

1 **Vessel Route Choice Theory and Modeling**

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1 **ABSTRACT**

2 To better describe vessel traffic in ports and inland waterways, a new maritime traffic model is developed. In our  
3 research, vessel behavior is categorized into a tactical level (route choice) and an operational level (the dynamics of  
4 the vessel behavior). This new maritime traffic model comprises two parts: the route choice model resulting in the  
5 vessel's preferred route, and the operational model describing the maneuvering behavior including interactions  
6 between vessels.

7 This paper presents the vessel route choice model, which is based on disutility or cost minimization. The  
8 cost is determined by characteristics of the infrastructure, such as expected sailing time and distance to the bank. It  
9 is assumed that the bridge team will try to follow a preferred route that minimizes the cost to the destination. To  
10 calculate this preferred route to the certain destination, the so-called value function is defined as the minimum  
11 disutility function in continuous time and space. Subsequently, the value function is solved using dynamic  
12 programming and numerical solution approach.

13 Based on an Automatic Identification System (AIS) dataset of unhindered vessel behavior in the Port of  
14 Rotterdam, the vessel route choice model is calibrated. The calibrated results of the route choice model show  
15 plausible preferred routes in the research area, which help us to understand the desired vessel behavior (route).  
16 These results could be used to improve vessel traffic management and provide a basis for predicting vessel behavior  
17 at the operational level.

## 1 INTRODUCTION

2 Due to the globalization of products trade, the usage of vessels for transportation increases all over the world. It is  
3 getting more and more important to find the balance between safety and capacity in busy ports and inland waterways:  
4 when measures are taken to increase capacity, usually the safety decreases. To optimize ports and waterway design  
5 and improve maritime traffic management, modeling tools can be used.

6 Vessel behavior including its speed and path is difficult to predict, especially in ports and inland waterways,  
7 since a lot of factors influence vessel behavior, such as waterway's geometry, human factors and external conditions  
8 including wind and visibility. Currently, some maritime models focus on calculating the risk probability of  
9 collisions or groundings (1-3), while other models mainly consider the hydrodynamics of vessels (4-6) or simulate  
10 the routing in a shipping network (7-9). In addition, most maritime simulation models focus on vessel dynamic and  
11 traffic for open seas. These models cannot be applied in constrained ports and waterways due to the fact that  
12 different factors affect sailing behavior in ports and waterways than in open seas (e.g. influence of banks and  
13 influence of water depth). Little research has been performed regarding the vessel route choice in inland waterways,  
14 interaction between vessels and human factors influencing maritime traffic. In order to optimize ports and waterway  
15 design and improve maritime traffic management, a new model needs to be developed to describe vessel traffic in  
16 ports and inland waterways.

17 In our research, vessel behavior is categorized into a tactical level and an operational level (10). The  
18 tactical level includes vessel route choice in inland waterways without external influences. The vessel route choice  
19 at the tactical level serves as the basis for vessel behavior at the operational level. The operational level includes the  
20 external influences and dynamics of the vessel behavior, e.g. all decisions related to the sailing taken for the coming  
21 short time period. In other words, at the operational level, it is hypothesized that vessels follow the preferred route  
22 generated at the tactical level as much as possible, while taking into account external influences and human factors.  
23 Therefore, our new maritime traffic model will comprise two parts: the route choice model resulting in preferred  
24 routes, and the operational model describing the sailing behavior including interactions between vessels, which was  
25 proposed in our previous research (11). This paper presents the vessel route choice model at the tactical level.

26 In vessel route choice theory, it is assumed that disutility or cost of each route for the vessel determined by  
27 characteristics of the infrastructure, such as expected sailing time and distance to the bank. The bridge team will try  
28 to follow a route that minimizes the disutility to reach their destination, being the preferred route. To calculate the  
29 preferred route, the so-called value function is defined as the expected minimum disutility function in continuous  
30 time and space. From this value function, the preferred route can be derived from the present position to the  
31 destination, which leads to the least disutility to the vessel. In other words, the bridge team will navigate their vessel  
32 in the direction in which the cost decreases most rapidly. The value function is obtained using dynamic  
33 programming and a numerical solution approach.

34 In recent research, AIS data have been proven to be a powerful tool to investigate maritime traffic (12,13).  
35 Automatic Identification System (AIS) is an onboard system transmitting vessel information (position, velocity,  
36 destination, etc.) between nearby vessels and shore stations. AIS data in the Port of Rotterdam are provided by the  
37 Maritime Research Institute Netherlands (MARIN, the leading institute for hydrodynamic research and maritime  
38 technology in the Netherlands). These data are used for model calibration in this paper.

