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1 Calibration and validation for the Vessel Maneuvering Prediction  
2 (VMP) model using AIS data of vessel encounters

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14 **Abstract**

15 The Vessel Maneuvering Prediction (VMP) model, which was developed in a previous work with the  
16 aim of predicting the interaction between vessels in ports and waterways, is optimized in this paper by  
17 considering the relative position and vessel size (length and beam). The calibration is carried out using  
18 AIS data of overtaking vessels in the port of Rotterdam. The sensitivity analysis of the optimal  
19 parameters shows the robustness of the calibrated VMP model. For the validation, the optimal  
20 parameters are used to simulate the whole path of overtaken vessels and vessels in head-on encounters.  
21 Compared to the AIS data, the validation results show that the different deviations in longitudinal  
22 direction range from 33 m to 112 m, which is less than 5% of the waterway stretch. Both the calibration  
23 and validation show that the VMP model has the potential to simulate vessel traffic in ports and  
24 waterways.

25

26

27 **Keywords:** the VMP model, calibration, validation, overtaking encounter, head-on encounter

## 28 **1. Introduction**

29 With the development of international transportation, maritime traffic flows have increased  
30 substantially in recent decades. As both vessel number and size increase sharply, more and more  
31 concern is raised about the safety and capacity of maritime traffic, especially in ports and waterways. In  
32 these restricted areas, the interactions between vessels are more frequent than open waters. Many models  
33 have been developed to investigate maritime traffic, most of which focus either on the risk of collisions  
34 and groundings (Goerlandt and Kujala, 2011; Montewka et al., 2010; Qu et al., 2011), or on vessel  
35 hydrodynamics and maneuverability (Sariöz and Narli, 2003; Sutulo et al., 2002). Although progress has  
36 been made on the investigation of vessel behavior, such as vessel speed, course and path (Aarsæther and  
37 Moan, 2009; Xiao, 2014), few models have considered vessel characteristics, vessel encounters and  
38 traffic state, such as waterway geometry and external conditions including wind, visibility and current.  
39 Thus, vessel speed and course in ports and waterways cannot be accurately predicted.

40 To address this need, a new maritime traffic operational model was developed recently by applying  
41 differential game theory (Hoogendoorn et al., 2013). The approach of this model was adapted from an  
42 approach that was successfully applied to predict the behavior of pedestrians (Hoogendoorn and Bovy,  
43 2003; Hoogendoorn and Bovy, 2004) as there are many similarities between vessels and pedestrians:  
44 both vessels and pedestrians (1) have specific origin and destination; (2) are constrained by boundary  
45 (bank for vessels, and wall or other obstacles for pedestrians); (3) can influence each other; (4) are  
46 influenced by external conditions, such as weather conditions. In this model, vessel behavior is  
47 described at two levels: a tactical level and an operational level. The tactical level includes vessel route  
48 choice (the desired course) and desired speed, which serve as the reference (guide) at the operational  
49 level. The desired course and desired speed represent the optimal course and speed when the vessel is  
50 not influenced by extreme external conditions and other vessels. The operational level includes the

51 dynamics of the vessel sailing behavior, e.g. longitudinal acceleration and angular speed of the vessel.  
52 Although the route choice model is assumed to be very simple in the previous work (Hoogendoorn et al.,  
53 2013), the framework for the model was created. Based on this framework, the route choice model at  
54 tactical level was further developed (Shu et al., 2015b). The results of this study serve as an input into  
55 the operational model, which is called Vessel Maneuvering Prediction (VMP) model in this paper. The  
56 VMP model was introduced by considering the influence range in different directions of the vessel to be  
57 homogeneous and the model was only calibrated for unhindered vessel behavior (Shu et al., 2015a), in  
58 which the influence between encountered vessels is not considered.

