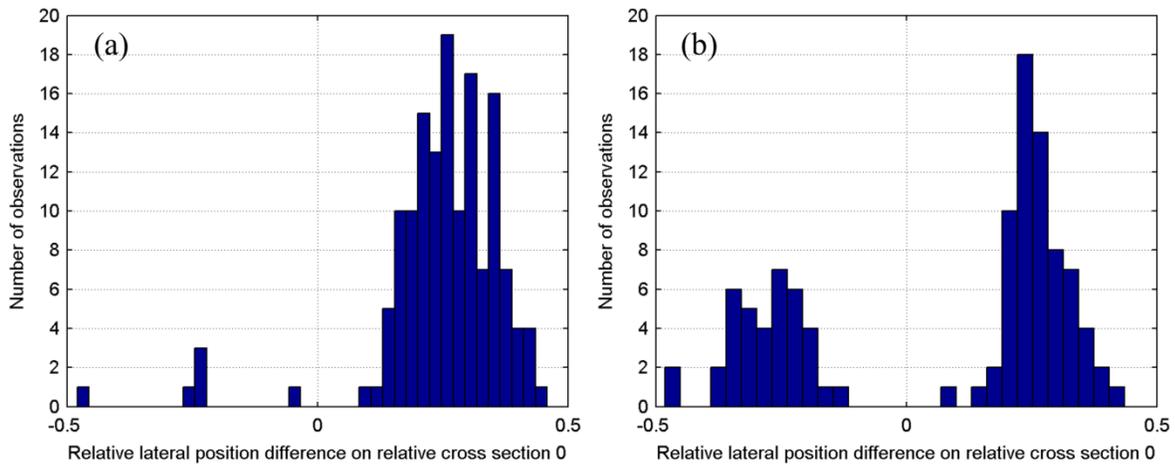
641 vessel speed (b), course (d) and distance to starboard bank (f) by current for GDC vessels at cross
642 section 51-68 in Oude Maas-Sea.

643



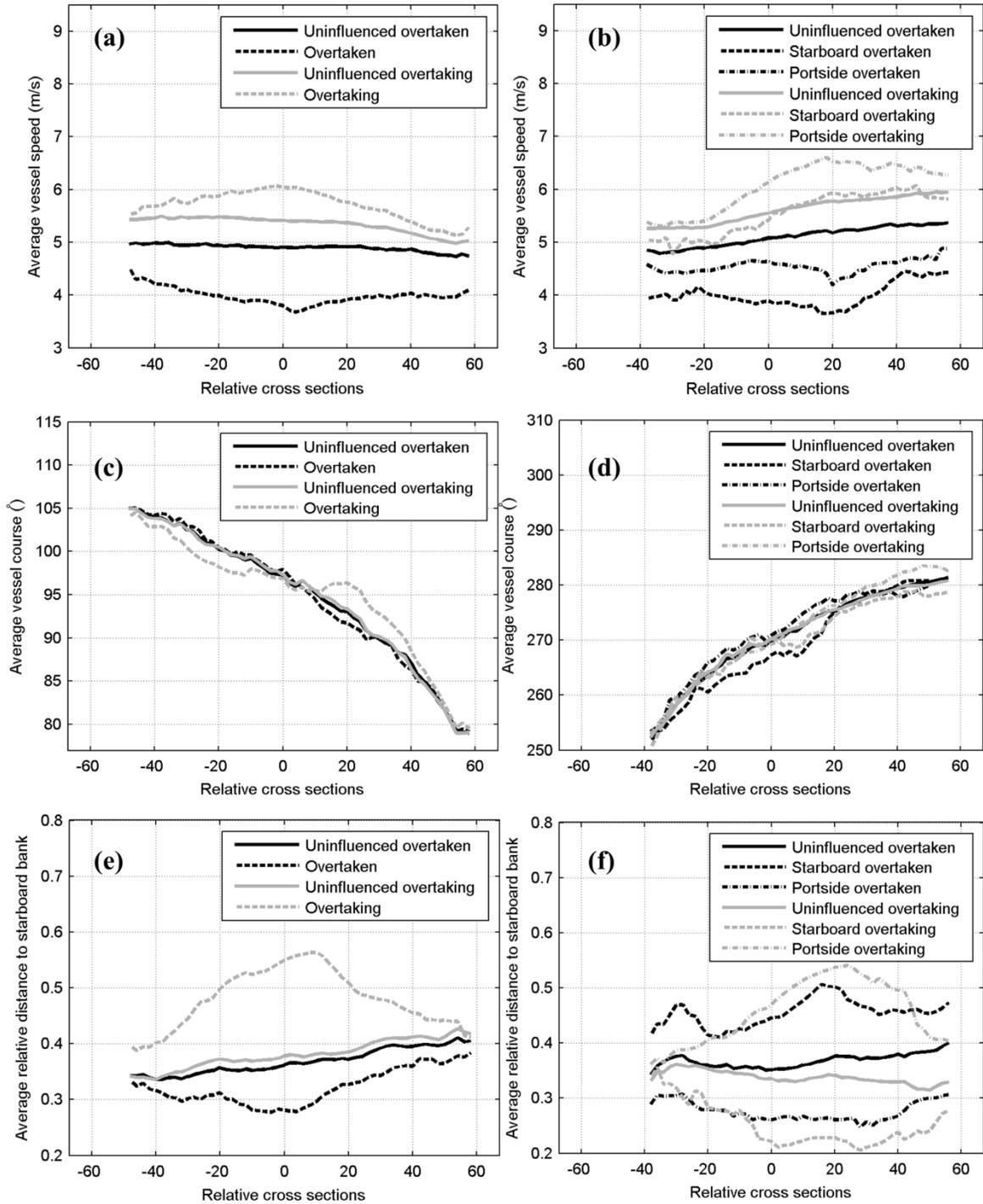
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645 Fig. 9. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)
646 by head-on encounters in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d)
647 and distance to starboard bank (f) by head-on encounters in Nieuwe Maas-Sea.
648



649
650 Fig. 10. Histograms of relative lateral position difference of overtaken and overtaking vessels at
651 relative cross section 0 in Sea-Nieuwe Maas (a) and Nieuwe Maas-Sea (b).

652



653
 654 Fig. 11. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)
 655 by overtaking encounters in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course
 656 (d) and distance to starboard bank (f) by overtaking encounters in Nieuwe Maas-Sea.