39 The remainder of this paper is structured as follows. Firstly, the vessel behavior theory at the tactical level  
40 is proposed, followed by an optimal route choice model for vessels in ports and restricted waterways. Then, the  
41 calibration process and results of the vessel route choice model are described. Finally, conclusions and  
42 recommendations for future research are presented.

## 43 VESSEL BEHAVIOR AT THE TACTICAL LEVEL

44 Our research focuses on the vessel behavior in the two-dimensional space, including vessel position and velocity.  
45 Our previous research (14,15) showed that a lot of factors influence vessel behavior, such as vessel characteristics  
46 (e.g. vessel type and size), waterway geometry and external conditions (e.g. wind, visibility and current).

47 As mentioned before, we investigate vessel route choice at the tactical level. In the approach, the bridge  
48 team is considered as the "brain" of the vessel. In the vessel route choice theory, it is assumed that disutility or cost  
49 of each route for the vessel is determined by characteristics of the infrastructure, which will be proposed and  
50 included in the running cost in the next section. To identify the preferred route, the bridge team will predict and  
51 minimize this expected disutility or cost  $C$ .

52 In our research, we investigate vessel behavior in a waterway stretch, which is defined by two cross  
53 sections. These two cross sections can be considered as the entrance and the destination for vessels sailing in this  
54 direction. The vessel route  $x(\cdot)$  is a continuous function, uniquely determined by the velocity trajectory  $v(\cdot)$  through

1 the waterway. Since the position is the derivative of the velocity, so optimizing the velocity also optimizes the route.  
 2 Then, the utility optimization for the vessel route will yield the optimized velocity choice at the tactical level.

3 It should be noted here that both vessel course and speed are included in this optimized velocity. As we  
 4 discussed before, vessel speed is influenced by external influences (e.g. wind and visibility) and is determined by the  
 5 bridge team according to the traffic situation and the infrastructure at the operational level. Therefore, the vessel  
 6 route choice model will mainly consider vessel course, rather than vessel speed.

7 In equation (1), the optimal course (over a time period) is defined as that minimizes the cost, given the  
 8 current time and position of the vessel:

$$v^*(\cdot) = \arg \min C(v(\cdot)|t_0, x_0) \quad (1)$$

9 where  $t_0$  and  $x_0$  are the current time and position of the vessel. This way, the vessel route choice problem becomes  
 10 the optimization for vessel velocity in the research area.

11 In the next section, we will discuss the expected disutility and the solution for the vessel route choice  
 12 optimization.

### 13 OPTIMAL ROUTE CHOICE FOR VESSELS

14 With respect to the vessel behavior at the tactical level, it is assumed that the bridge team chooses a route by  
 15 predicting and minimizing the expected disutility of following this route, which is determined by characteristics of  
 16 the infrastructure. The contributions of these characteristics to the cost  $C$  will be introduced in following sections.

17 The decision making process of the bridge team is feedback-oriented. That means for each time step, the  
 18 bridge team will reconsider the expected disutility and make the choice for the preferred route in the next time steps  
 19 to minimize the expected cost. This is a continuous feedback control system including input (velocity) and the  
 20 controlled output (location).

21 As we know, vessels sometimes deviate from their planned path when they encounter other vessels. To  
 22 flexibly adapt vessels to other routes, the expected minimum perceived disutility for all locations  $x$  and instants  $t$  is  
 23 proposed. The so-called value function  $W(t, x)$  is defined as expected minimum perceived disutility function in  
 24 continuous time and space (16). Based on the solution of  $W(t, x)$ , the optimal route choice for vessels can be  
 25 determined.

### 26 Vessel kinematics under uncertainty

27 As mentioned above, velocity and location are considered as control input and output, respectively. To apply the  
 28 control, consider the location  $x$  (the state) and the velocity  $v$  (the control) for a vessel. The vessel position at instant  $t$   
 29  $x(t)$  is known to the bridge team and expressed by  $\hat{x}$ . Then, the bridge team will predict the route costs and  
 30 determine the future position  $x(\tau)$  for  $\tau > t$  using the vessel kinematics:

$$dx = vdt + d\varepsilon \quad \text{subject to } x(t) = \hat{x} \quad (2)$$

31 where  $v = v(\tau)$  denotes velocity of the vessel for  $\tau > t$ . The term  $d\varepsilon$  represents the small disturbance, which is  
 32  $N(0, \sigma^2)$ -distributed. The white noise reflects the uncertainty in the expected traffic conditions and is caused by lack  
 33 of experience or randomness of future conditions.