59 The aim of this paper is to improve the VMP model by considering the relative position and vessel  
60 size (length and beam), and then calibrate and validate the improved VMP model using the AIS data of  
61 vessel encounters. To improve the model, we consider the distinct influence ranges of the vessel in  
62 longitudinal and lateral direction, which correspond to the findings of a recent study that the vessels  
63 keep larger distance in longitudinal direction than in lateral direction, and vessel speed is influenced for  
64 both overtaking and overtaken vessels (Shu et al., 2017). In the calibration, the VMP model is used to  
65 simulate overtaking vessel maneuvers for each path segment (60 seconds), and then to compare the final  
66 position of the overtaking vessel from the AIS data. For the validation, the VMP model is used to  
67 simulate the whole vessel path in the research area for overtaking, overtaken vessels and the vessels in  
68 head-on encounters, respectively. Then, these simulated paths are used to compare with the observed  
69 vessel path from the AIS data.

70 This paper starts with an introduction of the improved VMP model in Section 2. Then, the  
71 calibration and validation approaches are presented in Section 3, followed by the results of the  
72 calibration and validation in Section 4. Finally, this paper ends with discussion and conclusions in  
73 Section 5.

## 74 2. The improved VMP model of vessel traffic

75 In this section, the improved VMP model is introduced. As we know, the bridge team controls the  
76 vessel through the engine to accelerate or decelerate the ship and the rudder to change the vessel course.  
77 The longitudinal acceleration  $u_1$  and angular speed  $u_2$  are therefore considered as the controls on the  
78 ship by the bridge team in the VMP model of vessel traffic (Hoogendoorn et al., 2013). The vessel  
79 coordinate system and the control are defined in our previous research as follows (Shu et al., 2015a):

$$\dot{x} = v \cos \left( \frac{\pi}{2} - \psi \right) \quad (1)$$

$$\dot{y} = v \sin \left( \frac{\pi}{2} - \psi \right) \quad (2)$$

$$\dot{v} = u_1 \quad (3)$$

$$\dot{\psi} = u_2 \quad (4)$$

80 where the state of the vessel is defined as  $\vec{\xi} = (x, y, v, \psi)$ , in which  $x$  and  $y$  denote the position, and  $v$   
81 and  $\psi$  denote vessel speed and course, respectively. In this coordinate system, Eqs. (1-2) represent the  
82 vessel speed in x-y coordinates and Eqs. (3-4) show the longitudinal acceleration and angular speed.

83 In the VMP model, it is assumed that the bridge team controls the vessel to maintain the desired  
84 speed and course as much as possible, to minimize the maneuvering effort and to keep sufficient  
85 distance to other vessels. In order to quantitatively describe these control objectives and combine them  
86 into the VMP model, the concept “cost” is introduced. By minimizing the objective function (total cost),  
87 the controls could be optimized and an optimal vessel speed, course and path could be achieved. Thus,  
88 the control objectives could be turned into a cost minimization problem. The control objective function  
89 is defined as follows (Hoogendoorn et al., 2013):

$$J = \int_t^{t+H} L(s, \vec{\xi}, \vec{u}) ds + \Phi(t + H, \vec{\xi}(t + H)) \quad (5)$$

90 where  $H$  denotes the prediction horizon, which is assumed to be a time period in which the bridge team  
 91 could predict the vessel behavior;  $L$  denotes the running cost (cost incurred in a small time interval  
 92  $[\tau, \tau + d\tau)$ );  $\vec{u} = (u_1, u_2)$  denotes the control, and  $\Phi$  denotes the terminal costs at terminal conditions,  
 93 which is the cost that is incurred when the vessel ends up with the state  $\vec{\xi}(t + H)$  at time instant  $t + H$ .  
 94 The terminal cost is assumed to be zero.

95 Corresponding to the control objectives, i.e. maintaining the desired speed and course as much as  
 96 possible, minimizing the maneuvering effort and keeping sufficient distance to other vessels, the running  
 97 cost  $L$  also includes three parts: costs for straying from the desired speed and desired course  $L^{stray}$ ,  
 98 propulsion and steering costs  $L^{effort}$  and the proximity costs  $L^{prox}$ :

$$L = L^{stray} + L^{effort} + L^{prox} \quad (6)$$

99 The straying costs and the propulsion and steering costs are defined as in our previous study  
 100 (Hoogendoorn et al., 2013). The straying costs are defined as follows:

$$L^{stray} = \frac{1}{2} (c_2^v (v^0(\vec{x}) - v)^2 + c_2^\psi (\psi^0(\vec{x}) - \psi)^2) \quad (7)$$

101 where  $c_3^v$  and  $c_3^\psi$  are weight factors for straying from the desired speed and desired course, respectively.  
 102  $v$  and  $\psi$  denote the current speed and course,  $v^0(\vec{x})$  and  $\psi^0(\vec{x})$  denote the desired speed and the desired  
 103 course at the position  $\vec{x}$ , which is the current position, respectively.

