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

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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

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

3

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 m^3/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 < 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

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:

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

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(%)	MPE(%)	p_r(%)	MPE(%)	p_r(%)	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

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
	APE (%)	5.3	0.2	13.3
Nieuwe Maas-Sea	K-S test result	1	0	1
	APE (%)	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
APE (%) - overtaken	23.2	0.8	23.1
K-S test - overtaking	1	0	1
APE (%) - 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
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

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

26

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.

548 **Acknowledgement**

27

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Figures
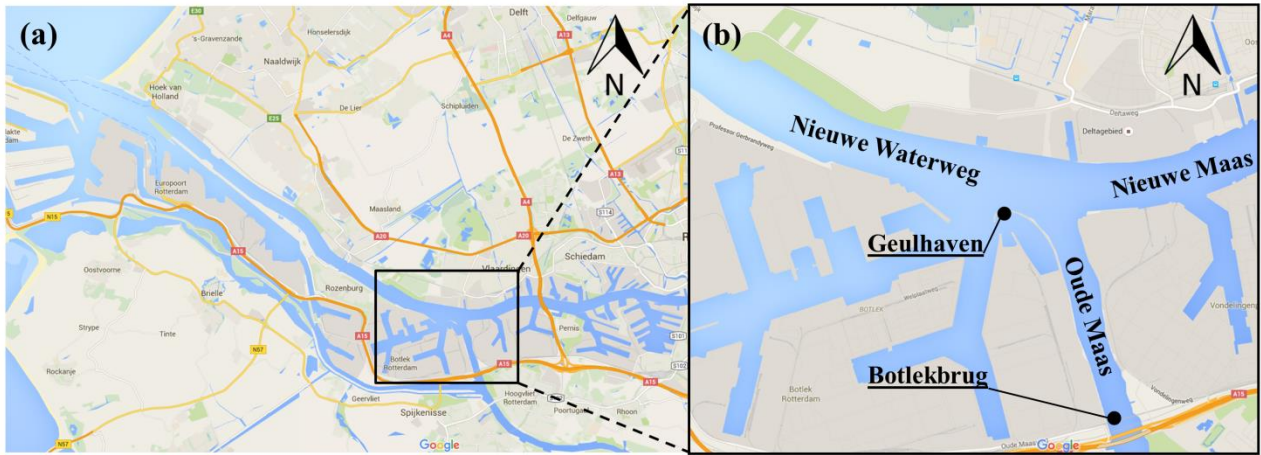
Fig. 1. (a) Location of research area: the Botlek area in the port of Rotterdam; (b) the zoom-in view

