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"Living without an aim is like sailing without a compass."

(生活没有目标，犹如航海没有罗盘.)

John Ruskin

Summary

Modeling is a promising approach to understand and predict the safety and efficiency of maritime traffic in ports and waterways. Different types of models have been developed over the years. Nevertheless, several important scientific challenges still remain. For instance, few models consider vessel behavior in ports and waterways under the influence of internal factors including vessel type and size, and external factors, such as wind and visibility. More data and research are needed to understand the influence of internal and external factors on vessel behavior including speed, course and path in ports and waterways; more research is also needed to explore human behavior of the bridge team for vessel maneuvering in ports and waterways. To address the needs listed, this thesis focuses on analyzing the influence of wind, visibility, current and vessel encounters on vessel speed, course and path using Automatic Identification System (AIS) data. Based on this analysis a new maritime traffic model has been developed that considers both internal and external factors, and aims to better predict the individual vessel behavior. The model can be used to provide data for the safety and efficiency assessment of vessel traffic in ports and inland waterways.

In the last decades, the AIS system, which is an onboard autonomous and continuous broadcast system that transmits vessel data between nearby vessels and shore stations, has been developed. This is used now by almost all vessels. Therefore, AIS data, including vessel speed, course and path, can serve as a valuable data source to investigate vessel behavior. In this thesis, AIS data from a part of the port of Rotterdam is analyzed to investigate influences of different factors, such as vessel size and type, external conditions and vessel encounters, on vessel behavior. Firstly, vessels are distinguished into influenced and unhindered vessels based on certain thresholds that we obtained from the AIS data. The influenced vessel behavior is compared with the behavior of unhindered vessels, which are not influenced by other vessels or strong external influences of wind, visibility and current. The analysis provides evidence showing that the vessel behavior including vessel speed, course and path is influenced by various factors. Ship speed and path is influenced by internal factors (including vessel type, size, waterway geometry and navigation direction) and external factors (including wind, visibility, current, overtaking and head-on encounters), while ship course is only influenced by overtaking and head-on encounters. It can also be concluded that the AIS data is a useful source to get insights into vessel behavior.

To develop a new maritime traffic model, the optimal control theory is used, which was successfully applied to describe pedestrian and vehicle traffic. In this thesis, the use of optimal control for maritime traffic is motivated by similarities between vessels and pedestrians, such as the fact that both choose a certain route in two-dimensional space and will adapt the actual

path and speed depending on external circumstances. In this approach, vessel behavior is separated into a tactical and an operational level. The new maritime traffic model comprises one model at each level, which are called the route choice (RC) model and the vessel maneuvering prediction (VMP) model. The tactical level includes the RC model, in which it is assumed that the bridge team follows a preferred route corresponding to the minimized cost. This cost in optimal control theory is formulated based on the characteristics of each route, including expected sailing time, distance to the bank, waterway bend effect and sailing speed. The output of the RC model is the desired course, representing the optimal course with a minimized cost to the predefined destination, when the vessel is not influenced by other vessels or external conditions (e.g. current, wave, wind). Therefore, the desired course is used to generate the optimal route, and is input into vessel behavior at the operational level. The VMP model calculates the dynamics of the vessel sailing behavior, described by the longitudinal acceleration and turning of the vessel. In the VMP model a trade-off is made between following the desired course, minimizing the maneuvering effort and keeping a safe distance to other vessels. To this end, the cost includes the deviation from the desired course, acceleration (or turning) and proximity to other vessels, respectively. Similar to the RC model, the cost needs to be minimized.

In this thesis, both the RC model and the VMP model are calibrated using AIS data. The aim of the calibration is to find the model parameters that result in the best prediction of the model, compared to AIS data. Because RC model is used to simulate the unhindered vessel behavior, the AIS data of unhindered vessel behavior is used for the calibration purpose. The objective function is formulated based on the difference between the optimal route and the real path from AIS data of unhindered vessels. For the VMP model, the calibration is carried out using AIS data of overtaking vessels. The assumption is made that the model describes general vessel behavior, thus the parameters determined by this calibration are also applicable for overtaken vessels and vessels in head-on encounters. The use of overtaking vessels is also motivated by the fact that the overtaking vessels normally have a larger deviation from their desired speed and path.