104 The propulsion and steering costs are defined by:

$$L^{effort} = \frac{1}{2} (c_3^v u_1^2 + c_3^\psi u_2^2) \quad (8)$$

105 where  $c_3^v$  and  $c_3^\psi$  are weight factors of the effort of the bridge team to accelerate (decelerate) and turning  
 106 the vessel. So, these two factors correspond to the control (the longitudinal acceleration and angular  
 107 speed).

108 The main improvement of the model focuses on the proximity costs, which are defined based on the  
 109 relative position between the simulated vessel and the encountered vessel as follows:

$$L^{prox} = \begin{cases} c_1(e^{-d/R} - e^{-1}), & d < R \\ 0, & d \geq R \end{cases} \quad (9)$$

110 where  $c_1$  is the weight factor for this proximity cost,  $d$  denotes the distance between the simulated vessel  
 111 and the encountered vessel, and  $R$  is the scaling parameter, which indicates the range within which the  
 112 simulated vessel is influenced by the other vessel and this parameter is determined by the relative  
 113 position between the simulated vessel and the encountered vessel. As shown in Eq. (9), the proximity  
 114 costs increase when the encountering vessels approach each other, and the proximity costs equal to zero  
 115 when the distance is larger than the scaling parameter. In the data analysis of vessel encounters, it was  
 116 found that the influence distance between encountering vessels in longitudinal direction is much larger  
 117 than in lateral direction (Shu et al., 2017). This results in an elliptical influence area. As an example, the  
 118 elliptical influence area of an overtaking vessel is shown in Fig. 1.

119 As shown in Fig. 1, the elliptical influence area has a semi-major axis  $a$  and a semi-minor axis  $b$ .  
 120 The scaling parameter  $R$  could be interpreted as the radius of the ellipse, which is a function of the  
 121 parameters  $a$ ,  $b$  and the angle  $\theta$  (the angle between the course of the own vessel and the line connecting  
 122 the locations of the two encountering vessels):

$$R(\theta) = \frac{ab}{\sqrt{a^2 \sin^2 \theta + b^2 \cos^2 \theta}} \quad (10)$$



123 In the VMP model, it is also assumed that a larger vessel size will lead to larger influence distances.  
124 Then, the major axes  $a$  and minor axes  $b$  depend on the vessel length and beam of the own vessel and  
125 the other vessel as follows:

$$a = p * (L_A + L_B)/2 \quad (11)$$

$$b = q * (B_A + B_B)/2 \quad (12)$$

126 where  $p$  and  $q$  are scaling coefficients of the vessel length,  $L_A$  and  $L_B$  are the lengths of the two vessels  
127 in encounter, and  $B_A$  and  $B_B$  correspond to vessel beam. Thus, the VMP model is improved by  
128 considering the different influence range of the vessel in longitudinal and lateral direction and the  
129 proximity costs are improved with three parameters: the weight factor  $c_1$ , and scaling coefficient  $p$  and  
130  $q$ .

### 131 3. Research approach

132 In this section, the calibration and validation approaches are presented. The aim of the calibration is  
133 to find the model parameters that result in the best prediction of the model, and the purpose of the  
134 validation is to confirm that the model and its optimized parameters can generalize the calibration data.  
135 The data used in both approaches come from the Automatic Identification System (AIS) system, which  
136 is used to record vessel data between vessels and shore stations. In recent decades, it has been developed  
137 and implemented as a mandatory tool on all ships by 1 July 2008 (Eriksen et al., 2006).

138 In this paper, the AIS data of 146 overtaking encounters and 162 head-on encounters are used. These  
139 data are provided by Maritime Research Institute Netherlands (MARIN) and analyzed using dedicated  
140 software called “ShowRoute”, which is developed by MARIN and used to investigate AIS data. These  
141 data were selected in the Botlek area in the port of Rotterdam and used to analyze the vessel behavior in  
142 previous studies (Shu et al., 2017). The waterway stretch is around 2.5 km and the sailing time in the

143 research area approximately equals 500 seconds, given the average vessel speed of 5 m/s (Shu et al.,  
144 2013).