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.
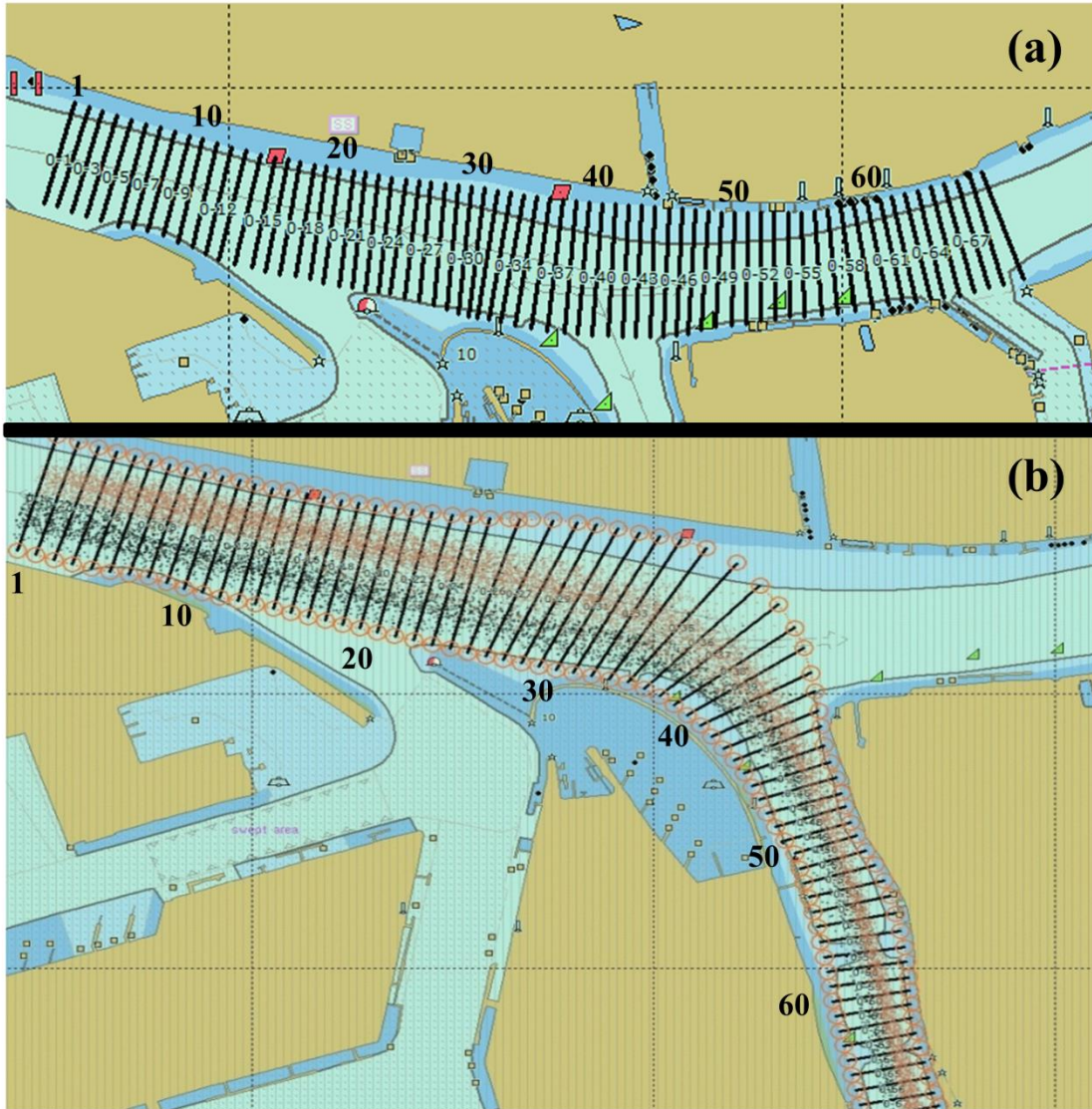
611

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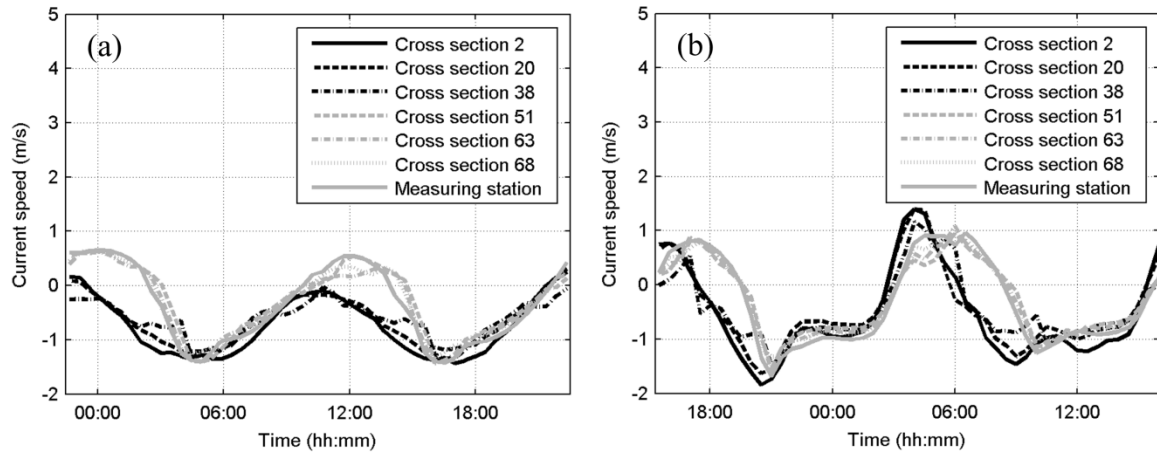
Fig. 3. The simulated current speed at the condition of (a) neap-average discharge and (b) spring-average discharge, at different cross sections and at the measuring station over one day, simulated by the model Delft3D.

