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

Shu, Y; Daamen, W; Ligteringen, H; Hoogendoorn, SP

Publication date
2016

Document Version
Accepted author manuscript

Published in
Proceedings of the Transportation Research Board 95th annual meeting

Citation (APA)
Shu, Y., Daamen, W., Ligteringen, H., & Hoogendoorn, SP. (2016). Verification of the route choice model and the operational model of vessel traffic. In s.n. (Ed.), *Proceedings of the Transportation Research Board 95th annual meeting* (pp. 1-14). Transportation Research Board (TRB).

VERIFICATION OF THE ROUTE CHOICE MODEL AND THE OPERATIONAL MODEL OF VESSEL TRAFFIC

Yaqing Shu, Corresponding Author
Department of Transport & Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, PO Box 5048, 2600 GA Delft – The Netherlands
Phone +31 15 278 76 90
Fax +31 15 278 31 79
e-mail y.shu@tudelft.nl

Winnie Daamen
Department of Transport & Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, PO Box 5048, 2600 GA Delft – The Netherlands
Phone +31 15 278 59 27
Fax +31 15 278 31 79
e-mail w.daamen@tudelft.nl

Han Ligteringen
Department of Hydraulic Engineering
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, PO Box 5048, 2600 GA Delft – The Netherlands
Phone +31 15 278 42 85
Fax +31 15 278 31 79
e-mail h.ligteringen@tudelft.nl

Serge Hoogendoorn
Department of Transport & Planning
Faculty of Civil Engineering and Geosciences
Delft University of Technology
Stevinweg 1, PO Box 5048, 2600 GA Delft – The Netherlands
Phone +31 15 278 54 75
Fax +31 15 278 31 79
e-mail s.p.hoogendoorn@tudelft.nl

Word count: 4,531 words text + 8 tables/figures x 250 words (each) = 6,531 words

15/11/2015

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

INTRODUCTION

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

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

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

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

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

MARITIME TRAFFIC CONTROL FRAMEWORK

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

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

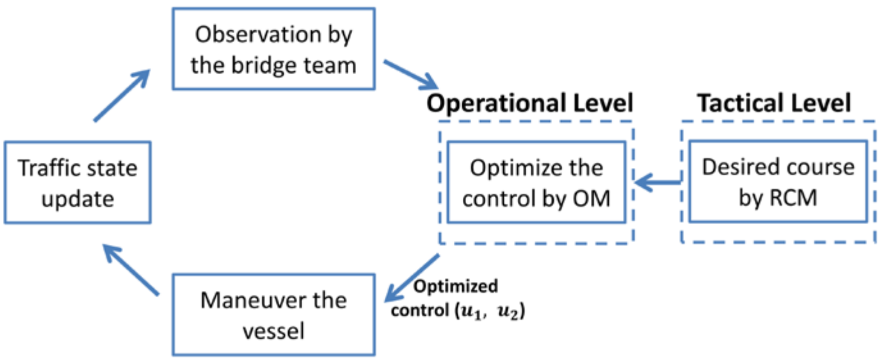

FIGURE 1 Maritime traffic control framework.

THE OPERATIONAL MODEL

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

System dynamics

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

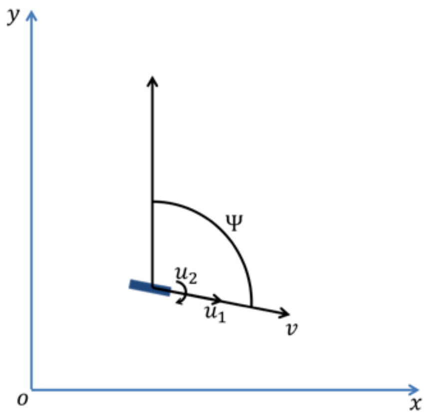

FIGURE 2 Vessel coordinate system and control.

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

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

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

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

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

Model by optimal control

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

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

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

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.

The control objective function J is defined by:

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

where H is the prediction horizon used when making a decision at time instant t, L denotes the running cost (cost incurred in a small time interval $[\tau, \tau + \mathrm{d}\tau)$), $\vec{u} = (u_1, u_2)$ denotes the control, and Φ denotes the terminal costs at terminal conditions, which is the cost that is incurred when the vessel ends up with the state $\vec{\xi}(t+H)$ at time instant $t+H$.