34 Here, we investigate vessels sailing in ports and waterways, where they sail at relatively low speed. This  
 35 speed is around 10 knots, which is normally far below the physical limitation of the vessel. So this physical  
 36 limitation is not considered in our research.

### 37 Generalized expected utility

38 In vessel route choice, we investigate vessel velocity and position in waterways. Consider a part of waterway  
 39 between two cross sections, which are set as the origin and the destination respectively.

40 Let  $[t, t_t)$  denote the planning period of the bridge team, where  $t$  and  $t_t$  are respectively the current time  
 41 and the terminal time (planning horizon). The vessel is expected to reach its destination during this time period. Let  
 42  $t_a$  denote the time of arrival at the destination, and let  $T = \min(t_t, t_a)$ . Consider an arbitrary control  $v_{[t, T)}$  resulting  
 43 in the trajectory  $x_{[t, T)}$ , the expected disutility or cost  $C$  is defined as

$$C(T, v_{[t, T)}) = \int_t^T L(\tau, x(\tau), v(\tau))d\tau + \phi(T, x(T)) \quad (3)$$

44 where  $L$  and  $\phi$  respectively denote the so-called running cost and the terminal cost. The running cost  
 45  $L(\tau, x(\tau), v(\tau))$  reflects the cost incurred in a small time period  $[\tau, \tau + d\tau)$ , given the location  $x(\tau)$  at time  $\tau$  and

1 control velocity  $v(\tau)$ . The terminal cost  $\phi(T, x(T))$  reflects the penalty incurred due to the vessel ending up at  
 2 position  $x(T)$  at the terminal time  $T$ , but not at the destination. This expected utility is input into the dynamic  
 3 programming problem identified later.

#### 4 **Specification of terminal cost**

5 As defined in the previous section, the terminal time  $T$  either equals the final time  $t_t$  of the planning period or the  
 6 time  $t_a$  at which the vessel arrives at the destination. The terminal cost is defined as

$$\phi(T, x(T)) = \begin{cases} 0, & T < t_t \\ \phi, & T = t_t \end{cases} \quad (4)$$

7 The terminal cost  $\phi$  thus reflects the penalty for not having arrived at the destination at the end of the prediction  
 8 horizon. When the vessel arrives at the destination in time, the penalty is zero. So the vessel will aim to reach the  
 9 destination within the prediction horizon.

#### 10 **Specification of running cost**

11 By definition, the running cost  $L$  reflects the influence of different characteristics of the infrastructure considered by  
 12 the bridge team. For simplicity, it is assumed that these attributes are independent and the running cost is linear-in-  
 13 parameters as follows:

$$L(t, x, v) = \sum_{k=1,2,\dots} c_k L_k(t, x, v) \quad (5)$$

14 where  $L_k$  denote the contributions on vessel route choice of  $k$  different characteristics of the infrastructure, and  $c_k$   
 15 are relative weights for these factors. It should be noted that all weights cannot be uniquely determined from AIS  
 16 data, since only the relative importance of the weights can be found. Furthermore, weight factors  $c_k$  are different for  
 17 different vessel groups according to AIS data analysis. For example, small vessels follow a path closer to their  
 18 starboard bank compared to large vessels.

19 The data analysis showed that both banks and the vessel characteristics have influence on vessel route  
 20 choice (14). In our approach, we consider the following characteristics of the infrastructure in the running costs for a  
 21 specific vessel category: expected sailing time, counteract the bend waterway effect explained below, discomfort  
 22 due to proximity to banks and sailing at a certain speed. These running costs are described below.

#### 23 *Expected sailing time*

24 For the expected sailing time, we define  $L_1$  as follows:

$$L_1(t, x, v) = 1 \quad (6)$$

25 The definition above results in the route cost

$$\int_t^T c_1 \cdot L_1(\tau, x(\tau), v(\tau)) d\tau = \int_t^T c_1 d\tau = c_1(T - t) \quad (7)$$

26 It means that the contribution of expected sailing time on running cost equals the expected sailing time, multiplied  
 27 by the weight  $c_1$ . The weight factor  $c_1$  reflects the time-pressure for the bridge team to arrive in time at their  
 28 destination.