145 In this paper, the VMP model is assumed to be generic for different types of encounters, which  
146 means that the parameters determined by calibrating for data from overtaking vessels are applicable for  
147 overtaken vessels and vessels in head-on encounters. As overtaken vessels and vessels in head-on  
148 encounters are in many cases in the equilibrium situation (without longitudinal acceleration and angular  
149 speed) (Shu et al., 2017), the overtaking vessels are more suitable for the calibration because they  
150 normally have a larger deviation from their desired speed and path. The vessels that are in equilibrium  
151 situation cannot be used for the calibration because the resulting model parameters would be equal to  
152 zero.

153 In addition, it is assumed that the bridge team has enough experience to predict the speed and course  
154 of the other vessels, and they can use it in their decision-making procedure. Based on this assumption,  
155 the AIS data of the encountered vessel is considered as a known input in this research. This assumption  
156 is made in this first step to calibrate and validate the VMP model, with the aim to simultaneously  
157 simulate multiple vessels in future research.

### 158 ***3.1 Calibration approach***

159 In this section, the calibration including calibration set-up, objective function and sensitivity analysis  
160 is presented.

#### 161 ***3.1.1 Calibration Set-Up***

162 The parameters of the VMP model, consisting of weight factors  $c_1, c_2^v, c_2^\psi, c_3^v$  and  $c_3^\psi$ , and the scaling  
163 coefficients  $p$  and  $q$  need to be calibrated. It should be noted that all weight factors cannot be uniquely

164 determined from the data, since only the relative importance of the weights can be determined. Without  
165 loss of generality, we set  $c_1 = 1$ . Then, the parameters to be calibrated are  $\beta^T = (c_2^v, c_2^\psi, c_3^v, c_3^\psi, p, q)$ .

166 In this calibration, all paths of overtaking vessels have been broken down into multiple small  
167 segments, which have the same time period as the prediction horizon. The prediction horizon  $H$  is taken  
168 as 60 seconds, which is a reasonable time period for the bridge team to maneuver the vessel. The  
169 calibration is performed for each path segment and the final position of the predicted vessel path is  
170 compared with the AIS data.

171 To run the VMP model, the desired speed and desired course serve as inputs, while the vessel speed,  
172 course and path are the outputs. We assume that the desired course generated by the Route Choice  
173 model (Shu et al., 2015b) is applicable for all vessels in the research area, because it was found that  
174 vessel course is hardly influenced by vessel size and type (Shu et al., 2013). In terms of the desired  
175 speed, it was found that overtaking vessels increase their speed before the CPA (Closest Point of  
176 Approach) and decrease the speed after the CPA (Shu et al., 2017). Therefore, the desired speed is set as  
177 the maximum speed  $v_{max}$  before the CPA and set as the end speed  $v_{end}$  after CPA, as shown in Fig. 2.  
178 This way, the variability of the desired speed is considered, which is closer to reality than setting a  
179 constant desired speed.

### 180 3.1.2 Objective function for calibration

181 The calibration process aims at minimizing the difference between the vessel path predicted by the  
182 VMP model and the observed path from AIS data. As shown in Fig. 3, an overtaking vessel sails from  
183 left to right and the observed vessel position at the end of the prediction horizon is  $\vec{x}_{data}$ . The VMP  
184 model predicts that the overtaking vessel is at position  $\vec{x}_{sim}$  at the end of the prediction horizon. Then,

185 the parameters should be chosen such that the distance between the position  $\vec{x}_{data}$  and the position  $\vec{x}_{sim}$   
186 is minimized.

