

## Verification of the route choice model and the operational model of vessel traffic

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1 **VERIFICATION OF THE ROUTE CHOICE MODEL AND THE OPERATIONAL**  
2 **MODEL OF VESSEL TRAFFIC**

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## ABSTRACT

Due to the ever-increasing economic globalization, it is important to simulate vessel behaviors to investigate safety and capacity in ports and inland waterways. To this aim, we developed a new maritime traffic model, which comprises two parts: the route choice model and the operational model.

This paper presents the operational model, which describes vessel sailing behavior by optimal control. In the operational model, the main behavioral assumption is that all actions of the bridge team, such as accelerating and turning, are executed to force the vessel to sail with the desired speed and course. In the proposed theory, deviating from the desired speed and course, accelerating, decelerating and turning will provide disutility (cost) to the vessel. By predicting and minimizing this disutility, the longitudinal and angular acceleration can be optimized, thus predicting individual vessel sailing behavior.

To verify the route choice model and operational model, a case study is carried out, applying the models to predict individual vessel behavior (path, speed and course) in the entrance channel to the Maasvlakte I, port of Rotterdam. The simulation results show a good prediction on the vessel path and vessel course. As currently no other model was built specifically to predict the vessel behavior in port area, the current methods provide a fundamental basis to investigate the vessel behavior in restricted waterways. In addition, this research shows the potential of the model to increase the safety and capacity in ports and inland waterways.

*Keywords:* vessel operational model, AIS data, vessel route choice model, verification, case study

## 1 INTRODUCTION

2 Due to the ever-increasing economic globalization, the scale of transportation through ports and  
3 inland waterways increased sharply. One of the main concerns for maritime traffic is the balance  
4 between safety and capacity: when measures are taken to increase capacity, usually the safety  
5 decreases, and vice versa. This holds even stronger for ports and inland waterways, where the  
6 vessel sailing is restricted by the waterway geometry, such as the bank and water depth.

7 To improve maritime traffic management and optimize port and waterway design,  
8 modeling tools are mainly used in three ways. Some models calculate the collision and  
9 grounding probability (1-3). The second type of models predicts vessel maneuvering by  
10 including hydrodynamics of vessels (4-6). The last type of models is related to simulating the  
11 routing in a shipping network (7-9). These models focus mostly on vessel dynamics and  
12 maritime traffic for open seas and they cannot be applied in constrained ports and inland  
13 waterways, where the vessel behavior (speed, course and path) is influenced by different factors,  
14 such as waterway geometry, water depth and interaction between vessels. To predict vessel  
15 behavior in ports and inland waterways, it is important to include the influence of these factors  
16 on vessel behavior. However, little research has been performed on these factors. Advances in  
17 maritime safety in ports and inland waterways require additional effort in developing models  
18 considering additional complexity in these areas.

19 Significant effort has been made to develop a new maritime traffic model to predict  
20 vessel behavior and traffic in ports and inland waterways (10-13). In this model, vessel behavior  
21 is categorized into a tactical and an operational level. The tactical level includes vessel route  
22 choice, which is reflected by the desired course at each location. This desired course represents  
23 the optimal course when the vessel is not influenced by other vessels or external conditions (e.g.  
24 current, wave, wind). Similar to the desired course, the desired speed is the optimal vessel speed  
25 when the vessel is not influenced by other vessels or external conditions. Together with vessel  
26 route choice (desired course), the desired speed serves as input for vessel behavior at the  
27 operational level. The operational level includes the dynamics of the vessel sailing behavior, e.g.  
28 longitudinal and angular acceleration of the vessel.

29 The objective of this paper is to verify the applicability of the route choice model and the  
30 operational model by using the Automatic Identification System (AIS) data collected from  
31 another part of the Port of Rotterdam. These data contain vessel information transmitted between  
32 vessels and shore stations, such as vessel speed, course, position, etc. In recent research, AIS  
33 data have been proven to be a powerful tool to investigate maritime traffic (14,15) and develop  
34 and calibrate simulation models. In the case study, the desired course is generated by the  
35 calibrated route choice model. Together with the desired course, the desired speed generated  
36 from AIS data is used as an input of the operational model to predict paths, courses and speeds of  
37 individual vessels. The predicted paths and courses are then compared to AIS data, to verify if  
38 the model predictions are sufficiently accurate.