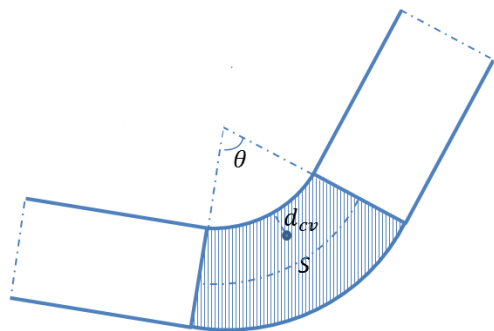
#### 29 *The waterway bend effect*

30 By including the sailing time, as stated in the previous paragraph, we assume that vessels prefer to sail in a straight  
 31 line towards their destination. In bended waterways, this implies that vessels will cut corners. However, previous  
 32 AIS data analysis (14) showed that vessels normally sail along the centerline of the waterway in the bend area of the  
 33 waterway. In the route choice model, a term is therefore added to the running cost to counteract the bend waterway  
 34 effect to make sure vessels are sailing along the waterway in the bend area. An example of a bend waterway is  
 35 shown in FIGURE 1, where the bend area is shadowed. In the figure,  $\theta$  denotes the change of waterway direction  
 36 before the bend and after the bend.  $S$  denotes the average arc length, which approximately equals the length of the  
 37 middle line of the bend waterway. Then,  $\theta/S$  reflects the direction change in unit distance, which could be defined  
 38 as strength of the bend.  $d_{cv}$  is the distance to the convex bank.

39 To counteract this influence caused by a bend in waterways, a linear decreasing utility from the convex  
 40 bank is defined as  $L_2$  as follows

$$L_2 = -\frac{\theta}{S} \cdot d_{cv}(x) \quad (8)$$

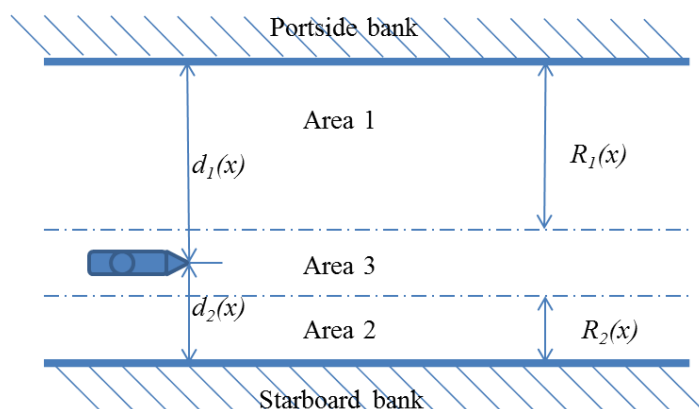
1 It should be noted that this cost is only added in the bend area of the waterway. Then, in the bend area,  $L_2$  provides  
2 repulsion from the convex bank.



3  
4 **FIGURE 1 Example of bend waterway and parameters.**

#### 5 *Discomfort due to proximity to banks*

6 As we know from AIS data analysis, sailing vessels normally keep a certain distance to the bank, which in the  
7 present case has been defined as the five meter water depth line. The bridge team will adjust its course to make sure  
8 that their vessel is not too close to either portside bank or starboard bank. In our approach, it is assumed that a vessel  
9 is influenced by the bank when it is closer to the bank than a certain threshold distance. As shown in FIGURE 2, a  
10 vessel sails to the right and its present location is  $x$ . Let  $d_1(x)$  and  $d_2(x)$  denote the distance to the portside bank  
11 and the starboard bank respectively,  $R_1$  and  $R_2$  describe how far both banks can influence the vessel. The vessel is  
12 influenced by the portside bank only when it sails in Area 1, which means that  $d_1(x)$  is less than  $R_1$ . The starboard  
13 bank influences the vessel in a similar way. In Area 3, the vessel is not influenced by either bank.  
14



15  
16 **FIGURE 2 Waterway area division according to portside and starboard bank.**

17  
18 We add the influence of the two banks in the expected route cost as a monotonously decreasing (linear) function of  
19 the distance to the bank in the corresponding area. Running cost components  $L_3$  and  $L_4$  denote the contributions  
20 from the portside and starboard bank, respectively. They are defined as

$$L_3(t, x, v) = \begin{cases} 0, & d_1(x) > R_1 \\ \frac{R_1 - d_1(x)}{R_1}, & d_1(x) \leq R_1 \end{cases} \quad (9)$$

$$L_4(t, x, v) = \begin{cases} 0, & d_2(x) > R_2 \\ \frac{R_2 - d_2(x)}{R_2}, & d_2(x) \leq R_2 \end{cases} \quad (10)$$

21 The scaling parameters  $R_1$  and  $R_2$  are defined as

$$R_1 = [d_1(x) + d_2(x)] \cdot r_1 \quad (11)$$

$$R_2 = [d_1(x) + d_2(x)] \cdot r_2 \quad (12)$$

1 where  $r_1$  and  $r_2$  describe the percentage of the waterway width, in which both banks influence vessel behavior and  
2 contribute to the cost function.