187 Let  $m$  denote the number of vessel paths and let  $n_i$  denote the number of segments for vessel path  $i$ ,  
188 then we have the objective function for the calibration as follows:

$$E(\beta) = \frac{1}{m} * \frac{1}{n_i} * \sum_{i=1}^m \sum_{j=1}^{n_i} (\vec{x}_{data}^{i,j} - \vec{x}_{sim}^{i,j})^2 \quad (13)$$

189 This way, the calibration problem becomes a multi-variable nonlinear optimization problem as  
190 follows:

$$\beta^* = \arg \min E(\beta) \quad (14)$$

### 191 *3.1.3 Sensitivity analysis*

192 Based on the calibration results, a sensitivity analysis is performed to get insight into the influence of  
193 each parameter on the error and the robustness of the calibration, as well as the reliability of the optimal  
194 parameter set. To this end, each model parameter is varied while keeping the other parameters constant  
195 at their estimated value. The relationships between model parameters and the error provide insight into  
196 the model's parameter properties and the sensitivity.

### 197 *3.2 Validation approach*

198 The validation is performed to see if the calibrated parameters could be used to predict the vessel  
199 path for other datasets accurately (within the allowed error margin). Contrary to the path segments used  
200 in the calibration, the validation simulates the whole path using the optimized parameters. In the  
201 validation, the optimized parameters are applied for all three scenarios: overtaking vessels, overtaken  
202 vessels and head-on vessels. Among these scenarios, the overtaking and overtaken vessels are from the  
203 same dataset. Similar as in the calibration, the vessel is simulated while the encountered vessel path is

204 considered as a known input (described by the AIS data). Then, the calibrated parameters are used by  
 205 the VMP model to predict each vessel path every 10 seconds.

206 To evaluate the simulation quality, the comparison between the simulated path and the real path  
 207 focuses on four aspects in both the longitudinal and lateral direction: the final position of the whole path,  
 208 the maximum absolute deviation, the average absolute deviation and average percentage of good  
 209 predictions (within the allowed error margin). To quantify how well the simulated path fits the vessel  
 210 path from AIS data, 8 goodness of fit measures are defined. Considering the overtaking vessel as an  
 211 example, Fig. 4 shows the simulated vessel path for the overtaking vessel and the real path from AIS  
 212 data, as well as the parameters used to formulate the measures. It should be noted that the scheme to  
 213 determine the port side or starboard overtaking is not included in this VMP model yet, so the simulated  
 214 overtaking may happen on the other side than the real one, when the whole vessel path is simulated by  
 215 the VMP model. The results for these overtaking and overtaken paths will not be included in the  
 216 validation results and the choice of the overtaking side is left for further research.

217 As shown in Fig. 4, the origin of the simulated overtaking vessel is  $\vec{x}_0^i$ , in which  $i$  denotes vessel path  
 218 id. The maximum deviation happens when the overtaking and overtaken vessels are located at positions  
 219  $\vec{x}_{sim}^{i,max}$  and  $\vec{x}_{data}^{i,max}$ , while the simulated path and the real path end at  $\vec{x}_{sim}^{i,end}$  and  $\vec{x}_{data}^{i,end}$ , respectively. The  
 220 deviations  $E_{lo}^F$  and  $E_{la}^F$  are the average difference for the final position of simulated path and AIS path in  
 221 the longitudinal and lateral direction, respectively:

$$E_{lo}^F = \frac{1}{m} \sum_{i=1}^m (|\vec{x}_{data}^{i,end} - \vec{x}_{sim}^{i,end}| * \cos \alpha_{end}^i) \quad (15)$$

$$E_{la}^F = \frac{1}{m} \sum_{i=1}^m (|\vec{x}_{data}^{i,end} - \vec{x}_{sim}^{i,end}| * \sin \alpha_{end}^i) \quad (16)$$

222 where  $m$  denotes the number of vessel paths,  $\alpha_{end}^i$  denotes the angle between the longitudinal direction  
 223 for the last AIS data recorded and the line connecting the two end positions. This angle is used for the  
 224 projection of the error in the longitudinal and lateral direction.