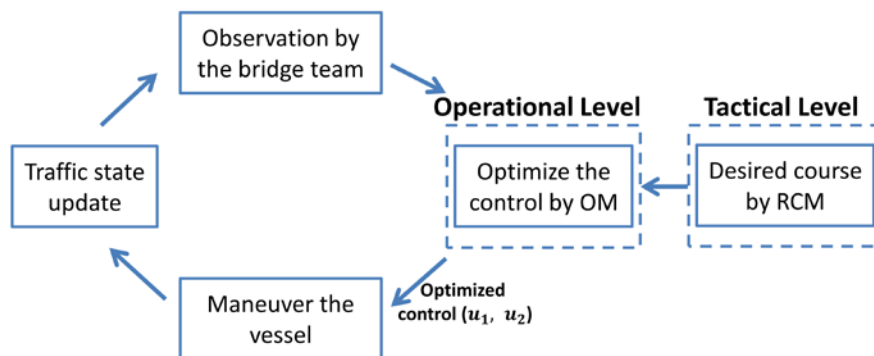
39 Based on this objective, the remaining of this paper is structured as follows. Firstly, the  
40 maritime traffic control framework is presented. Then, the operational model is demonstrated in  
41 detail, followed by the case study set-up, modeling results and discussion. Finally, conclusions  
42 and recommendations for future research are proposed.

## 1 MARITIME TRAFFIC CONTROL FRAMEWORK

2 As discussed before, the newly developed vessel model describes vessel sailing behavior at a  
3 tactical level and at an operational level. To determine the vessel sailing behavior, the bridge  
4 team is considered as the “brain” of the vessel. They will observe and predict the vessel sailing  
5 context, and then maneuver the vessel by accelerating, decelerating or turning. These  
6 maneuvering can be considered as the control for the vessel.

7 The control framework is shown in Figure 1. The traffic state (sailing context) is  
8 observed by the bridge team and serves as input into the operational model. Taking the desired  
9 course generated by the route choice model as starting point, the control in longitudinal direction  
10 (longitudinal acceleration  $u_1$ ) and angular direction (angular acceleration  $u_2$ ) is optimized in the  
11 operational model. With this optimized control, the bridge team will make a maneuver leading to  
12 the next traffic state, consisting of vessel speed, course and position.

13



14

15

16 **FIGURE 1 Maritime traffic control framework.**

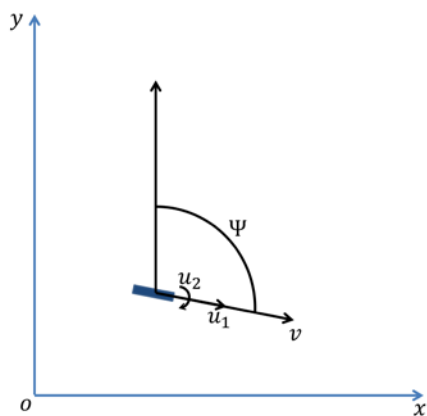
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## 18 THE OPERATIONAL MODEL

19 In this section, the system dynamics of the vessel are introduced, followed by the optimal control  
20 theory and numerical solution approach.

### 21 System dynamics

22 In this research, we consider the vessel behavior in two dimensions. As shown in the vessel  
23 coordinate system in Figure 2, a vessel is geometrically represented by a rectangle in the x-y  
24 coordinates and sails to the bottom right, under the longitudinal acceleration  $u_1$  and the angular  
25 acceleration  $u_2$ .



1  
2  
3 **FIGURE 2 Vessel coordinate system and control.**  
4

5 In this vessel coordinate system, let  $\vec{\xi} = (x, y, v, \psi)$  denote the state of the vessel, in  
6 which  $x$  and  $y$  determine the position,  $v$  is the vessel speed and  $\psi$  is the course angle. To describe  
7 the vessel dynamics and the control, we come to the following mathematical model:

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

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

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

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

### 8 **Model by optimal control**

9 As mentioned before, the bridge team controls the vessel based on the traffic state by  
10 accelerating, decelerating or turning. In the model, the control objectives can be defined as  
11 follows:

- 12 • Maximize the sailing efficiency (restricting deviations from the desired speed and the  
13 desired course).
- 14 • Minimize the maneuvering costs (accelerating, decelerating and turning).

15 Using the control objective functions, we can turn the control of vessel dynamics into a cost  
16 minimization problem.

17 In the operational model, the main behavioral assumption is that all actions of the bridge  
18 team, such as accelerating and turning, are executed to force the vessel to sail with the desired  
19 speed and course. In the proposed theory, deviating from the desired speed and course,  
20 accelerating, decelerating and turning will provide disutility (cost) to the vessel. By predicting  
21 and minimizing this disutility, the longitudinal and angular acceleration can be optimized.