### 3 *Sailing at a certain speed*

4 To arrive at the destination in time, it is necessary to have an appropriate speed. However, high speed means high  
5 energy consumption, which will result in high cost. Speed choice is thus a trade-off between the time remaining to  
6 sail to the destination and the energy consumption due to sailing at a certain speed. For simplicity we assume the  
7 energy consumption to be a quadratic function of the vessel speed as follows:

$$L_5(t, x, v) = \frac{1}{2} v^2 \quad (13)$$

## 8 **Modeling by dynamic programming and numerical solution**

9 To solve the route choice problem in continuous time and space, the so-called value function  $W(t, x)$  is defined as  
10 the expected minimum perceived disutility function. To solve the value function, a dynamic programming approach  
11 and a numerical solution approach are used in the model. The solution of  $W(t, x)$  describes the minimum cost to the  
12 destination for a vessel located at position  $x$  at instant  $t$ . Based on this solution, the optimal course and speed can be  
13 determined. For details, we refer to previous work (17).

## 14 **ROUTE CHOICE MODEL CALIBRATION**

15 In this section, the vessel route choice model is calibrated using AIS data. We firstly introduce the AIS data and  
16 unhindered vessel behavior, being the vessel behavior without influence of other vessels. As we discussed before,  
17 vessel encounters are considered at the operational level, but not at the tactical level. So only unhindered vessel  
18 behavior should be used to calibrate the vessel route choice model at the tactical level. Then, the calibration set-up  
19 and the objective function for calibration are described. Finally, calibration results are presented.

## 20 **AIS data and unhindered paths**

21 In our research, the class of small General Dry Cargo (GDC) vessels less than 3600 gross tonnage is used. AIS data  
22 of these vessels in the Botlek area in the Port of Rotterdam from January 2009 to April 2011 are selected. As shown  
23 in FIGURE 3, the research area is called "Sea-Nieuwe Maas", which is corresponding to vessels sailing from the  
24 Sea (in the west) to the Nieuwe Maas river (in the east). To compare lateral positions of these tracks and easily  
25 calculate the average path, 69 cross sections with intervals around 50 meters are defined in the research area. These  
26 cross sections are approximately perpendicular to the waterway axis and used to select AIS data. Endpoints of these  
27 cross sections are located at the five meters water depth line, since it is found in the data analysis that vessels will  
28 not pass the five meters depth line. For the areas without five meters water depth line, such as entrances to basins or  
29 waterway branches, endpoints are created such that the boundary remains smooth. In the model, these five meters  
30 water depth lines will form the effective waterway for vessel sailing.  
31



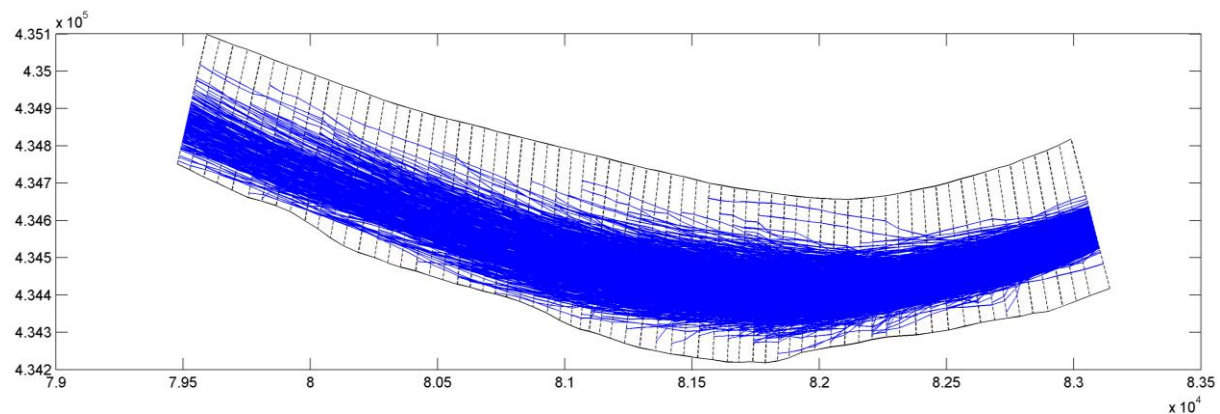
32 **FIGURE 3 Waterway of Sea-Nieuwe Maas and 69 cross sections.**  
33  
34

1 In our previous research (15), AIS data analysis provided insight into vessel behavior. It was found that  
 2 vessels deviate from their planned path when they encounter other vessels, especially during overtaking.