225 The deviations  $E_{lo}^M$  and  $E_{la}^M$  correspond to the maximum deviation between the simulated path  
 226 and the AIS path in the longitudinal and lateral direction, respectively. These two are defined as:

$$E_{lo}^M = \frac{1}{m} \sum_{i=1}^m (|\vec{x}_{data}^{i,max} - \vec{x}_{sim}^{i,max}| * \cos \alpha_{max}^i) \quad (17)$$

$$E_{la}^M = \frac{1}{m} \sum_{i=1}^m (|\vec{x}_{data}^{i,max} - \vec{x}_{sim}^{i,max}| * \sin \alpha_{max}^i) \quad (18)$$

227 where  $\alpha_{max}^i$  denotes the angle between the longitudinal direction at the position where the maximum  
 228 deviation occurred and the line connecting the two compared positions.

229 The deviations  $E_{lo}^A$  and  $E_{la}^A$  denote the average deviation of the simulated path and AIS path in  
 230 the longitudinal and lateral direction, respectively. They are defined by:

$$E_{lo}^A = \frac{1}{m} * \frac{1}{n_i} * \sum_{i=1}^m \sum_{j=1}^{n_i} (|\vec{x}_{data}^{i,j} - \vec{x}_{sim}^{i,j}| * \cos \alpha_{i,j}) \quad (19)$$

$$E_{la}^A = \frac{1}{m} * \frac{1}{n_i} * \sum_{i=1}^m \sum_{j=1}^{n_i} (|\vec{x}_{data}^{i,j} - \vec{x}_{sim}^{i,j}| * \sin \alpha_{i,j}) \quad (20)$$

231 where  $n_i$  denotes the number of path segments of vessel path  $i$ , and  $j$  denotes the id of path segment.

232 The last two measures are defined to present the average percentage of good predictions, which  
 233 are within the error margin. The error margin is taken as 5% of the relative error in the longitudinal  
 234 direction, while 5% of the waterway width is used in lateral direction. The measures  $P_{lo}$  and  $P_{la}$  are  
 235 calculated as follows:

$$P_{lo} = \frac{1}{m} * \sum_{i=1}^m P_{lo}^i \quad (21)$$

$$P_{la} = \frac{1}{m} * \sum_{i=1}^m P_{la}^i \quad (22)$$

236 where  $P_{lo}^i$  and  $P_{la}^i$  represent the percentage of good predictions (the prediction error less than the error  
 237 margin) of the vessel path  $i$  at longitudinal direction and lateral direction, respectively.

238 Among these measures of fit, the first six measures are formulated as the average of the deviation of  
 239 the final position, the maximum deviation and the average deviation. The histogram of these deviations  
 240 is also shown in the result section to provide more insight into the simulation quality. In addition, some  
 241 example paths have been randomly chosen from each scenario and presented in the next section to  
 242 compare with the actual path from AIS data and unhindered path (generated by the desired course), for  
 243 more in-depth discussion.

## 244 **4. Results**

245 In this section, the calibration results including the optimal parameters and sensitivity analysis are  
 246 presented, followed by the validation results and example simulated paths.

### 247 ***4.1 Calibration results***

248 By applying the optimization approach, the best fit of the VMP model to the AIS data of overtaking  
 249 vessels is determined. The optimal model parameters are shown in Table 1. The obtained error is 458 m<sup>2</sup>,  
 250 which is the mean square of the distance of the final position between the simulated path and actual path  
 251 from AIS data. This implies that the prediction error is around 21 meters while the prediction period is  
 252 60 seconds.

253

254

**Table 1.** Calibration results for the VMP model for three different datasets.

<b>Parameters</b>	$c_2^v$	$c_2^\psi$	$c_3^v$	$c_3^\psi$	$p$	$q$
Unit	$[s^2/m^2]$	$[1/rad^2]$	$[s^4/m^2]$	$[s^2/rad^2]$	-	-
Optimal value	0.59	0.32	682	257	8	3.9

255

256

It can be seen that all parameters have positive values, which is as expected because these

257

parameters are weight factors and scaling parameters. Compared to  $c_2^v$  and  $c_2^\psi$ ,  $c_3^v$  and  $c_3^\psi$  are much

258

larger. Compared to vessel speed and course, the values of longitudinal acceleration and angular speed

259

are normally very small. This will result in large values of  $c_3^v$  and  $c_3^\psi$ . The scaling parameters  $p$  and  $q$

260

equal to 8 and 3.9, which means that the influence range in longitudinal and lateral direction is around 8

261

times the vessel length and 3.9 times the vessel width, respectively. They are consistent with our

262

expectation that vessels have stronger influence in the longitudinal direction than in the lateral direction,

263

considering the fact that vessel length is much larger than vessel beam.