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

- Straying from the desired speed and course costs expressed by

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

- Maneuvering costs, indicated by

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

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

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

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

subject to Eq. (1-4).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

CASE STUDY

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

Set-up

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

Scenario introduction

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

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

We investigate the vessels sailing from the North Sea to the berth, which is the direction from upper left to the bottom part in Figure 3. In this direction, 307 vessel paths from AIS data from the North Sea to the Maasvlakte I are available for the case study. These paths are shown on the left-hand side of Figure 5. It should be noted that the vessel paths spread much wider in the end of the trip, because vessels are very close to the basin and they prepare to enter the basin, which is at the left bottom on the left-hand side of Figure 3. Although most vessels sail bow-first into the basin, some vessels have to sail stern-first and turn around in the basin. Through this maneuver, these ships exceed the boundary, as can be seen in Figure 5. In this paper, we do not consider these inconsistencies, which are the preparation for mooring (entering the basin).

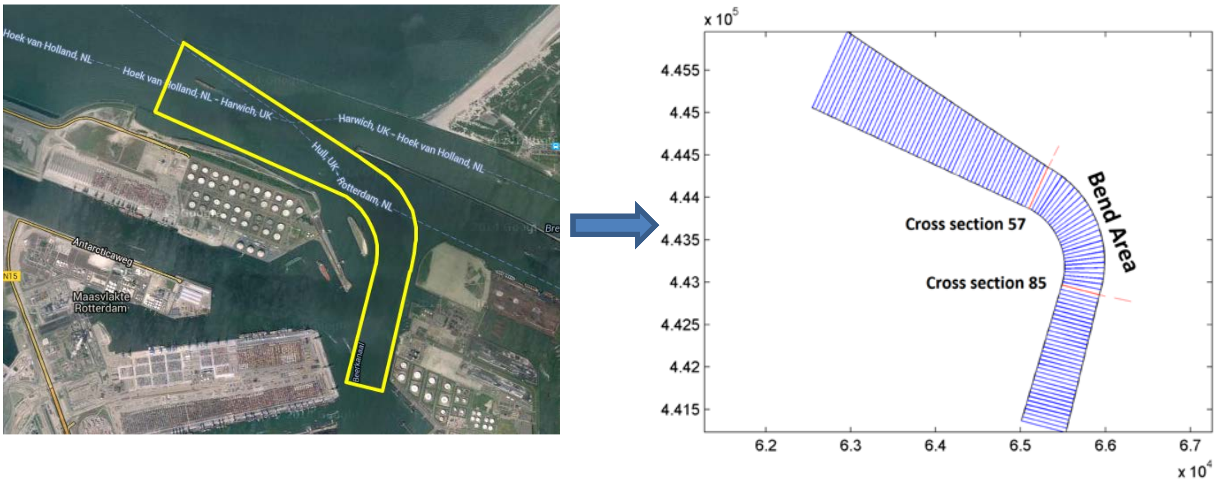

FIGURE 3 Converting the research area geometry to RD coordinates and cross sections.

Optimized parameters

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

TABLE 1 Optimized parameters for the route choice model and the operational model

Route choice model	**Parameters**	c_4	c_5	r_1	r_2
	Optimized results	0.0199	0.0123	0.45	0.254
Operational model	**Parameters**	c_2^v	c_2^ψ	c_3^v	c_3^ψ
	Optimized results	1.00	7.99	33.6	393.41

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

Desired course by the route choice model

To apply the dynamic programming approach and the numerical solution approach, the research area is discretized into 5 × 5 meters grid. Based on the optimized parameters in Table 1, the desired course in continuous space is generated by the route choice model in each cell formulated by the grid. The desired course is shown in Figure 4, where the arrow in each cell indicates the desired course and forms the so-called desired course field for vessel sailing from the upper left to the bottom of the figure. In this course field, it can be found that when the vessel is close to the bank, she will be repelled from the bank. The vessel will also smoothly follow the bend. This desired course is plausible and corresponds to the AIS data analysis.