22 The control objective function  $J$  is defined by:

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

23 where  $H$  is the prediction horizon used when making a decision at time instant  $t$ ,  $L$  denotes the  
24 running cost (cost incurred in a small time interval  $[\tau, \tau + d\tau)$ ),  $\vec{u} = (u_1, u_2)$  denotes the control,

1 and  $\Phi$  denotes the terminal costs at terminal conditions, which is the cost that is incurred when the  
 2 vessel ends up with the state  $\vec{\xi}(t + H)$  at time instant  $t + H$ .

3 Since the interaction between vessels and external conditions is not yet integrated in the  
 4 operational model, the running cost contains only two items:

- 5 • Straying from the desired speed and course costs expressed by

$$L^{stray} = \frac{1}{2}(c_2^v(v^0(\vec{x}) - v)^2 + c_2^\psi(\psi^0(\vec{x}) - \psi)^2) \quad (6)$$

- 6 • Maneuvering costs, indicated by

$$L^{maneu} = \frac{1}{2}(c_3^v u_1^2 + c_3^\psi u_2^2) \quad (7)$$

7 Here,  $c_2^v$ ,  $c_2^\psi$ ,  $c_3^v$  and  $c_3^\psi$  are weight factors of these costs.  $v^0(\vec{x})$  and  $\psi^0(\vec{x})$  denote the  
 8 desired speed and desired course at the location  $\vec{x}$ .

9 To minimize the objective function, we assume that the longitudinal acceleration and the  
 10 angular acceleration the bridge team selects satisfies:

$$\vec{u}_{[t,t+H]}^* = \arg \min J(\vec{u}_{[t,t+H]}) \quad (8)$$

11 subject to Eq. (1-4).

12 For the vessel state  $\vec{\xi} = (x, y, v, \psi)$ , we define the shadow costs (or co-state) as  $\vec{\lambda} =$   
 13  $(\lambda_x, \lambda_y, \lambda_v, \lambda_\psi)$  to formulate the so-called Hamiltonian function (16):

$$\mathcal{H} = L + \vec{\lambda} \cdot \frac{d\vec{\xi}}{dt} \quad (9)$$

14 where the shadow costs describe the relative change in the cost in case of a (small) change in the  
 15 state. The Hamiltonian function and the shadow costs satisfy:

$$-\frac{d\vec{\lambda}}{dt} = \frac{\partial \mathcal{H}}{\partial \vec{\xi}} \quad (10)$$

16 In this optimal control, the initial condition is the vessel state in  $\vec{\xi}$  at  $t$ , which is the  
 17 vessel's current position, speed and course. For the terminal condition, we assume that the vessel  
 18 will reach its optimal speed and course at the end of the prediction horizon, at instant  $t + H$ ,  
 19 which means the shadow costs are zero.

20 According to the so-called optimality conditions for the optimal control:

$$\mathcal{H}(t, \vec{\xi}, \vec{u}^*, \vec{\lambda}) \leq \mathcal{H}(t, \vec{\xi}, \vec{u}, \vec{\lambda}) \quad \forall \vec{u} \quad (11)$$

21 the optimal control  $u_1^*$  and  $u_2^*$  can be determined:

$$u_1^* = -\lambda_v / c_3^v \quad (12)$$

$$u_2^* = -\lambda_\psi / c_3^\psi \quad (13)$$

22 By substituting Eq. (6), Eq. (7) and Eq. (9) in Eq. (10), we obtain the following equations, which  
 23 express the shadow costs dynamics:

$$-\dot{\lambda}_v = c_2^v(v - v^0) + \lambda_x \cos\left(\frac{\pi}{2} - \psi\right) + \lambda_y \sin\left(\frac{\pi}{2} - \psi\right) \quad (14)$$

$$-\dot{\lambda}_x = c_2^v(v^0 - v) \frac{\partial v^0}{\partial x} + c_2^\psi(\psi^0 - \psi) \frac{\partial \psi^0}{\partial x} \quad (15)$$

$$-\dot{\lambda}_y = c_2^v(v^0 - v) \frac{\partial v^0}{\partial y} + c_2^\psi(\psi^0 - \psi) \frac{\partial \psi^0}{\partial y} \quad (16)$$

$$-\dot{\lambda}_\psi = c_2^\psi(\psi - \psi^0) + \lambda_x v \sin\left(\frac{\pi}{2} - \psi\right) - \lambda_y \cos\left(\frac{\pi}{2} - \psi\right) \quad (17)$$

1 Then, we will use Pontryagin's method to solve the system of these equations (17).

## 2 CASE STUDY

3 In our previous work, the route choice has been calibrated and presented (12,13). The operational  
4 model has been calibrated as well (18). Both models have been calibrated based on AIS data,  
5 which will be used in this research as well. To verify the route choice model and the operational  
6 model, a case study is carried out by applying the models in another situation than it has been  
7 calibrated for. We compare the simulation results to AIS data to assess the quality of the model.  
8 This section contains two parts: 1) case study set-up and 2) results comparison and discussion.