3 As mentioned before, vessel route choice is at the tactical level, where the influence of vessel encounters is  
 4 not considered. To eliminate the influence of vessel encounters, empirical vessel paths are classified into hindered  
 5 paths and unhindered paths according to the influence of other vessels. Here, a path is defined unhindered if the  
 6 distance to other vessels is at least 2 km, during the whole trip of the vessel. AIS data of unhindered paths are then  
 7 used for the calibration.

8 However, these unhindered paths concentrate in the right part of the waterway. To be able to estimate the  
 9 influence of the banks, more data are needed to describe the vessel route choice in the areas close to banks. To  
 10 provide more data in these areas, parts of hindered vessel paths are used. For hindered vessel paths, vessels normally  
 11 deviate from their planned path and sail into the area closer to the banks. It is assumed that the influence of other  
 12 vessels ends after the encounter. At that moment, both vessels have the largest deviation when they are closest to  
 13 each other. Hindered vessel paths after the encounter can then be considered as unhindered and used for calibration  
 14 as well. Including these, the tracks of the AIS dataset used for calibration cover most of the waterway, see FIGURE  
 15 4. In the figure, longitude and latitude coordinates are transformed into coordinates of the ‘Rijksdriehoeksstelsel’  
 16 (RD), which is the national grid of the Netherlands. This national grid is used as a basis for geographical indications  
 17 and files, such as Geographic Information Systems.

18 The definitions of the parameters of the bend waterway are given in FIGURE 1. According to bend strength  
 19  $\theta/S$ , the waterway is divided into two parts: the area from cross section 1 to cross section 42 and the area from cross  
 20 section 42 to cross section 69. Based on different bend strength, vessels in these two parts will have different  
 21 contributions to cost from the bend effect.



22  
 23 **FIGURE 4 AIS data used for vessel route choice calibration from Sea to Nieuwe Maas.**

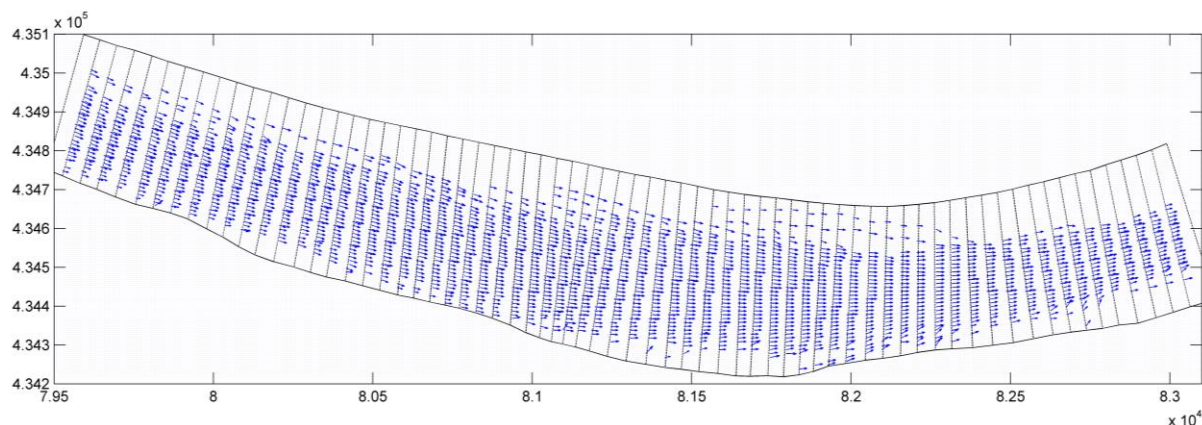
#### 24 **Calibration set-up and objective function**

25 As mentioned before, only the ratio between the weights can be determined by AIS data. Without loss of generality,  
 26 we can set  $c_1 = 1$ . Then, the parameters that need to be calibrated are in the vector  $\beta^T = (c_2, c_3, c_4, r_1, r_2, c_5)$ .

27 In our research, vessels have a two-dimensional motion including vessel speed and course. As we discussed  
 28 before, vessel speed is determined at the operational level by the bridge team according to the vessel engine power  
 29 or influence of other vessels and external influences (such as wind and visibility), but not at the tactical level.  
 30 Therefore, only vessel course is considered in the objective function in calibration of route choice model. The  
 31 calibration process aims at minimizing the difference between vessel course measured from AIS data and vessel  
 32 course predicted by the vessel route choice model.