In the case study, the new maritime traffic model with calibrated parameters has been applied in another part of the port of Rotterdam to predict individual vessel behavior (path, speed, and course). Compared to the real path from AIS data, the simulation results showed a good prediction of the vessel path: root-mean-square deviation of 6% relative difference in lateral direction and 3.68° for vessel course.

The new traffic model will have important implications for practice. It may support the port authority in the assessment of the safety and capacity of existing harbor channels, to improve the maneuvering of the bridge team, to assist in the design of new channels or the improvement of existing channels and in the design and evaluation of new port lay-outs with respect to capacity and safety.

Several recommendations for future research are proposed. Firstly, although many external factors showed strong influence on vessel behavior according to the data analysis, not all of these factors have been considered in the present model, such as wind and current. Secondly, this thesis has only investigated one vessel category in detail, future research shall expand it to

include different vessel categories. Finally, the present model can be extended to derive the desired speed and be simultaneously applied for multiple vessels without fundamental change.

Samenvatting

Het gebruik van modellen blijkt een kansrijke aanpak te zijn om de veiligheid en de efficiëntie van maritiem verkeer in havens en vaarwegen te begrijpen en te voorspellen. Er zijn verschillende soorten modellen door de jaren heen ontwikkeld. Desondanks bestaan er nog voldoende wetenschappelijke uitdagingen. Weinig modellen beschouwen bijvoorbeeld het scheepsgedrag in havens en vaarwegen onder invloed van interne factoren, zoals scheepstype en -afmetingen, en externe factoren, zoals wind en zichtafstand. Meer data en onderzoek zijn nodig om inzicht te krijgen in de invloed van deze interne en externe factoren op het scheepsgedrag op basis van variabelen als vaartuigsnelheid, koers en vaarroutes. Ook is er meer onderzoek nodig om het menselijk gedrag van de stuurman te onderzoeken en met name zijn invloed op het manoeuvreren van schepen in havens en vaarwegen. Om deze kennishiaten aan te pakken richt dit proefschrift op het analyseren van de invloed van wind, zichtafstand, waterstromingen en interacties van schepen op vaartuigsnelheid, koers en vaarroute met behulp van Automatic Identification System (AIS) data. Op basis van deze analyses is een nieuw maritiem verkeersmodel ontwikkeld dat rekening houdt met zowel interne als externe factoren en beoogt het gedrag van individuele schepen beter te voorspellen. Het model kan worden gebruikt om informatie te leveren voor de evalueren van de veiligheid en de efficiëntie van het scheepvaartverkeer in havens en binnenwateren.

In de laatste decennia is het AIS-systeem ontwikkeld: een autonoom en continu zendsysteem aan boord van schepen dat scheepsgegevens verzendt aan nabijgelegen schepen en walstations. Tegenwoordig wordt dit door bijna alle schepen (verplicht) gebruikt, zodat AIS-data, waaronder vaartuigsnelheid, koers en route, kunnen dienen als een waardevolle gegevensbron om het scheepsgedrag te onderzoeken. In dit proefschrift worden AIS-data uit een deel van de Rotterdamse haven geanalyseerd om de invloeden van verschillende factoren, zoals de afmetingen en het scheepstype, de externe omstandigheden en de interactie met andere vaartuigen, op het scheepsgedrag te onderzoeken.

Ten eerste wordt onderscheid gemaakt tussen schepen die beïnvloed zijn door hun omgeving (bijvoorbeeld andere schepen en wind) en ongehinderde schepen. Dit wordt gedaan op basis van drempelwaarden die we hebben verkregen uit de AIS-data. Het beïnvloede vaargedrag wordt vergeleken met het gedrag van ongehinderde schepen. De analyses tonen aan dat de snelheid en de vaarroute van het schip worden beïnvloed door interne factoren (scheepstype, afmetingen, waterweggeometrie en navigatie-richting) en externe factoren (waaronder wind, zichtafstand, waterstromingen, inhaalmanoeuvres en directe confrontaties), terwijl de koers van het schip alleen wordt beïnvloed door inhaalmanoeuvres en frontale ontmoetingen. In het algemeen kan ook worden geconcludeerd dat de AIS-gegevens een nuttige bron zijn om inzicht te krijgen in het scheepsgedrag.