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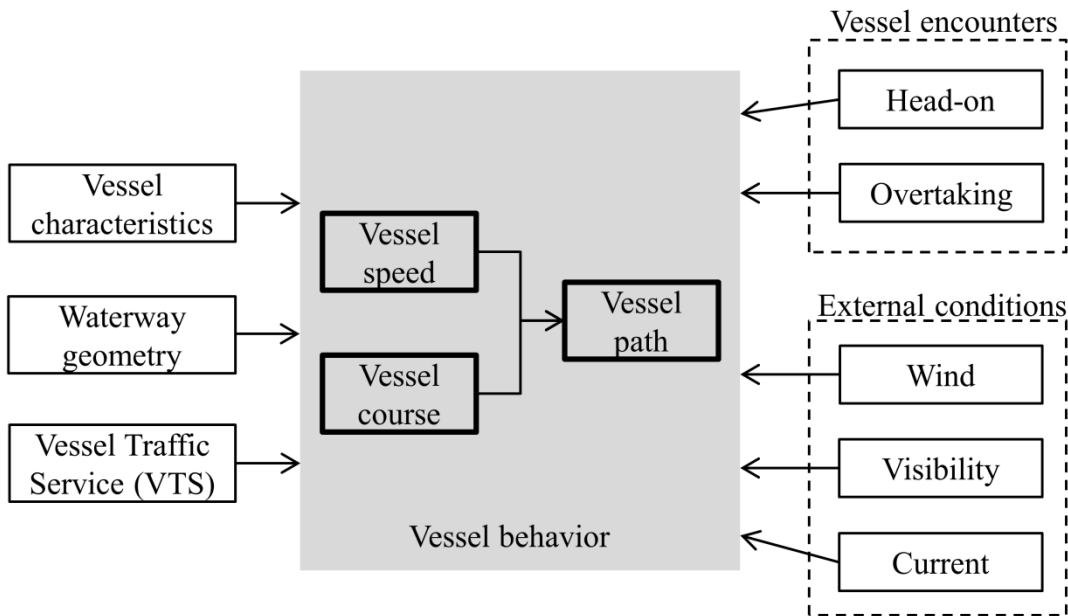
Fig. 4. Vessel behavior and potential factors influencing vessel behavior.

624

Bow wind

45° 45°

Portside wind 90° 90° Starboard wind

90°

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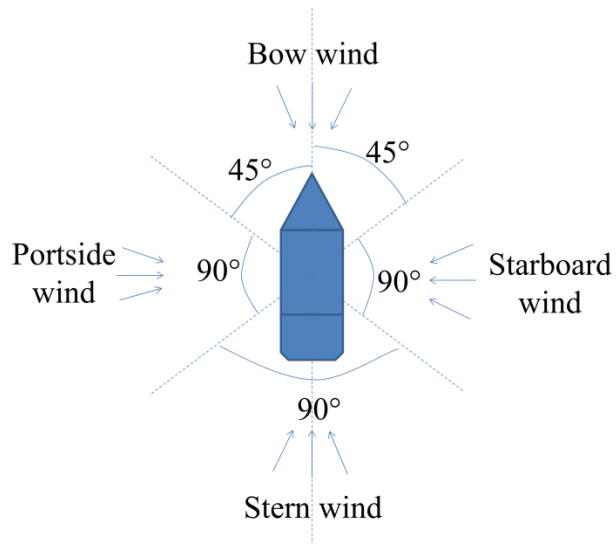
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626   Fig. 5. Four wind categories based on the angle between vessel course and wind direction.