264

Based on the six optimal parameter values in Table 1, the relationships between each parameter and

265

the error by varying each parameter while keeping the other parameters constant at their optimal value

266

are shown in Fig. 5.

267

It is clear that all curves for these parameters are smooth. For parameters  $c_2^v$ ,  $c_2^\psi$ ,  $c_3^v$ ,  $c_3^\psi$  and  $q$ , the

268

curves have a single and clear minimum, which means the optimal values are taken at the global

269

minimum. Thus, it also means that the calibration method is robust and the optimal values for these

270

parameters are reliable. Regarding the parameter  $p$ , the error decreases with the increase of the scaling

271

parameter up to 8, after which the  $p$  value remains stable. It means that the model is not sensitive to the

272

$p$  value and the optimal  $p$  value is difficult to be determined when the  $p$  value is larger than 8. However,



273 it is not meaningful to investigate the situation for larger p value ( $p > 8$ ), which leads to a unrealistically  
 274 large influence range in longitudinal direction (exceeding the research area).

275 In addition, the optimal values of these two scaling parameters indicate that the influence range in  
 276 longitudinal direction is much larger than in the lateral direction, which is consistent with our  
 277 expectation. In general, this sensitivity analysis indicates the robustness of the calibration and the  
 278 reliability of the optimal parameter set.

#### 279 **4.2 Validation results and examples**

280 By applying the validation approach, the goodness of fit measures is calculated for overtaking  
 281 vessels, overtaken vessels and head-on vessels, as shown in Table 2. As mentioned in section 3.2, the 23  
 282 vessel paths in which overtaking occurred on the other side of the overtaken ship than the actual side are  
 283 removed from these validation results, and 10 vessel paths of simulated overtaken vessels are filtered in  
 284 the same way.

285 **Table 2.** The goodness of fit measures for the validation of different scenarios.

	Overtaking vessels	Overtaken vessels	Head-on vessels
$E_{lo}^F$	102 m	79 m	58 m
$E_{la}^F$	50 m	51 m	78 m
$E_{lo}^M$	112 m	85 m	68 m
$E_{la}^M$	67 m	60 m	83 m
$E_{lo}^A$	62 m	44 m	33 m
$E_{la}^A$	29 m	27 m	34 m
$P_{lo}$	67 %	60 %	81 %
$P_{la}$	50 %	55 %	49 %

286  
 287 The deviations in longitudinal direction range from 33 m to 112 m. Considering the waterway stretch  
 288 of around 2.5 km, all measures representing the error in longitudinal direction are less than the 5% of the  
 289 waterway stretch. In the lateral direction, the deviations vary from 27 m to 83 m, which is relatively

290 large given the waterway width of around 430 m. However, the deviation in lateral direction is also  
291 influenced by the deviation in longitudinal direction, as the vessel path is compared by time line. So it is  
292 difficult to judge the simulation quality based on the deviation in lateral direction here.

293 The data clearly showed that the best prediction in longitudinal direction is for head-on encounters,  
294 as all the deviations in longitudinal direction for head-on encounters are smaller than other scenarios,  
295 and the percentage of good prediction is around 81%, which is better than for the other scenarios as well.  
296 This may be caused by the fact that the speed is hardly influenced by the head-on encounters. However,  
297 the prediction in lateral direction for head-on encounters is obviously worse than for the other scenarios.  
298 This could imply that the elliptical influence area does not work well for head-on vessel encounters. It  
299 suggests to improve the cost function for vessel influence in the VMP model in future research,  
300 specifically for head-on encounters. As mentioned in Section 3.2, the histograms of the deviations for  
301 the first six goodness of fit measures are shown in Fig. 6-8.