Om een nieuw maritiem verkeersmodel te ontwikkelen wordt optimal control theorie gebruikt, die al eerder met succes is toegepast om voetgangers- en wegverkeer te beschrijven. Het gebruik van optimal control in dit proefschrift voor maritiem verkeer wordt gemotiveerd door de overeenkomsten tussen het gedrag van schepen en voetgangers, zoals het feit dat beide een bepaalde route kiezen in een tweedimensionale ruimte en dat ze hun daadwerkelijke route en snelheid aanpassen aan de externe omstandigheden. In deze nieuwe benadering wordt het scheepsgedrag gescheiden in een tactisch en een operationeel niveau. Het nieuwe maritieme verkeersmodel bevat het routekeuze-model (tactisch niveau) en het manoeuvre-model (operationeel niveau). In het routekeuze-model wordt aangenomen dat de stuurman een voorkeursroute volgt met zogenaamde geminimaliseerde kosten. Deze kosten worden in optimal control theorie geformuleerd op basis van de kenmerken van elke route, waaronder verwachte vaartijd, afstand tot de oever, effect van bochten in de waterweg en gewenste vaarsnelheid. De uitvoer van het routekeuze-model is de gewenste koers: de optimale koers met geminimaliseerde kosten voor de vooraf gedefinieerde bestemming, wanneer het vaartuig niet wordt beïnvloed door andere vaartuigen of externe omstandigheden. Deze gewenste koers is invoer voor het manoeuvre-model dat het scheepsgedrag op operationeel niveau beschrijft. Het manoeuvre-model berekent de dynamiek van het vaargedrag, beschreven door de longitudinale versnelling en het draaien van het vaartuig. In het manoeuvre-model wordt een afweging gemaakt tussen het volgen van de gewenste koers, het minimaliseren van de manoeuvreerinspanning en het houden van een veilige afstand tot andere schepen. De kosten bevatten daarom respectievelijk de afwijking van de gewenste koers, versnelling (of draaiing) en de nabijheid tot andere schepen. Net als bij het routekeuze-model moeten de kosten worden geminimaliseerd om het optimale vaargedrag te kunnen berekenen.

In dit proefschrift zijn zowel het routekeuze-model als het manoeuvre-model gekalibreerd met behulp van AIS-data. Het doel van de kalibratie is om waarden voor de modelparameters te vinden waarmee de simulatieresultaten de AIS-data, en dus de werkelijkheid, zo goed mogelijk benaderen. Voor het kalibreren van het routekeuze-model wordt gebruik gemaakt van de AIS-data van ongehinderde schepen. De doelfunctie is gebaseerd op het verschil tussen de optimale route en de daadwerkelijk gevaren route op basis van AIS-data van ongehinderde schepen. Voor het manoeuvre-model wordt de kalibratie uitgevoerd met AIS-data van inhalende vaartuigen. Er wordt verondersteld dat het model generiek vaartuiggedrag beschrijft. Dat wil zeggen dat de parameters die voor deze kalibratie worden gebruikt, ook het gedrag van ingehaalde schepen en schepen in directe conflictsituaties beschrijven. Bovendien is het voor de kalibratie van het manoeuvre-model nodig om een versnelling te berekenen, die optreedt wanneer schepen een afwijking hebben van hun gewenste snelheid en pad, hetgeen geldt voor inhalende vaartuigen, maar niet voor ongehinderde schepen.

In een case study is het nieuwe maritieme verkeersmodel met gekalibreerde parameters toegepast in een ander deel van de haven van Rotterdam om individueel scheepsgedrag (route, snelheid en koers) te voorspellen. De simulatieresultaten tonen een goede voorspelling van de vaartuigroute in vergelijking met de route uit de AIS-data: een kwadratisch-gemiddelde afwijking van 6% relatief verschil in laterale richting en 3,68° voor de koers van het vaartuig.