33 As we can see in FIGURE 4, vessel paths concentrate in the right part of the waterway and they are not  
 34 uniformly distributed. Overlapping paths provide similar inputs to the calibration. To combine a lot of repetitive  
 35 inputs, a “meshgrid” of  $10\ m \times 10\ m$  is used to generate velocity field, which will be used to determine the  
 36 difference. FIGURE 5 shows the generated a velocity field based on the “meshgrid” and AIS data in FIGURE 4.  
 37 This velocity field will be used to compare with the simulated results based on route choice model.





1  
2  
3  
4 **FIGURE 5 Velocity field based on AIS data in the meshgrid of 10 m × 10 m.**

5 In the simulation model, the part of the cross section 69 (the rightmost), where 99% of the unhindered  
6 vessels pass, is defined as the destination. To use the numerical solution approach, we discretize the waterway into  
7 small 5m × 5m-cells and define the time step as 0.5 seconds. Then, the value function can be solved for the whole  
8 research area, as well as the optimal course field. As we discussed before, only vessel course is considered in the  
9 route choice model calibration. This optimal course field will be used to compare with the velocity field in FIGURE  
10 5.

11 Let  $\alpha_{data}$  denote vessel course in the velocity field in FIGURE 5. Correspondingly,  $\alpha_{sim}$  is the optimized  
12 course for the same point in the “meshgrid” calculated by the route choice model based on a given  $\beta$ . For these  $m$   
“meshgrid” points, the average square error is defined as

$$E(\beta) = \frac{1}{m} \sum_{i=1}^m (\alpha_{data} - \alpha_{sim})^2 \quad (14)$$

13 So the calibration problem becomes a multi-variable nonlinear optimization problem as following, which could be  
14 solved by the function “fminsearch” in MATLAB.

$$\beta^* = \arg \min E(\beta) \quad (15)$$

### 15 Calibration Results

16 By applying the described optimization method, the best fit of the route choice model to the AIS data is found. The  
17 calibration results are summarized in TABLE 1.

18  
19 **TABLE 1 Calibration Results for Vessel Route Choice Model**

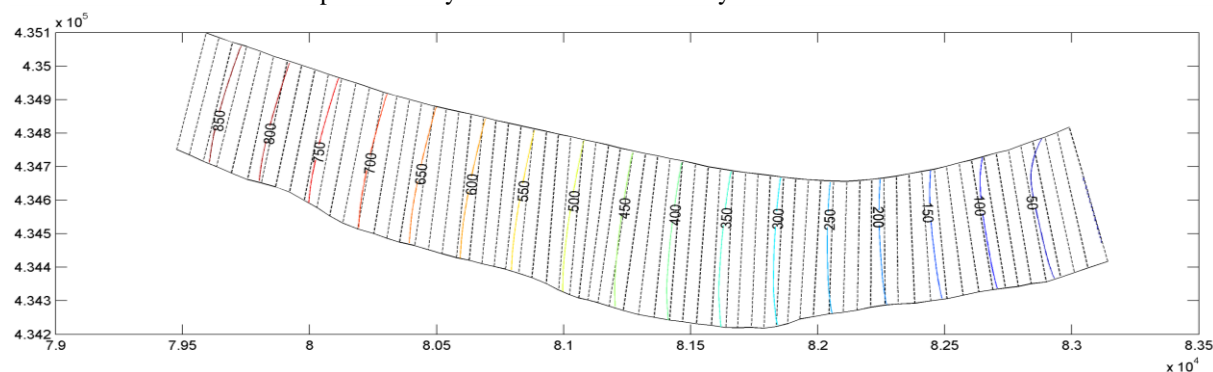
Optimized parameters	$c_2$	$c_3$	$c_4$	$r_1$	$r_2$	$c_5$
	0.0211	0.0122	0.0215	0.5414	0.2305	0.0218
Error	19.92					

20  
21 In the model, the values of parameters  $c_3$  and  $c_4$  reflect the cost when the vessel is very close to the  
22 portside bank and starboard bank.  $c_3$  and  $c_4$  also have the largest influence from both banks, since the influence of  
23 banks is a linear decreasing function of the distance to the bank in equations (9) and (10). That means that banks  
24 contribute to the cost function between 0 ~ 0.02. Compared to the contribution of sailing time (equals 1), these two  
25 values seem small, but they cannot be neglected as they provide the repulsion of both banks.

26 The parameters  $r_1$  and  $r_2$  describe the percentage of the waterway width, in which both banks contribute to  
27 the cost function. Calibration results show that portside bank have influence when the distance between the vessel  
28 and the portside bank is less than 54% of the waterway width. For the starboard bank, the influence area is 23% of  
29 the waterway width. The rest area around 23% of the waterway is the area where banks do not have influence on  
30 vessel behavior. This area could be considered as unhindered area, where the vessels will concentrate. This is  
31 corresponding to the phenomenon observed in FIGURE 4.