### 9 Set-up

10 In this section, the case study set-up is presented. We firstly introduce the scenario, consisting of  
11 the infrastructure geometry, the demand profile and the fleet composition. After that, an  
12 overview of the optimized parameters for the route choice model and the operational model is  
13 given. Then, the desired course generated by the route choice model is presented, followed by  
14 the desired speed derivation. Finally, the operational model is applied to predict the vessel  
15 behavior in the research area.

#### 16 Scenario introduction

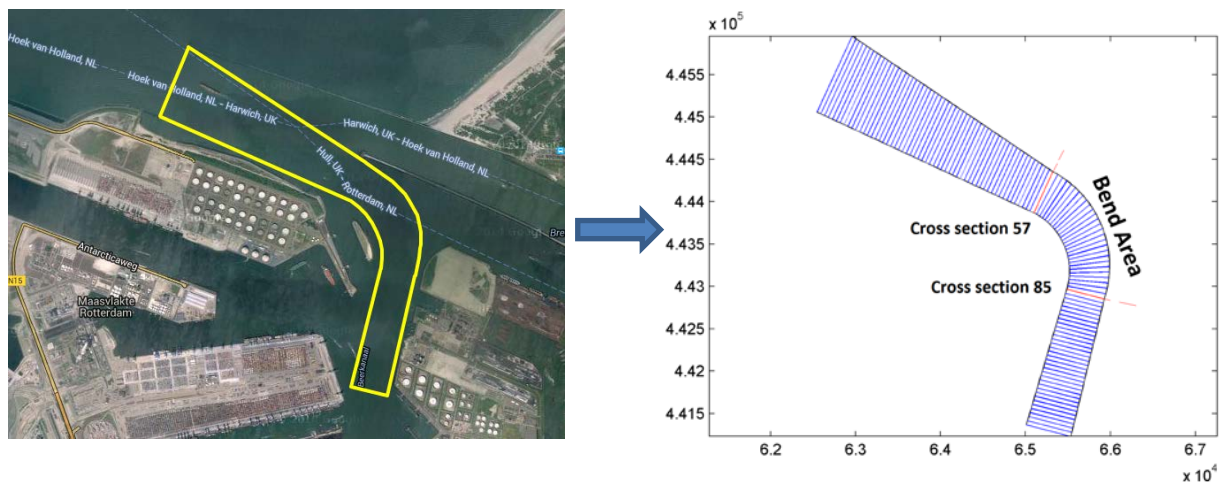
17 The case study area is the entrance channel to the Maasvlakte I in the port of Rotterdam, which is  
18 shown on the left-hand side of Figure 3. The research area is selected since an AIS data analysis  
19 has been carried out in this area in a previous study (19). The AIS data from 2009 are available  
20 for our case study.

21 In Figure 3, the research area geometry is defined by the yellow lines according to the  
22 buoys, the bank and the curves in the turning area. Based on this geometry, we transfer the  
23 geographical coordinates to the Rijksdriehoeksgrid (RD) coordinates (right-hand side of Figure  
24 3), which is the national grid of the Netherlands. This national grid in meters can be conveniently  
25 used to calculate the vessel movement. In addition, 119 cross sections with intervals around 50  
26 meters are defined in the research area to calculate and compare the vessel behavior in the lateral  
27 direction. These cross sections are approximately perpendicular to the waterway longitudinal  
28 direction, and can be used to extract the AIS data on each cross section.

29 We investigate the vessels sailing from the North Sea to the berth, which is the direction  
30 from upper left to the bottom part in Figure 3. In this direction, 307 vessel paths from AIS data  
31 from the North Sea to the Maasvlakte I are available for the case study. These paths are shown  
32 on the left-hand side of Figure 5. It should be noted that the vessel paths spread much wider in  
33 the end of the trip, because vessels are very close to the basin and they prepare to enter the basin,  
34 which is at the left bottom on the left-hand side of Figure 3. Although most vessels sail bow-first  
35 into the basin, some vessels have to sail stern-first and turn around in the basin. Through this



1 maneuver, these ships exceed the boundary, as can be seen in Figure 5. In this paper, we do not  
 2 consider these inconsistencies, which are the preparation for mooring (entering the basin).  
 3



4  
 5 **FIGURE 3** Converting the research area geometry to RD coordinates and cross sections.  
 6

7 *Optimized parameters*

8 In this section, an overview of the optimized parameters for the route choice model and the  
 9 operational model is given in Table 1.