Het nieuwe verkeersmodel kan belangrijke implicaties hebben voor de praktijk. Het model kan het havenbedrijf ondersteunen bij de beoordeling van de veiligheid en capaciteit van bestaande havengeulen, manoeuvres door de stuurman helpen verbeteren, helpen bij het ontwerpen van nieuwe vaarwegen of het verbeteren van bestaande vaarwegen en bij het ontwerp en de evaluatie van nieuwe havenconfiguraties met betrekking tot capaciteit en veiligheid.

Hoewel dit onderzoek aantoont dat veel externe factoren, zoals wind en waterstromingen, een sterke invloed hebben op het scheepsgedrag, zijn niet al deze factoren in het huidige model opgenomen. Ten tweede is er in dit proefschrift slechts één categorie schepen in detail onderzocht. In toekomstig onderzoek zal dit moeten worden uitgebreid naar verschillende categorieën. Ten slotte kan het huidige model worden uitgebreid met een generiek model voor het bepalen van de gewenste snelheid (nu wordt daar historische data voor gebruikt) en tegelijkertijd worden toegepast voor meerdere schepen.

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C	Expected disutility (cost)
c_k	Weight factors in running cost in the route choice model, with $k = 1, 2, \ldots$
D_t	Width of the waterway on cross section t
$d_1(x)$	Distance to the portside bank
$d_2(x)$	Distance to the starboard bank
d_{cv}	Distance to the convex bank
H	Prediction horizon in the VMP model
L	Running cost
L_k	Running cost contributed by different factors in the route choice model, with $k = 1, 2, \ldots$
L^{effort}	The propulsion and steering costs in the VMP model
L^{prox}	The proximity costs in the VMP model
L^{stray}	The straying costs in the VMP model
N_a	The number of accident candidates
P	Collision frequency
P_c	Causation probability
p_r	The percentage of cross sections, on which the null hypothesis of K-S test is rejected
p	Scaling coefficient of semi-major axis for the elliptical influence area
q	Scaling coefficient of semi-minor axis for the elliptical influence area
R	Scaling parameter in the VMP model
R_1	Influence range of portside bank
R_2	Influence range of starboard bank
r_1	Influence range of portside bank in percentage of the waterway width
r_2	Influence range of starboard bank in percentage of the waterway width
S	Average arc length for the bend area in the route choice model
t_0	Current time
t_t	Terminal time
u_1	Longitudinal acceleration
u_2	Angular speed
v	Vessel's speed
$v^0(\vec{x})$	Desired speed
$W(t,x)$	Value function

x_0	Current vessel position
$x(t)$	Vessel position at instant *t*
$\vec{x}_{data}$	Vessel position from AIS data
$\vec{x}_{sim}$	Vessel position by model simulation
θ	The change of waterway direction before the bend and after the bend in the route choice model
ϕ	Terminal cost
ψ	Vessel course
$\psi^0(\vec{x})$	Desired course
$\vec{\lambda}$	Shadow cost or co-state

List of Abbreviations

AIS	Automatic Identification System
APE	Absolute Percentage Error
COG	Course over ground
CPA	Closest Point of Approach
DOF	Degrees Of Freedom
ETA	Event tree analysis
FSA	Formal Safety Assessment
FTM	Fast Time Maneuvering
FTT	Fast Time Traffic
IMO	International Maritime Organization
GDC	General Dry Cargo
GT	Gross tonnage
LNG	Liquefied Natural Gas
MAPE	Mean Absolute Percentage Error
MMSI	Maritime Mobile Service Identity
MRA	Maritime Risk Assessment
MTS	Maritime Transport System
OM	Operational model
RCM	Route choice model
RMSD	Root-mean-square deviation
RoRo	Roll-on-roll-off
RTS	Real Time Simulation
SOG	Speed over ground
SOLAS	Safety of Life at Sea
VHF	Very High Frequency
VMP	Vessel Maneuvering Prediction
VTS	Vessel Traffic Service

Chapter 1

Introduction

Nowadays, maritime transportation is an essential part of the international trade all over the world. International shipping is carrying around 90% of world trade. With the expansion of maritime traffic, the number of vessels has sharply increased in last decades and more than 90,000 vessels are in operation by 2018 (Nations, 2018). The increased maritime traffic draws more and more concern about the balance between safety and capacity of the maritime traffic: when measures are taken to increase capacity, usually the safety decreases, and vice versa. While pursuing higher capacity for ports and waterways, accidents, especially collisions between vessels or between vessels and infrastructures, are more likely to occur.