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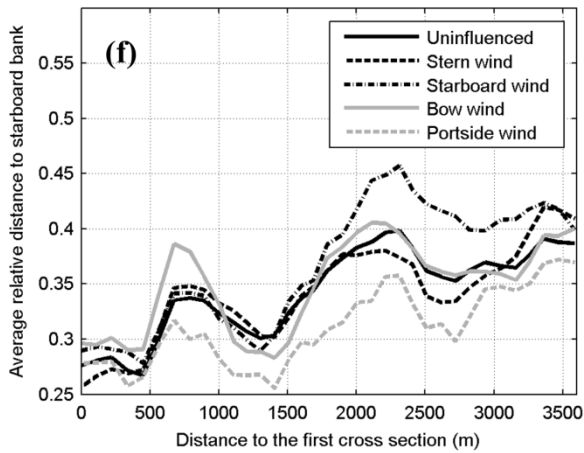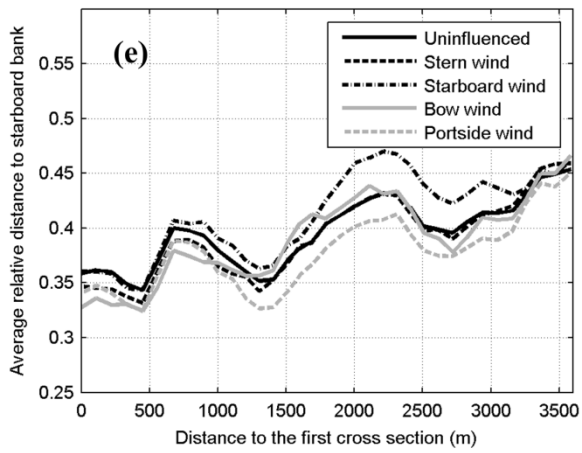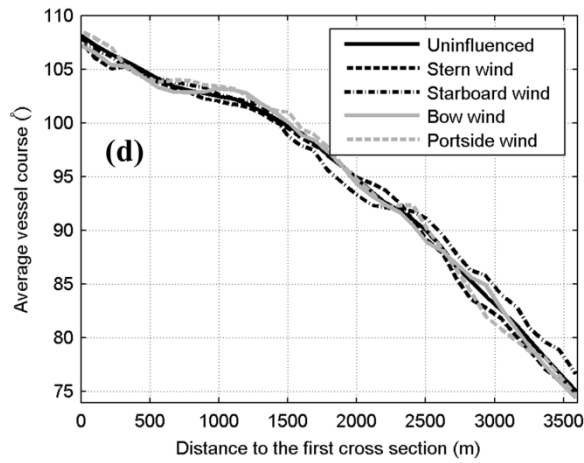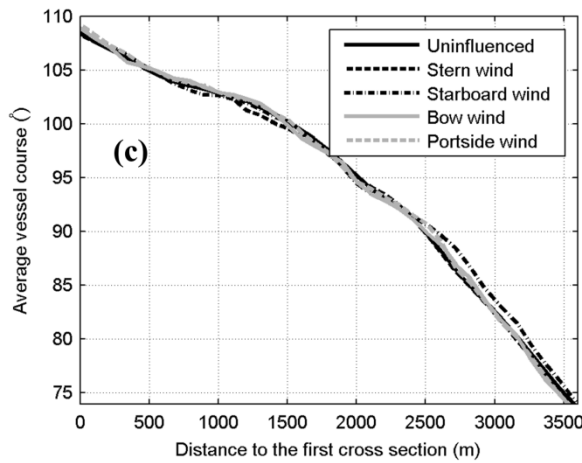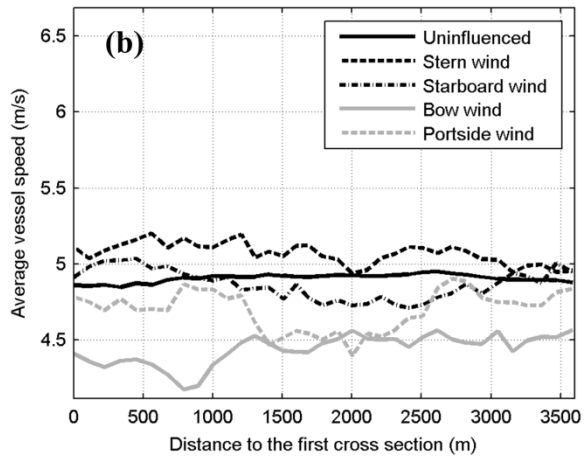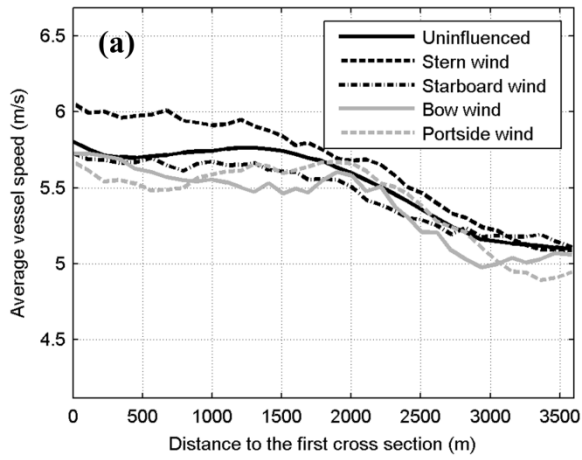
629   Fig. 6. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)

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.