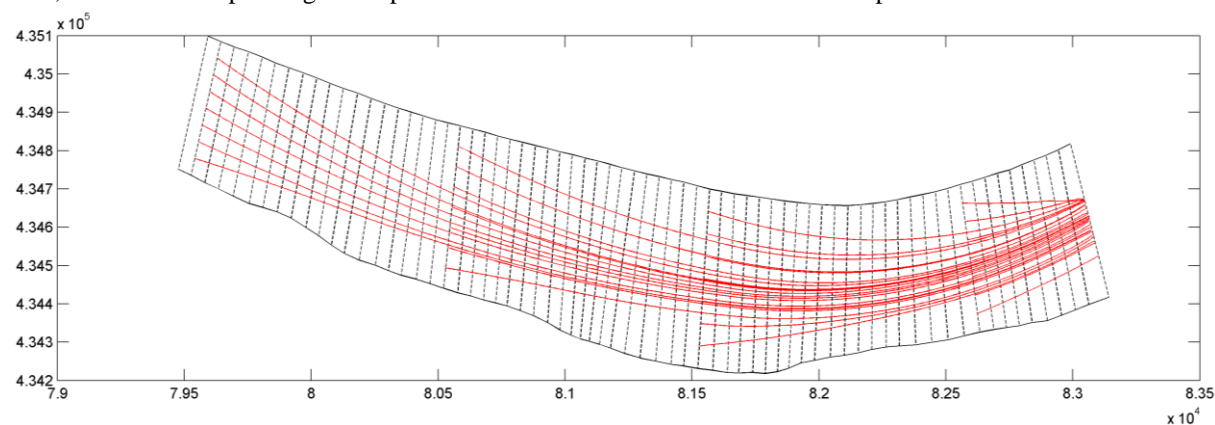
32 Applying the calibrated results shown in TABLE 1, the expected minimum disutility function is generated  
33 in the research area. The contour lines and corresponding value for this value function are shown in FIGURE 6.

1 Vessels will follow the preferred route, which is perpendicular to these contour lines. The shape of contour lines  
 2 indicates that vessels will be pushed away from the bank when they are too close to the bank.



3  
 4 **FIGURE 6 Contour lines for value function.**

5  
 6 On cross section 2, 20, 40 and 60, several example tracks of route choice are generated in FIGURE 7. It can be seen  
 7 that when vessels are too close to the bank, they will be pushed away from the bank and sail towards the unhindered  
 8 area, which is corresponding to the phenomenon in FIGURE 4 and is what we expect.



9  
 10 **FIGURE 7 Example tracks on cross sections 2, 20, 40 and 60.**

## 11 CONCLUSIONS AND RECOMMENDATIONS

12 In this paper, an approach is proposed to generate vessel route choice in continuous time and space for ports and  
 13 inland waterways. A dynamic programming approach and a numerical solution approach are used to solve the value  
 14 function, which can be used to generate optimal course and speed. Furthermore, this vessel route choice model is  
 15 calibrated based on AIS data of unhindered paths and hindered path.

16 The calibrated results show the repulsion from two banks, which is corresponding to the observation in AIS  
 17 data. The repulsion range of the portside bank is around 54% and the repulsion range of the starboard bank  
 18 approximately equals to 23%, which result in the fact that vessels concentrate in the right part of the waterway. The  
 19 results also show plausible example preferred routes in the research area, which help us to understand the desired  
 20 vessel behavior (route). In the model, the waterway geometry is input, so the route choice model is also applicable in  
 21 other parts.

22 The vessel route choice model provides the preferred routes for vessels, which could be used as a reference  
 23 guide for both the bridge team and Vessel Traffic Services (VTS), and therefore can help to improve the waterway  
 24 traffic management. In addition, the preferred routes generate by the route choice model could be used to indicate  
 25 the dangerous area for vessels, considering the maneuverability of vessels. Thus, in decision-making level, the  
 26 model is able to be used to control the vessel traffic, design new ports or extend existing ports and inland waterways.

27 Suggestions for future research are the inclusion of cost of other infrastructural elements in the route choice,  
 28 such as dams and jetties. This way, the actual sailing environment will be reflected in the model and make the model  
 29 generic. In addition, AIS data sets from other areas and in other sailing directions will be used to calibrate and  
 30 validate the model.

1 Furthermore, the vessel route choice model will serve as input to the maneuvering model at the operational  
2 level. Both route choice model and maneuvering model form the new maritime traffic model, which describes  
3 maritime traffic by predicting single vessel behavior.

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