The conflict between safety and capacity holds even stronger for ports and inland waterways. Vessels are restricted by banks, shallow waters and other facilities in these areas, which result to the high density of traffic. The high density of vessel traffic is one of the main reason accounting for maritime traffic accidents (Mazaheri et al., 2015; Mullai et al., 2011). In addition, the possible serious consequences of maritime traffic accidents are critical in these areas, such as personal and property losses, traffic congestion and environmental influences both in the water and in the surroundings (Heij et al., 2011). The risk assessment showed that the collision, grounding and fires are the most frequent accidents in maritime traffic all over the world (Soares & Teixeira, 2001). For constrained water areas with high traffic density, such as the Gulf of Finland (Kujala et al., 2009) and the Singapore Strait (Qu et al., 2011), the collision and grounding are the most significant risks for maritime traffic. In recent years, one of the well-known examples of a maritime traffic accident is the Sewol ferry disaster in South Korea, in which 304 people were killed (BBC, 2014). The causal analysis of the accident shows that the main reason is the inappropriate maneuvering (sudden turning) by the bridge team (Kim et al., 2016). Another example is the sinking of Dongfang Zhi Xing, a river cruise ship, in which more than 400 people were killed (CNN, 2015). This maritime disaster happened under heavy storms and the strange vessel path revealed that the vessel was out of the control by the bridge team. Although the accident rate per ship per year decreases (Eliopoulou et al., 2007), the number of ship accidents per year generally increases, as the number of vessels increases significantly (Eliopoulou et al., 2013; Eliopoulou et al., 2016). The balance between safety and capacity attracts concerns not only for existing ports area, but also for the new port designs, existing port expansion (Almaz & Altiok, 2012; Dragović et al., 2014) and channel closure, which means the channel is closed due to constructing a new bridge over the waterway (Rahimikelarijani et al., 2018). Therefore, it is important to develop an effective tool to predict the behavior of ships in busy waterways, in order to assess the traffic safety in relation to the capacity.

1.1 Existing maritime models

Many models have been developed to investigate maritime traffic. In this section, an overview of existing maritime models is provided. Some of existing maritime traffic models are used to simulate vessel behavior, while others focus on risk assessment of maritime traffic. In general, these simulation models can be categorized into four groups: Real Time Simulation (RTS) models, Fast Time Maneuvering (FTM) models, Fast Time Traffic (FTT) models and Maritime Risk Assessment (MRA) models (Li et al., 2012). The RTS models work in real time and they are used in a vessel simulator for research or training purpose, during which a human bridge team takes part in the maneuvering of the ship (Lataire et al., 2018). Both the FTM and the FTT models work in fast time. The FTM models focus on simulating a single vessel path taking into account vessel speed, course and hydrodynamics, while the FTT models normally are use to simulate vessel traffic under certain condition without going into details of individual vessel maneuvering and behavior. The MRA models are used to investigate the risk of maritime traffic, involving more ships. In this section, these four groups of models are introduced in detail.

1.1.1 Real Time Simulation models

The RTS models focus on the behavior of a single vessel, i.e. speed and course. They are used by computer-aided real time simulators, which include either large and expensive visual components or cheap visual equipment, such as bird’s eye view. These visual conponents are not used by other types of simulation models. As humans (the bridge team) are involved in the maneuvering of the ship, the simulators need to work in real time. Besides the own vessel movement, the real time simulators are able to generate visual environment and transfer the commands from the bridge team to the computer system. The own vessel movement and visual environment are generated based on three types of technology: hydrodynamic model of ship movements, large-scale 3D visual projection aided by visual software and man-machine interfaces (Xiao, 2014).