302 In the remainder of this section, some example paths have been randomly chosen for each scenario  
303 and plotted in Fig. 9, and compared to the actual path from AIS data and unhindered path (generated by  
304 the desired course). The first example is to simulate overtaking vessel sailing from left to right. It can be  
305 seen that the predicted path in the middle part of the stretch is closer to the starboard bank, meaning that  
306 the influence between two vessels in the VMP model is not strong enough during that period. In the  
307 right part of the stretch, the simulated vessel deviates from the desired path and then the simulated path  
308 is consistent with the AIS overtaking path, which implies the influence between two vessels is  
309 reasonably predicted in this situation. In the remaining two examples, the predicted paths are nearer to  
310 the shore, compared to both the AIS path and desired path. This could mean that the influence between  
311 vessels, as calibrated for overtaking vessels, is too strong for overtaken and head-on vessels. These

312 findings based on example paths suggest that the further research should focus on the different influence  
313 range for different types of encounters.

## 314 **5. Discussion and conclusions**

315 In this paper, the VMP model is optimized by considering the relative position and vessel size  
316 (length and beam). Furthermore, the model is calibrated and validated using the AIS data of vessel  
317 encounters. The calibration results and the sensitivity analysis showed the robustness of the calibration  
318 and the reliability of the optimal parameters. In the validation of the three scenarios, it was found that  
319 the different goodness of fit measures in longitudinal direction are less than 5% of the waterway stretch.

320 It should be noted that several factors influence the calibration results. Firstly, the calibration results  
321 are influenced by the desired speed and desired course, which are important inputs to the model. As we  
322 can see in Eq. (7), the costs for straying from the optimal path were based on the difference between the  
323 real speed and the desired speed, as well as the real course and the desired course. In this research, the  
324 desired speed is based on empirical data. A better solution would be a derivation of the desired speed  
325 based on waterway geometry and vessel characteristics. For the desired course, the results of the Route  
326 Choice model for one representative vessel category is used. Since the dataset used for calibration  
327 comprises several vessel categories, this contributes to the error in the calibration of the VMP model.

328 Secondly, some differences between measured and simulated vessel paths can be attributed to non-  
329 constant maneuvering style and different experience of the bridge team. The encounter pattern, such as  
330 port side or starboard overtaking, is not regulated by international or local rules. The maneuvering  
331 behavior of the bridge team is normally determined according to the traffic situation at that moment  
332 based on their experience, which is difficult to be integrated in the model.

333 As far as we know, this is the first study on vessel maneuvering prediction including speed, course  
334 and path in ports and waterways using a simulation model. Based on the calibration and validation, it  
335 can be concluded that the VMP model has potential to simulate the vessel traffic in ports and waterways.  
336 This paper also provides a fundamental basis for better optimizing and simulating vessel traffic in future.  
337 The approach to determine the port side or starboard overtaking for overtaking encounters is not  
338 included yet and this is an important improvement for the VMP model in future research. In the  
339 validation, the example paths suggest that different influence range for different encounters should be  
340 considered. In addition, single vessel is simulated in this paper and the future research will focus on  
341 simulating multiple vessels simultaneously. Another future research direction is to determine different  
342 calibration parameters for different vessel categories.

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382

383 **Figure captions**

384

385 Fig. 1. Elliptical influence area of overtaking vessel and the definition of scaling parameter for the  
386 overtaking vessel.

387

388 Fig. 2. Definition of desired speed  $v^0$  for an overtaking vessel. The curve indicates the speed track of  
389 overtaking vessel in overtaking encounters. Axis  $x$  and  $y$  represent the longitudinal distance and vessel  
390 speed, respectively.

391

392 Fig. 3. Vessel path of overtaking and overtaken vessel from AIS data (solid line) and simulation path of  
393 overtaking vessel (dashed line) within the prediction horizon.

394

395 Fig. 4. Simulated vessel path (solid line) of overtaking vessel and the observed path (dashed line) from  
396 AIS data.

397

398 Fig. 5. The relationships between each parameter and the error by varying each parameter while keeping  
399 the other parameters constant at their optimal value.

400

401 Fig. 6. Histograms of the deviations from the first six good of fit measures for overtaking vessels.

402

403 Fig. 7. Histograms of the deviations from the first six good of fit measures for overtaken vessels.

404

405 Fig. 8. Histograms of the deviations from the first six good of fit measures for head-on vessels.

406

407 Fig. 9. Example simulated vessel paths compared to the actual path from AIS data and unhindered path  
408 generated by the desired course.