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

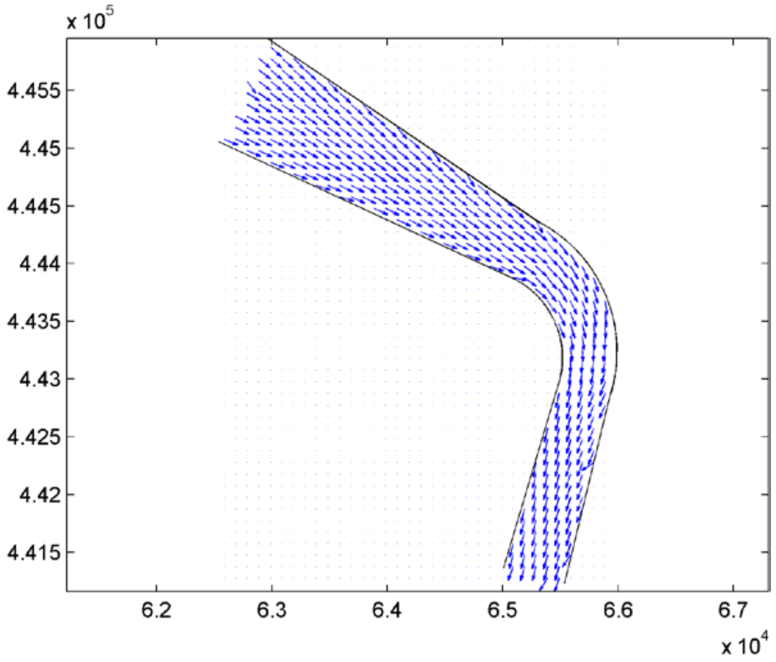

FIGURE 4 Desired course in continuous space by the route choice model.

Desired speed

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

Application of the operational model

We have calibrated the route choice model and the operational model based on AIS data of small General Dry Cargo (GDC) vessels *(11)*. In the available AIS data for this case study, the vessels are classified by the vessel deadweight tonnage (dwt). We have chosen to only model the vessels in the category ‘Smaller than 10,000 dwt’, which corresponds best to the vessel category for which we calibrated the model.

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

Results comparison and discussion

Vessel path

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

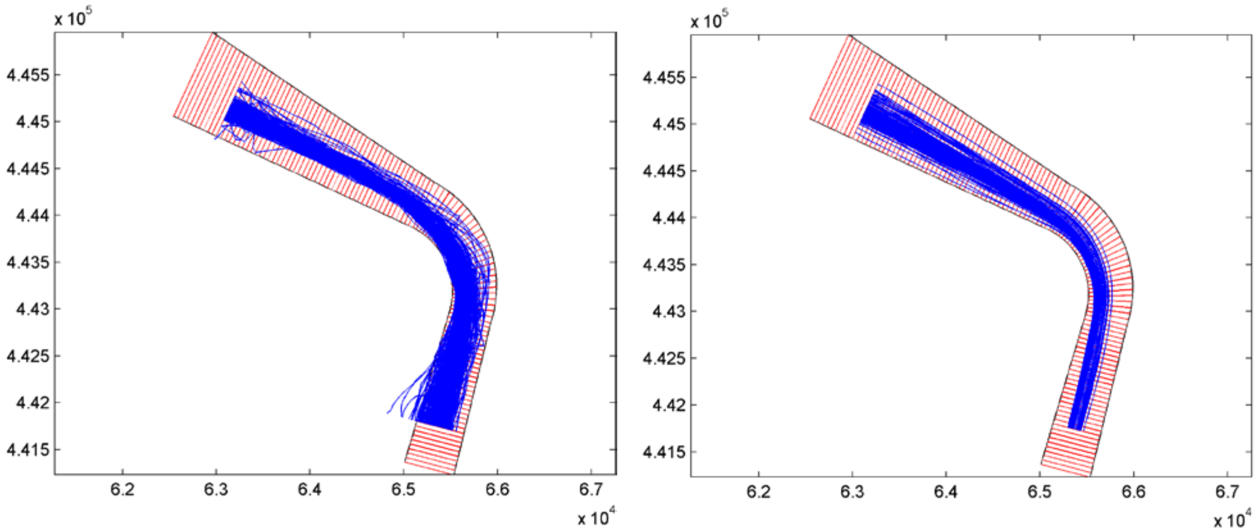

FIGURE 5 Real paths from AIS data (left) and simulated vessel paths (right).