The hydrodynamic model is usually based on a set of equations of motion of a rigid body. As we know, vessel dynamic movement is very complicated. It is a result of hydrodynamics, hydrostatics and aerodynamics. Thus, these equations are determined by a combination of different theories, experimental results and approximations. The large scale 3D visual projection is aided by visual software of computers. The display could be one monitor or a set of screens showing what the bridge team will see looking out from the vessel’s bridge. The view of the screens could vary from 240° to a full 360°.

There are many different vessel simulators all over the world, such as the vessel handling simulator of the Maritime Simulation Centre Warnemünde (Benedict et al., 2009) and the MERMAID 500 at MARIN (MARIN, 2010). Their functions are similar: they are used for research or training purpose.

The advantage of the RTS models is that they can simulate vessel movement in detail, as well as visual environment. In addition, these models contain human response, which is difficult to be simulated by other models. However, the disadvantage is obvious: the simulation speed is low and the cost of the system including the mock-up bridge and the visual display is very high.

1.1.2 Fast Time Maneuvering models

The apparent difference between the RTS models and the FTM/FTT models is that humans (the bridge team) are replaced by a computer-based model in the FTM/FTT models. By excluding the direct human involvement and modelling paradigm, the simulation speed depends on the computer hardware. The FTM/FTT models can run with the computer software on a single PC and they can run many times in a reasonably short time. The advantage of FTM/FTT models is the low costs and high simulation speed.

FTM models describe three dimensional movement of vessels by integrating ship hydrodynamics into ship basic mathematical model. However, Ship hydrodynamics is very complicated and include propulsion, resistance, seakeeping and ship maneuvering (Bertram, 2011). To calculate different conponents in ship hydrodynamics, either hydrodynamic coefficients or empirical formulas are used in FTM models (Jia & Yansheng, 1999). However, the disadvantage is the difficulty of calculating of hydrodynamic coefficients (Stern et al., 2011; Tyagi & Sen, 2006) and assumptions for empirical formulas. In order to avoid these disadvantages, some other researchers focus on the two dimensional movement of vessels, including ship speed, course and path. For instance, Sutulo et al. (2002) proposed a simplified mathematical model to predict vessel path in maneuvering simulation systems. Sariöz and Narli (2003) developed a FTM models to evaluate the basic vessel maneuvering characteristics under different environmental conditions.

1.1.3 Fast Time Traffic models

FTT models focus on assessing the safety and capacity of the infrastructures in waterways and port areas. Initially, vessel course and speed were not important for these models and were predefined. For example, Hasegawa et al. (2001) developed a navigational mathematical model to evaluate maritime traffic in Osaka Bay. Merrick et al. (2003) proposed a simulation model using a snapshot approach to estimate the number of vessel interactions for different alternative expansion plans in the San Francisco Bay area. Köse et al. (2003) developed a maritime traffic simulation to estimate the waiting time and number of waiting vessels at the entrance of the Strait of Marmara under specific traffic conditions. Özbaş and Or (2007) created a simulation model to assess the efficiency of the Istanbul Channel, such as number of vessels in queue and waiting time, by investigation of the vessel transits applying the Channel Traffic Rules and

Regulations, taking into account vessel types, cargo characteristics, meteorological and geographical conditions, pilotage and tugboat services. In recent years, Almaz and Altiok (2012) used a simulation model of the vessel traffic in Delaware River to investigate the influence of deepening on maritime traffic efficiency in the river. Xiao (2014) proposed a maritime traffic model with multi-agent system to simulate vessel maneuvering in ports and inland waterways. Bellsolà Olba et al. (2017) developed a simulation model including a simplified port network in order to evaluate the capacity of the infrastructures. The weakness of FTT models is that they normally do not consider the influence of external conditions and they use simplified vessel movement, i.e. vessels follow a fixed path and have constant speed.

1.1.4 Maritime Risk Assessment models

The MRA models focus on risk assessment of collision and grounding, which are important for maritime traffic safety and capacity. As shown in a previous study (Li et al., 2012), most of existing MRA models work on the accident probability or accident consequence analysis. In this section, the MRA models are categorized in two groups: probability estimation models and consequence estimation models.