10  
 11 **TABLE 1** Optimized parameters for the route choice model and the operational model  
 12

<b>Route choice model</b>	<b>Parameters</b>	$c_4$	$c_5$	$r_1$	$r_2$
	<b>Optimized results</b>	0.0199	0.0123	0.45	0.254
<b>Operational model</b>	<b>Parameters</b>	$c_2^v$	$c_2^\psi$	$c_3^v$	$c_3^\psi$
	<b>Optimized results</b>	1.00	7.99	33.6	393.41

13  
 14 We have calibrated the route choice model for four AIS data sets in another area in the  
 15 port of Rotterdam, covering four sailing directions (13). Here, we use the results (optimized  
 16 parameters) of this calibration, as shown in the first and second rows of Table 1. The parameters  
 17  $c_4$  and  $c_5$  denote the strength of the influence of the portside and starboard bank on the vessel  
 18 respectively, while the parameters  $r_1$  and  $r_2$  reflect the influence range of both banks in lateral  
 19 direction. It can be seen that the influence of the portside bank is larger than the starboard bank  
 20 both in strength and in range. The third and fourth rows of Table 1 show the chosen parameters  
 21  $c_2^v, c_2^\psi, c_3^v$  and  $c_3^\psi$  (weight factors of running costs) for the operational model. These optimized  
 22 parameters will be used when we apply the model in the case study described in the next sections.

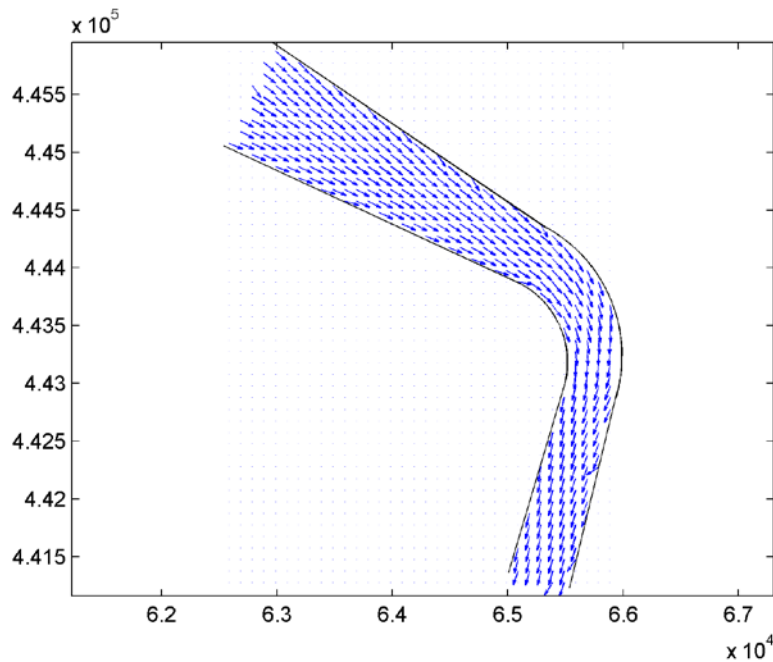
23 *Desired course by the route choice model*

24 To apply the dynamic programming approach and the numerical solution approach, the research  
 25 area is discretized into  $5 \times 5$  meters grid. Based on the optimized parameters in Table 1, the

1 desired course in continuous space is generated by the route choice model in each cell  
 2 formulated by the grid. The desired course is shown in Figure 4, where the arrow in each cell  
 3 indicates the desired course and forms the so-called desired course field for vessel sailing from  
 4 the upper left to the bottom of the figure. In this course field, it can be found that when the vessel  
 5 is close to the bank, she will be repelled from the bank. The vessel will also smoothly follow the  
 6 bend. This desired course is plausible and corresponds to the AIS data analysis.

7 Based on this course field, the desired course for any location in this area can be derived  
 8 by interpolation. This way, this desired course field could be used as input in the operational  
 9 model.

10



11

12

13 **FIGURE 4 Desired course in continuous space by the route choice model.**

#### 14 *Desired speed*

15 The desired speed is another input of the operational model. The desired speed may be  
 16 influenced by among other things the waterway geometry and the distance to the final  
 17 destination (berth). However, the relationships between the desired speed and these factors have  
 18 not yet been investigated, and are thus not included in the model. As an approximation, we will  
 19 use here the average vessel speed (from AIS data) on each downstream cross section as the  
 20 desired speed. For example, for a vessel sailing from the cross section  $M$  to the cross section  
 21  $M+1$ , the average speed at the downstream cross section  $M+1$  is considered as the desired speed.  
 22 It should be noted that the vessel speed mostly decreased a lot in this research area, when the  
 23 vessels sail from the open sea to their final destination (berth).