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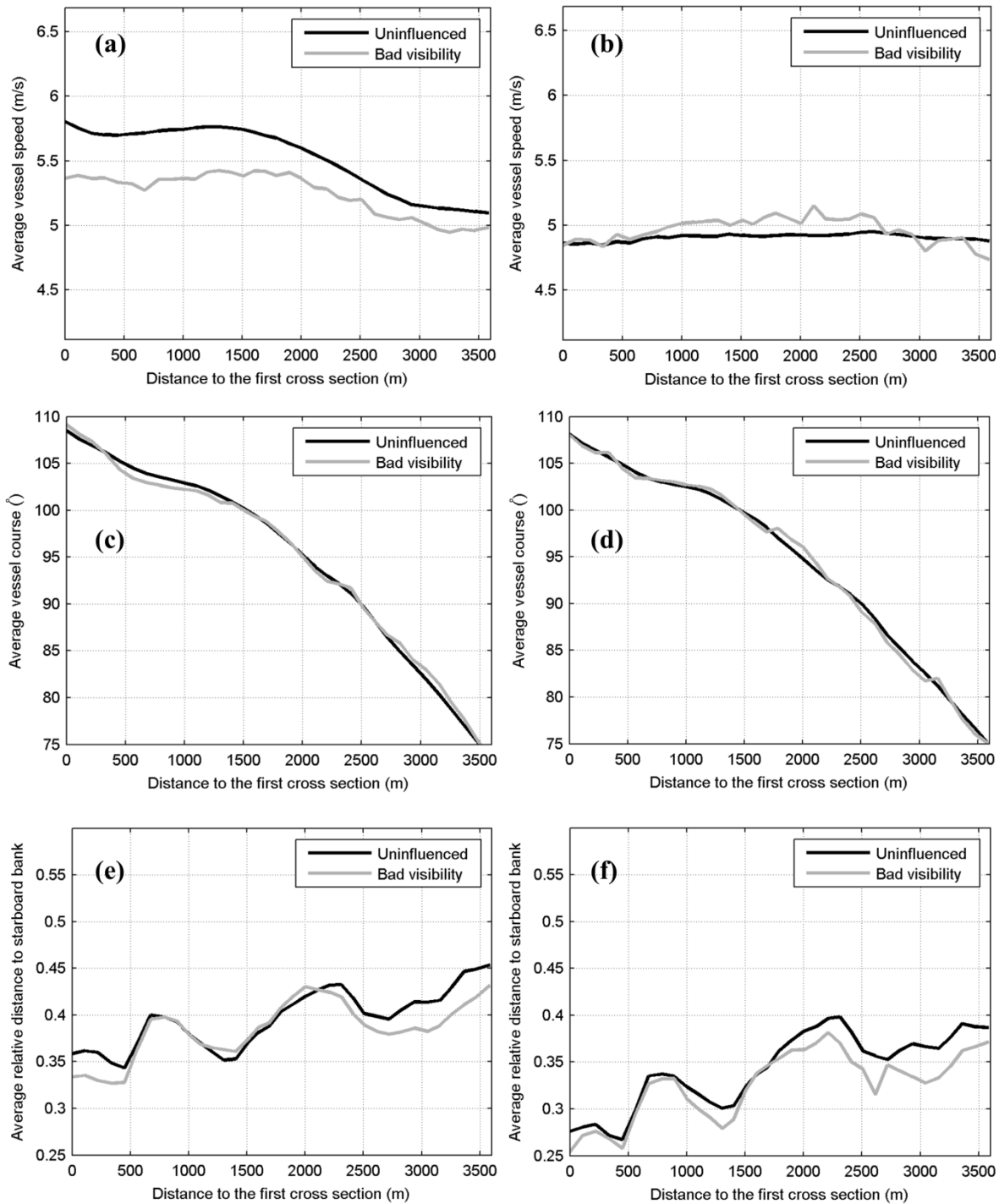
Fig. 7. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)

by visibility for container vessels in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed

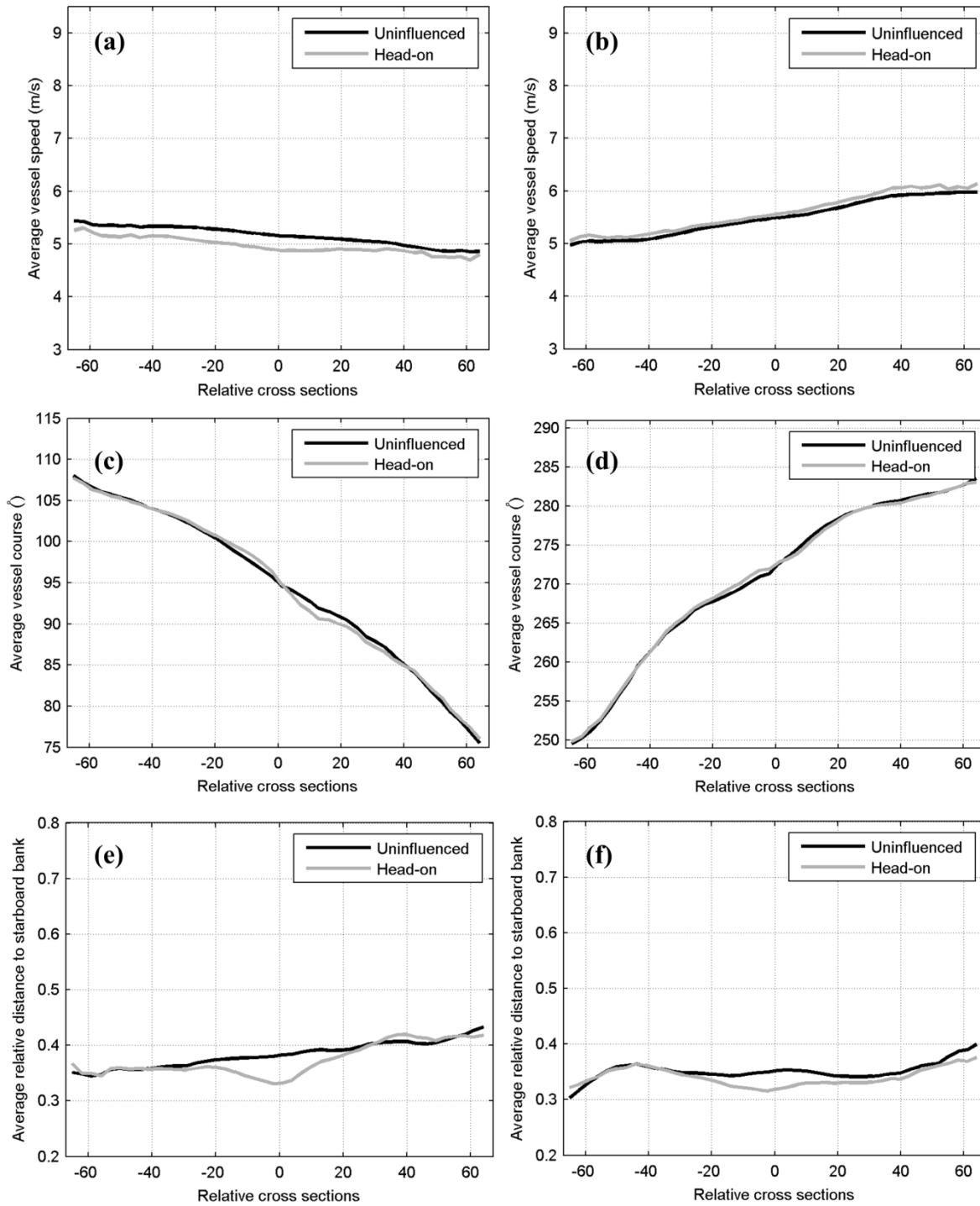(b), course (d) and distance to starboard bank (f) by visibility for GDC vessels in Sea-Nieuwe Maas.