Probability estimation models

Probability estimation models are designed to estimate the collision and grounding probability in a specific area. The probability estimation model is proposed for the calculation of the collision frequency, as follows (Macduff, 1974):

$$P = N_a P_c \tag{1.1}$$

Where P denotes the collision frequency, N_a is the number of accident candidates (geometrical probability), i.e. vessels on a collision course implying that an accident would occur if no avoidance maneuver was made, and P_c is the causation probability, which is the probability of failing to avoid the accident while being on a collision course by improper maneuvering, human error or external influences. The probability estimation models focus on investigating the geometrical probability and the causation probability. The maritime risk, as the collision frequency is often called, is the product of these two types of probability.

The geometrical probability is determined by geometry of the waterway, the vessel size, the traffic volume, etc. Many models were developed in this category to estimate the risk of maritime traffic. In 70s, the *model by Macduff* was developed to calculate the geometrical probability for groudings and collisions based on the geometry of the waterway and the vessels (Macduff, 1974), while the *Domain-based model* was proposed to calculate the geometrical probability for vessel evasive actions (Fujii & Tanaka, 1971). The ship domain, which a virtual area around the vessel, should not be entered by other vessels. The further development of the ship domain model focused on changing the domain shape and size (Coldwell, 1983; Davis et al., 1980; Goodwin, 1975; Zhu et al., 2001) and apply the ship domain to estimate the frequency of ship collisions (Koldenhof et al., 2009; Pietrzykowski & Uriasz, 2009; Szlapczynski, 2006). In 90s, *Pedersen's model* was developed to calculate the probability of grounding and collision events based on classification of vessels navigating in a certain area and given vessel traffic distribution (Pedersen, 1995). The Pedersen model was successfully applied in several further researches (Otto et al., 2002; Pedersen & Zhang, 1999). In 2002, *Kaneko's model* was developed to estimate the dangerous encounters, such as collision (Kaneko, 2002). Most recently, the *COWI model* was presented to deal with the collision and grounding separately (COWI, 2008).

The causation probability is dependent on the operational skills of the bridge team and vessel maneuverability. The simplest approach to estimate the causation probability is using historical data (Koldenhof et al., 2009; Macduff, 1974). The fault tree models are based on an analysis approach to understand the various causes leading to a maritime accident and to identify the best ways to reduce risk. This model was proposed in the Marine Accident Risk Calculation System (MARCS) which was further developed during the project "Safety of shipping in Coastal Waters" (SAFECO) of the European Commission (EC) (Fowler & Sørgård, 2000). Compared to Fault tree approach, the Bayesian network models are able to deal with different encounters including head-on, overtaking and crossing (Friis-Hansen et al., 2001; Otto et al., 2002). To assess the maritime traffic, it is possible to combine the Bayesian network with expert's judgment (Merrick & Van Dorp, 2006; Szwed et al., 2006). The Bayesian network was also used to integrate Human and Organizational Factors (HOF) into risk analysis to model the Maritime Transport System (MTS) by taking into account its different actors (i.e., operator, ship-owner, shipyard, port, environment and regulator) and their mutual influences (Trucco et al., 2008).

In summary, the probability estimation models focus on the risk level, but they do not reach the level of detail of individual vessel behavior including speed, course and path. In addition, the influence of individual factors (such as external conditions and vessel characteristics) on vessel behavior cannot be identified by probability estimation models.

Consequence estimation models

Consequence estimation models focus on the accident consequences. Two types of consequence estimation models will be introduced in this section: event tree analysis (ETA) models and mechanical models.

ETA approach is an inductive analytical technique that explores all possible outcomes resulting from a single initiating event (accident). The ETA approach is used by ETA models and combined with expert judgment and historical data in maritime traffic. Formal Safety Assessment (FSA) proposed by the IMO is a representative model based on ETA approach. Using the FSA model, IMO has published a series of reports on maritime traffic risk assessment for different types of vessels, such as container vessels (IMO, 2007a), cruise vessels (IMO, 2007b) and Liquefied Natural Gas (LNG) vessels (IMO, 2007c). ETA approach is applied in all of these reports to estimate the overall risk related to the various scenarios, such as collision, grounding and fire/explosion. Although the ETA models are powerful tools to investigate maritime traffic risk, the limitation of the model is the expert judgement and historical data used in these models.