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

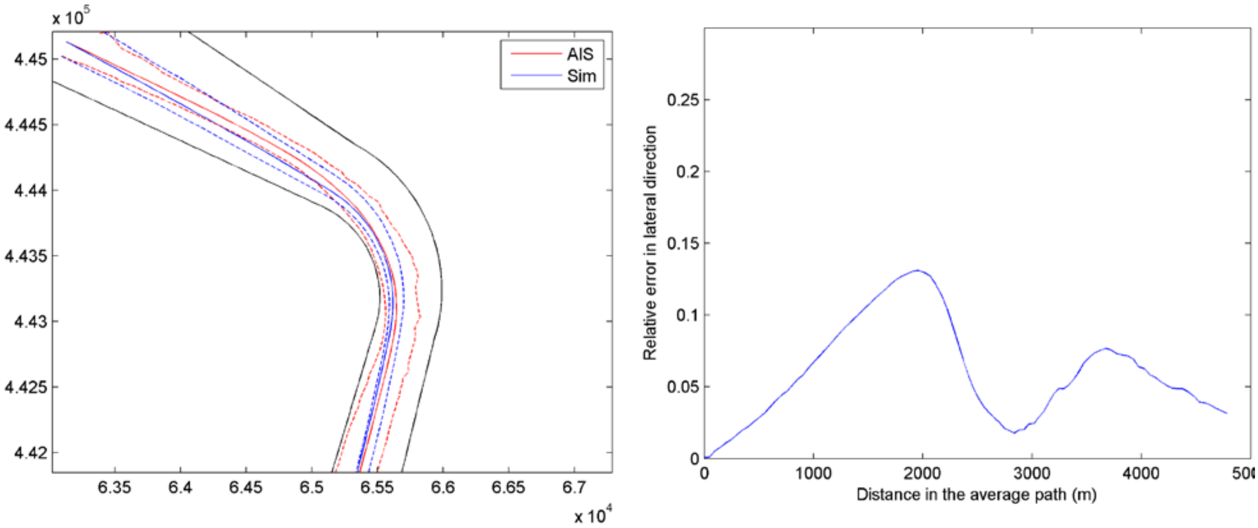

FIGURE 6 Average vessel path (solid lines) and their 95% confidence interval (dotted lines) comparison between AIS data and simulation results, and relative error in lateral direction.

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

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

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

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

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

Then the *RMSD* represents the mean relative error in the lateral direction. By applying Eq. (18), the value of *RMSD* is 6%. That means the average relative error in the lateral direction is 6 percent. This difference may be introduced by both the route choice model and the operational model. It was believed that the most of error can be attributed to the optimized parameters that were applied to generate the desire course in the route choice model, as these optimized parameters were achieved in a different situation than the case study situation. The rest of the error may be introduced by the operational model, as the factors influencing the vessel path, such as the interaction with other vessels and the influence of external conditions, have not been considered in the model at this stage.

Vessel course

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

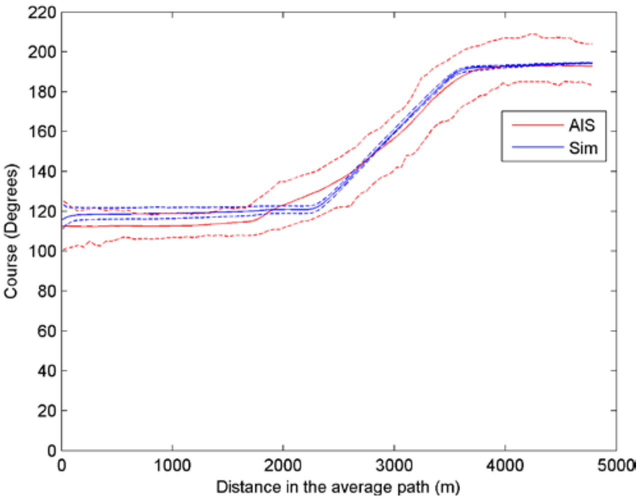

FIGURE 7 Average vessel course (solid lines) and their 95% confidence interval (dotted lines) comparison between AIS data and simulation results.

The *RMSD* for vessel course is defined by:

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

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

CONCLUSIONS AND RECOMMENDATIONS

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

In this case study, the desired course generated by the calibrated route choice model corresponds to the AIS data analysis: when the vessel is close to the bank, she will be repelled from the bank. The vessel will also smoothly follow the bend. Together with the desired course, the desired speed based on historical data serves as the inputs into the operational model. The parameters found in a previous calibration effort are used to predict vessel behavior in the research area. The generated paths by the operational model are concentrated on the right hand side of the waterway, which corresponds to the AIS data analysis.

Furthermore, we compared the vessel path and vessel course between the AIS data and simulation results using RMSD. The results show a good prediction on vessel path (6% relative difference in lateral direction) and vessel course (3.68 degrees). These errors may be attributed to the optimized parameters, which are achieved in a different situation than the case study situation. In addition, the factors (such as external conditions and vessel encounters) may also have contribution to the error, since they have not yet been included in the model at this stage. 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.