#### 24 *Application of the operational model*

25 We have calibrated the route choice model and the operational model based on AIS data of small  
 26 General Dry Cargo (GDC) vessels (11). In the available AIS data for this case study, the vessels  
 27 are classified by the vessel deadweight tonnage (dwt). We have chosen to only model the vessels

1 in the category ‘Smaller than 10,000 dwt’, which corresponds best to the vessel category for  
 2 which we calibrated the model.

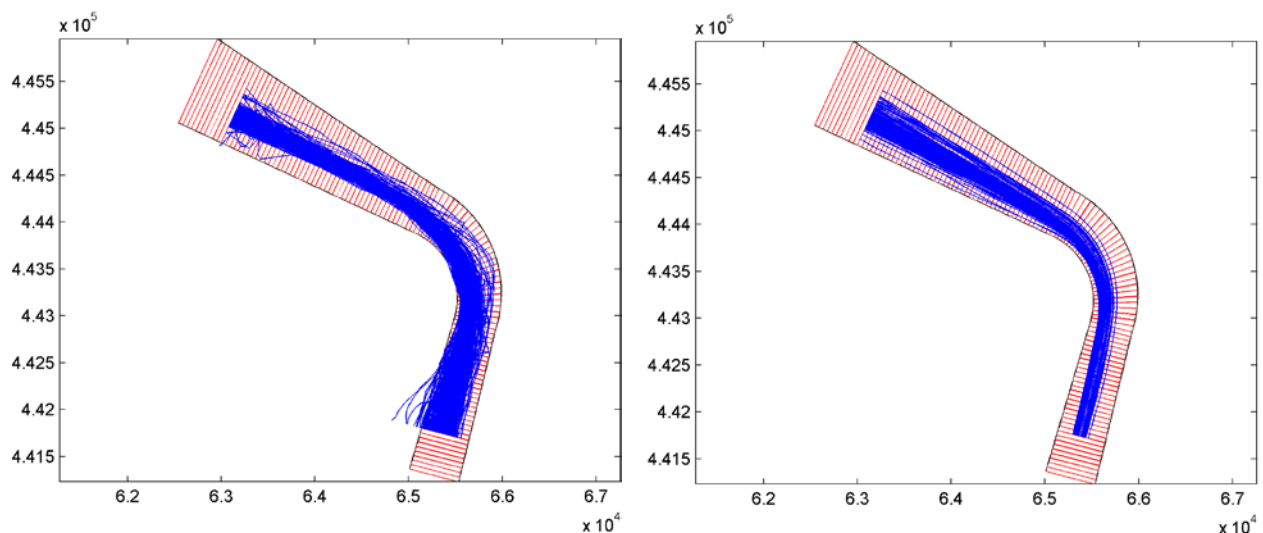
3 By using the desired course and the desired speed as input, this operational model is  
 4 applied to predict vessel speed, course and path. It should be noted that the simulation cannot  
 5 cover the whole area, since our operational model is based on prediction, which makes the vessel  
 6 to exceed the boundary when they are too close to the boundary. Then we consider the cross  
 7 section 10 as the origin and the cross section 110 as the destination. When generating the vessels  
 8 in the simulation, we use the real vessel state (position, speed and course) at cross section 10 as  
 9 the initial state, being input into the operational model.

## 10 Results comparison and discussion

### 11 *Vessel path*

12 Figure 5 shows the real paths from AIS data and predicted vessel paths in the research area.  
 13 Some real paths are drawn outside the boundary. These ships turn around in the waterway, as  
 14 they enter the basin stern-first, for logistic reasons. Compared to the AIS data paths on the left-  
 15 hand side, predicted paths have less variation in the paths since the interactions of other vessels,  
 16 human factors and external conditions are not included in the operational model.