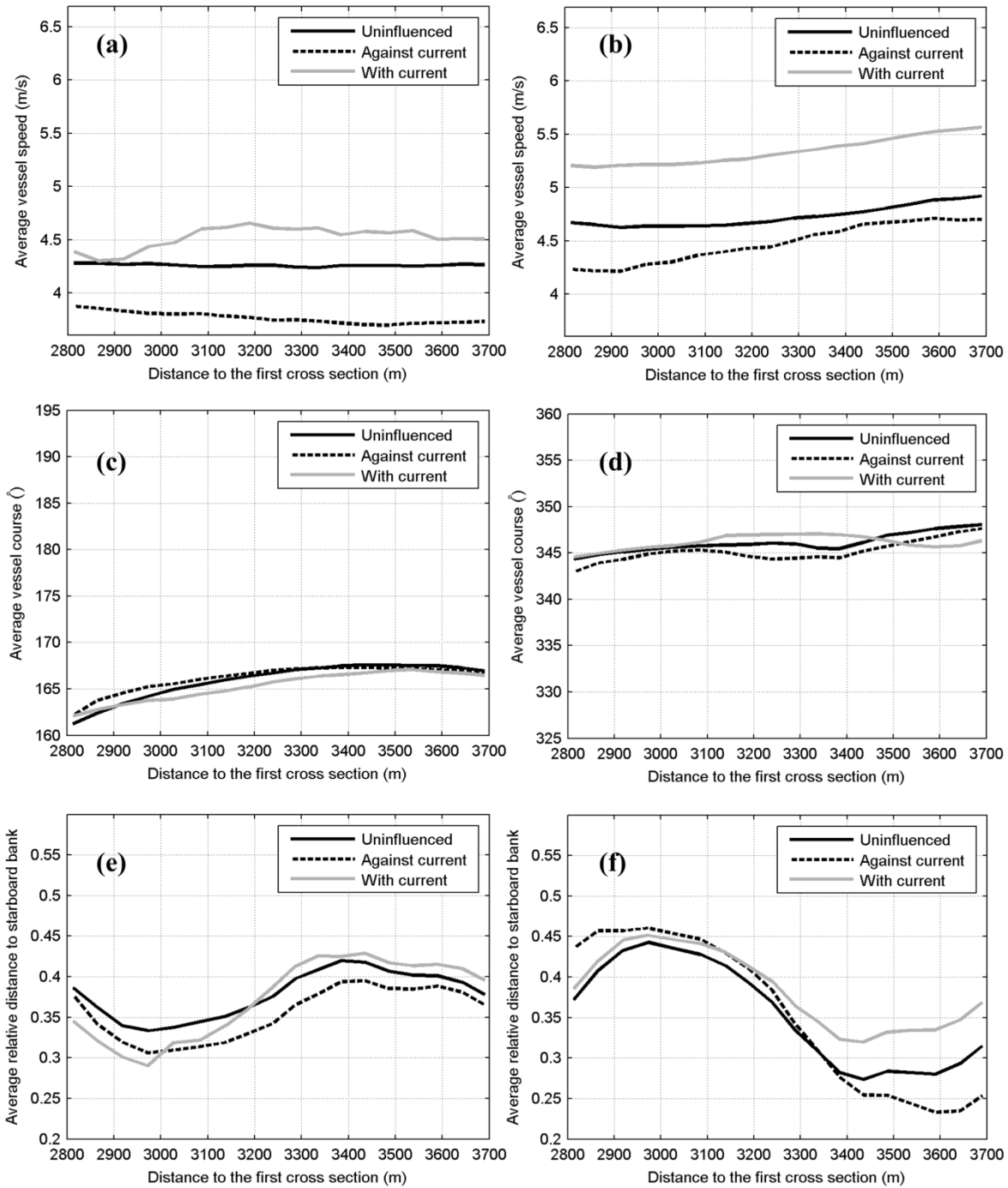
Fig. 8. Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e)