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

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

ACKNOWLEDGEMENT

This research is part of the research program “Nautical traffic model based design and assessment of safe and efficient ports and waterways”, sponsored by the Netherlands Organization for Scientific Research (NWO). The authors would like to thank Thijs de Boer and MARIN for providing AIS data. The fellowship of Yaqing Shu at Delft University of Technology is supported by the Chinese Scholarship Council (CSC).

REFERENCES

1 . Degre, T., C. Glansdorp, and C. van der Tak. The importance of a risk based index for vessels to enhance maritime safety. In *the 10th IFAC Symposium on Control in Transportation Systems*, Tokyo, Japan, 2003.

2 . Fowler, T.G. and E. Sørgård. Modeling ship transportation risk. *Risk Analysis*, Vol. 20, No. 2, 2000, pp. 225-244.

3 . Pedersen, P.T. Collision and grounding mechanics. In *WEMT*, Copenhagen, 1995.

4 . Sariöz, K. and E. Narli. Assessment of manoeuvring performance of large tankers in restricted waterways: a real-time simulation approach. *Ocean engineering*, Vol. 30, No. 12, 2003, pp. 1535-1551.
5 . Sutulo, S., L. Moreira, and C. Guedes Soares. Mathematical models for ship path prediction in manoeuvring simulation systems. *Ocean engineering*, Vol. 29, No. 1, 2002, pp. 1-19.
6 . Yoon, H.K. and K.P. Rhee. Identification of hydrodynamic coefficients in ship maneuvering equations of motion by Estimation-Before-Modeling technique. *Ocean Engineering*, Vol. 30, No. 18, 2003, pp. 2379-2404.
7 . Hsu, C.-I. and Y.-P. Hsieh. Routing, ship size, and sailing frequency decision-making for a maritime hub-and-spoke container network. *Mathematical and Computer Modelling*, Vol. 45, No. 7, 2007, pp. 899-916.
8 . Norstad, I., K. Fagerholt, and G. Laporte. Tramp ship routing and scheduling with speed optimization. *Transportation Research Part C: Emerging Technologies*, Vol. 19, No. 5, 2011, pp. 853-865.
9 . Kosmas, O. and D. Vlachos. Simulated annealing for optimal ship routing. *Computers & Operations Research*, Vol. 39, No. 3, 2012, pp. 576-581.
10 . Hoogendoorn, S., W. Daamen, Y. Shu, and H. Ligteringen. Modeling human behavior in vessel maneuver simulation by optimal control and game theory. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. No. 2326, 2013, pp. 45-53.
11 . Shu, Y., W. Daamen, H. Ligteringen, and S. Hoogendoorn. Vessel Speed, Course, and Path Analysis in the Botlek Area of the Port of Rotterdam, Netherlands. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. No. 2330, 2013, pp. 63-72.
12 . Shu, Y., W. Daamen, H. Ligteringen, and S. Hoogendoorn. Vessel route choice theory and modeling. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. No. 2479, 2015, pp. 9-15.
13 . Shu, Y., W. Daamen, H. Ligteringen, and S. Hoogendoorn. Vessel route choice model by optimal control and calibration. In *IWNTM 2014: International Workshop on Nautical Traffic Models, Wuhan, China*, 2014.
14 . Aarsæther, K.G. and T. Moan. Estimating navigation patterns from AIS. *Journal of Navigation*, Vol. 62, No. 04, 2009, pp. 587-607.
15 . Mou, J.M., C.v.d. Tak, and H. Ligteringen. Study on collision avoidance in busy waterways by using AIS data. *Ocean Engineering*, Vol. 37, No. 5, 2010, pp. 483-490.
16 . Fleming, W.H., H.M. Soner, and H.M. Soner. *Controlled Markov processes and viscosity solutions*. Springer, 2006.
17 . Hoogendoorn, S., R. Hoogendoorn, M. Wang, and W. Daamen. Driver, driver support, and cooperative systems modeling by dynamic optimal control. *Transportation Research Record: Journal of the Transportation Research Board (2316)*, Vol. No. 2012, pp. 20-30.
18 . Shu, Y., W. Daamen, H. Ligteringen, and S. Hoogendoorn. Operational model for vessel traffic using optimal control and calibration. In *IWNTM 2015: International Workshop on Nautical Traffic Models*, Espoo, Finland, 2015.
19 . De Boer, T. *Application of AIS data in a nautical traffic model*. Master Thesis, Delft University of Technology, the Netherlands, 2010.