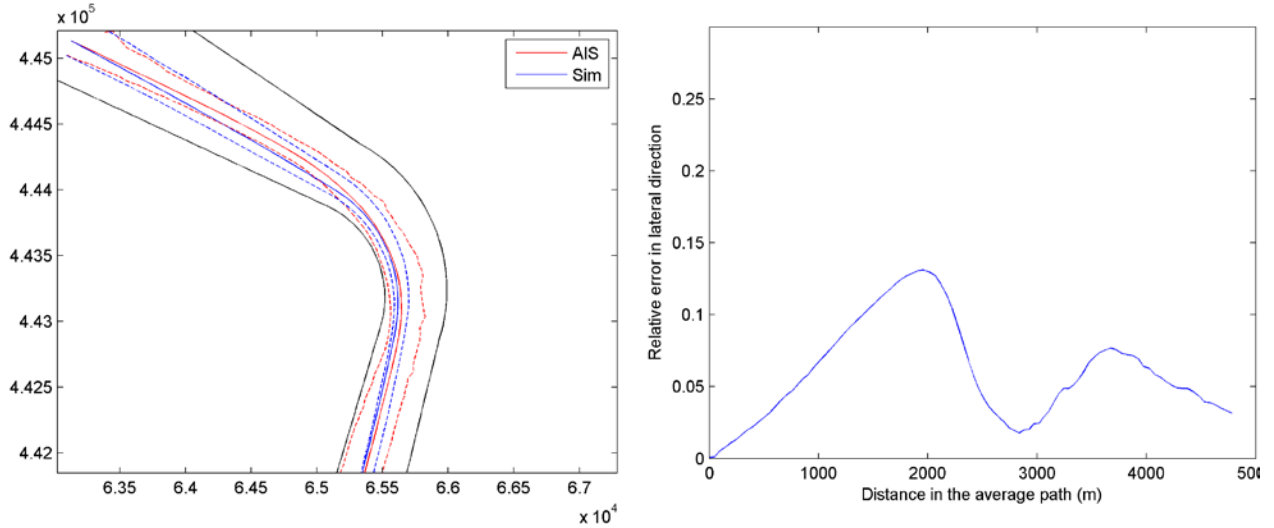
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18 **FIGURE 5 Real paths from AIS data (left) and simulated vessel paths (right).**

19

20 For the predicted paths, it can be seen that vessels concentrate on the right-hand side of  
 21 the waterway, which corresponds to the AIS data analysis (11). In the bend area, the vessel  
 22 tracks also follow the turning curve well. Compared to the lateral position of these tracks before  
 23 the bend area, it can be found that the vessels after the bend area are further away from the  
 24 starboard bank. In general, the simulated vessels are more concentrated in the center of the  
 25 waterway than the vessels in the AIS data.



1 **FIGURE 6 Average vessel path (solid lines) and their 95% confidence interval (dotted**  
 2 **lines) comparison between AIS data and simulation results, and relative error in lateral**  
 3 **direction.**

4  
 5 On the left-hand side of Figure 6, we show the average vessel path (solid blue line) of the  
 6 predicted vessel paths to the average vessel path (solid red line) from the AIS data with their 95%  
 7 confidence interval (dotted lines). The dot dash lines indicate the 95% confidence intervals  
 8 respectively for the AIS paths and simulation paths. It can be found that the distribution of the  
 9 AIS paths in the bottom is wider than the upper part, which can be explained by the mooring  
 10 behavior explained before. In addition, the simulation paths are more concentrated than AIS  
 11 paths, probably because we do not consider the factors that may increase the variability of the  
 12 paths in this case study. Comparing the average path of simulation paths in the lateral direction,  
 13 it can be seen that vessels are closer to the starboard bank in the bend area, which is  
 14 corresponding to the average path from AIS data. Apparently, the bridge team maneuvers the  
 15 vessel closer to the starboard bank to reduce the influence of other vessels.

16 On the right-hand side of Figure 6, the relative error in the lateral direction is given on  
 17 each cross section. The  $x$  axis is the distance in the average path of AIS data from origin (cross  
 18 section 10) to the destination. It can be seen that the largest relative error is around 13%.

19 To compare the difference between the average paths of predicted paths and the AIS  
 20 paths, the root-mean-square deviation ( $RMSD$ ) measure is used. Let  $n$  denote the number of the  
 21 data number (cross section number),  $(x_t^{sim}, y_t^{sim})$  and  $(x_t^{AIS}, y_t^{AIS})$  denote the coordinate of the  
 22 average simulation paths and average AIS paths on cross section  $t$ . Then, the  $RMSD$  on the  
 23 lateral position is expressed by:

$$RMSD = \sqrt{\frac{\sum_{t=1}^n ((x_t^{sim} - x_t^{AIS})^2 + (y_t^{sim} - y_t^{AIS})^2)}{(nD_t)^2}} \quad (18)$$

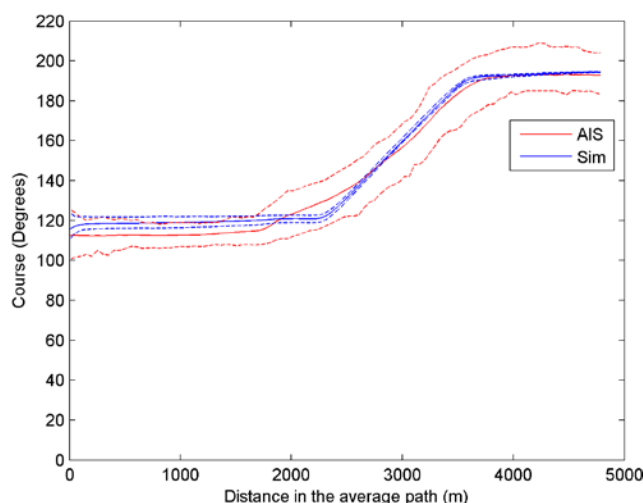
24 where  $D_t$  is the width of the waterway on cross section  $t$ .