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

641   vessel speed (b), course (d) and distance to starboard bank (f) by current for GDC vessels at cross

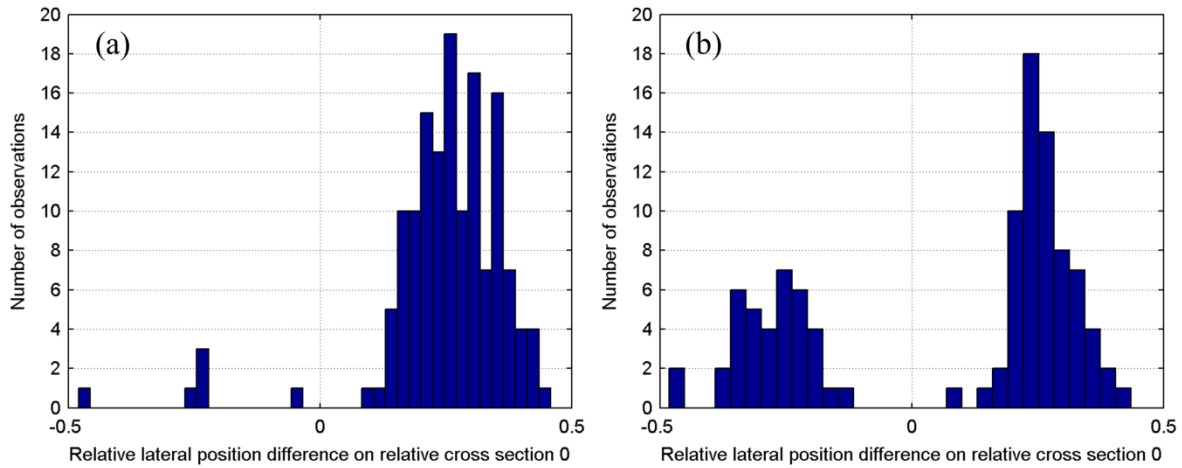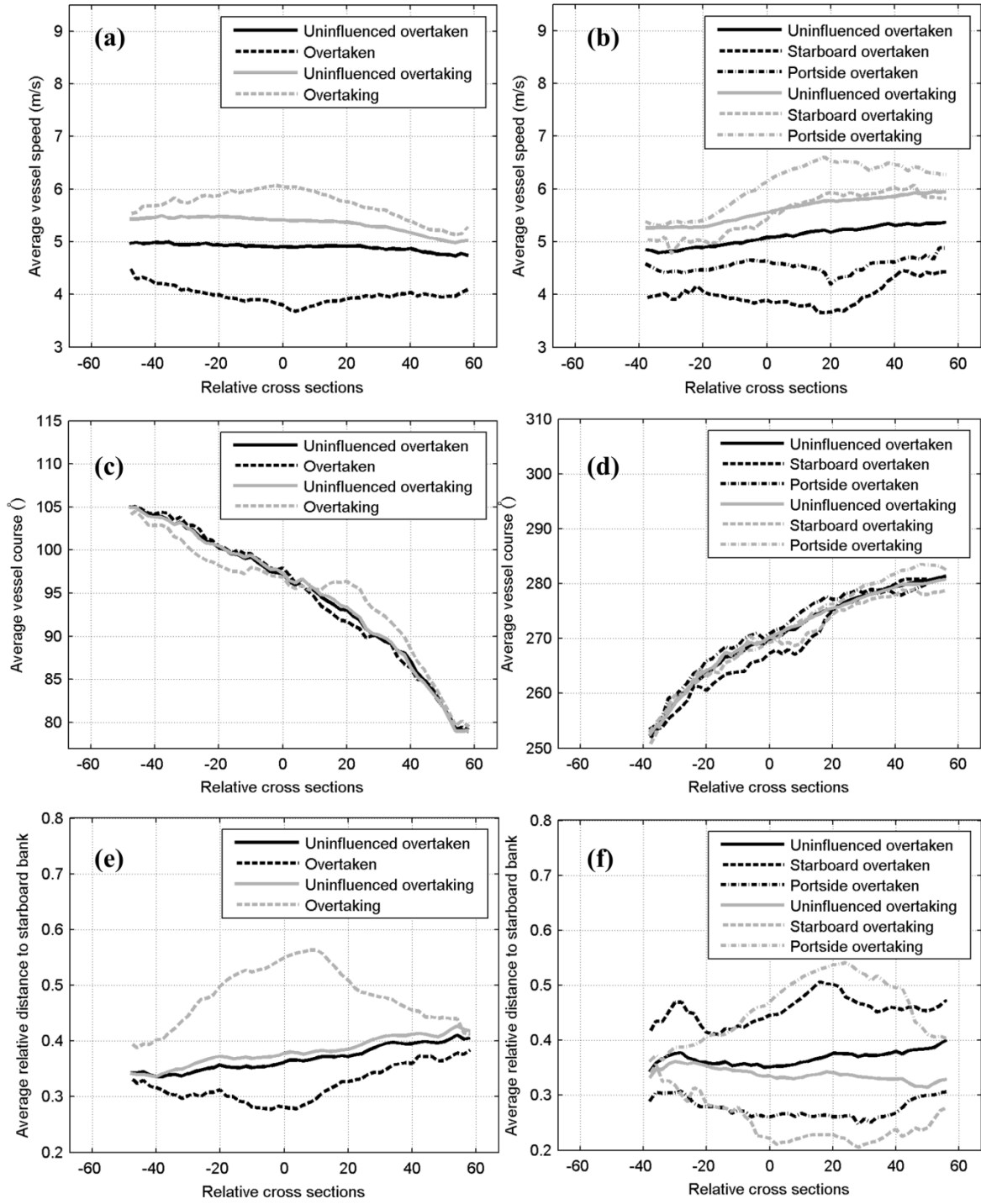642   section 51-68 in Oude Maas-Sea.

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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.

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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).

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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.

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