25 Then the  $RMSD$  represents the mean relative error in the lateral direction. By applying Eq.  
 26 (18), the value of  $RMSD$  is 6%. That means the average relative error in the lateral direction is 6  
 27 percent. This difference may be introduced by both the route choice model and the operational  
 28 model. It was believed that the most of error can be attributed to the optimized parameters that

1 were applied to generate the desired course in the route choice model, as these optimized  
 2 parameters were achieved in a different situation than the case study situation. The rest of the  
 3 error may be introduced by the operational model, as the factors influencing the vessel path, such  
 4 as the interaction with other vessels and the influence of external conditions, have not been  
 5 considered in the model at this stage.

### 6 *Vessel course*

7 In Figure 7, the vessel course of the AIS data and the simulation results are compared. It can be  
 8 found that the simulated vessel course is well in accordance with the AIS data. However, the  
 9 deviation of the simulation course is much less than the real course from AIS data. This can be  
 10 explained by that the factors influencing vessel behavior are not considered in this case study.  
 11



12  
 13  
 14 **FIGURE 7 Average vessel course (solid lines) and their 95% confidence interval (dotted**  
 15 **lines) comparison between AIS data and simulation results.**

16  
 17 The *RMSD* for vessel course is defined by:

$$RMSD = \sqrt{\frac{\sum_{t=1}^n (C_t^{sim} - C_t^{AIS})^2}{n}} \quad (19)$$

18 where  $C_t^{sim}$  and  $C_t^{AIS}$  denote the average vessel course from simulation results and the AIS data  
 19 on cross section  $t$ , respectively. And  $n$  is the data number. By using Eq. (19), the calculated  
 20 *RMSD* is 3.68 degrees. That means the prediction error for vessel course is around 3.68 degrees.

## 21 **CONCLUSIONS AND RECOMMENDATIONS**

22 In this paper, we presented the operational vessel sailing model in detail. Most importantly, we  
 23 carried out a case study by applying the route choice model and the operational model to verify  
 24 the applicability of both models as a whole, using the AIS data in the port of Rotterdam (the  
 25 entrance channel to the Maasvlakte I). The proposed model has been formulated using optimal  
 26 control theory and a numerical solution approach.

27 In this case study, the desired course generated by the calibrated route choice model  
 28 corresponds to the AIS data analysis: when the vessel is close to the bank, she will be repelled

1 from the bank. The vessel will also smoothly follow the bend. Together with the desired course,  
2 the desired speed based on historical data serves as the inputs into the operational model. The  
3 parameters found in a previous calibration effort are used to predict vessel behavior in the  
4 research area. The generated paths by the operational model are concentrated on the right hand  
5 side of the waterway, which corresponds to the AIS data analysis.

6 Furthermore, we compared the vessel path and vessel course between the AIS data and  
7 simulation results using RMSD. The results show a good prediction on vessel path (6% relative  
8 difference in lateral direction) and vessel course (3.68 degrees). These errors may be attributed to  
9 the optimized parameters, which are achieved in a different situation than the case study situation.  
10 In addition, the factors (such as external conditions and vessel encounters) may also have  
11 contribution to the error, since they have not yet been included in the model at this stage. As  
12 currently no other model was built specifically to predict the vessel behavior in port area, the  
13 current methods provide a fundamental basis to investigate the vessel behavior in restricted  
14 waterways.

15 This research shows the potential of the model to simulate vessel traffic in a selected area  
16 of a port. In the near future, we intend to simulate larger and more complex parts of the port. Our  
17 aim is that the model can be used by port authorities and port and waterway designers, to name  
18 but a few, to assess ports, to compare alternative designs and to investigate potential traffic  
19 management measures. For designers of ports and waterways, the model will be part of a port  
20 and waterway design support tool to investigate the safety and capacity of ports and inland  
21 waterways. For the port authority or administrative departments, such as Vessel Traffic Service  
22 (VTS), the model can be used to improve the management of maritime traffic, e.g. by testing the  
23 potential of time slot management.

24 Our future work will focus on the desired speed derivation for the operational model. The  
25 relationship between desired speed and the waterway geometry should be clarified. Then, the  
26 desired speed can be derived from the waterway geometry, not from historical data. In addition,  
27 more factors should be integrated into the operational model, such as the external conditions and  
28 interactions between vessels. Furthermore, the calibration will be performed for more vessel  
29 classes and different waterway layouts.

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