For the specific scenarios including collision and grounding, the mechanical models could be used to estimate the consequence of the maritime traffic accident, such as the vessel's damage and oil spill from tankers. Many mechanical models have been developed by several researchers. Some of these models are used to calculate the ship's damage (Ehlers et al., 2008; Fang & Das, 2005; Pedersen & Zhang, 1999), some of them focus on energy calculation (Glykas & Das, 2001; Pedersen & Zhang, 1998; Tabri et al., 2009), and others are dedicated to estimate the influence on environment after accidents, such as an oil spill (Gucma & Przywarty, 2008; Rawson et al., 1998).

Both event tree models and mechanical models could be used to assess the maritime traffic risk. However, similar to frequency estimation models, they focus on the level of the risk and they can only investigate the vessel behavior including speed, course and path in combination with an accident probability model that would describe the individual vessel behavior.

1.1.5 Conclusions

In this section, the existing maritime models are introduced in four groups: RTS models, FTM models, FTT models and MRA models. The advantage of the RTS models is the combination with visual environment and human response, while the weakness is the low simulation speed and the high simulation cost. Compared to the RTS models, the FTM models can run much faster and with low simulation cost, but the calculation of the hydrodynamics frequently depends on simplified empirical formulae. The FTT models work on predefined vessel speed and paths and do not consider details of individual vessel maneuvering and behaviour. The MRA models are suitable for risk assessment of maritime traffic and therefore can be used for regulation purpose. However, it is important to bear in mind that they cannot simulate the individual vessel behavior and these models are dependent on historical data.

1.2 Challenges for modelling maritime traffic

In this section, the current challenges for modelling maritime traffic are identified based on the overview of existing maritime models above.

Although significant achievements have been made in maritime traffic modelling by researchers in the past decades, many challenges still remain. These challenges include but are not limited to the following: *a*) understanding the impact of human behavior of the bridge team on vessel behaviour and integrate it into models; and *b*) getting a better understanding of the influence of external and internal factors (as defined below) on vessel behavior.

The first challenge is to develop the model to simulate human behavior of the bridge team. "Research has shown that 80 to 85% of all recorded maritime accidents are directly due to human error or associated with human error" (Harati-Mokhtari et al., 2007). It was also found that human factors are the largest cause group for maritime traffic accidents in the Gulf of Finland: 55% of the cases with a reported primary cause (Kujala et al., 2009). Thus, it can be concluded that human behavior plays an important role in maritime traffic safety. However, human behavior is very complicated and difficult to be simulated due to inter- and intra-personal heterogeneity. In addition, many factors could influence human behavior, such as experience, work load and time pressure. And these influences are difficult to be quantified and have a lack of support from the data.

The second challenge is to explore the influence of different external and internal factors on vessel behavior and get sufficient data to support the research. As we know, vessel movement is very complicated. External factors including waterway geometry, weather condition (wind, visibility), current, local regulations and other traffic on the water may influence vessel behavior. Internal factors consist of vessel type, vessel length and beam, vessel gross tonnage, load of the cargo and bridge team behavior. The vessel movement results from the influence of these factors. In this thesis, data of vessel behavior and influencing factors provide insights into vessel behaviour under different influencing factors and also serve as input into model calibration and validation. However, it is difficult to investigate the influence of an individual factor and it is even more difficult to distinguish the combined different influences of different factors by data analysis. For example, the current varies in time and in space and it is very difficult to get all the current data to investigate the influence of current on vessel behavior.

1.3 Research objectives and questions

The main research objective of this dissertation research is to develop a new FTM maritime traffic model considering both internal and external factors, including vessel characteristics, waterway geometry, external conditions and encounters with other vessels, aiming to better predict the individual vessel behavior, to provide data for the impact assessment of vessel traffic in ports and inland waterways. This means that the new model would function as a geometrical estimation model.

To achieve this objective, four research questions will be answered in this thesis:

1. Which factors (i.e. vessel type and size, external conditions, waterway geometry and vessel encounters) do significantly influence vessel behavior including speed, course and path? (AIS data analyses; chapters 2 and 3 of this thesis)

2. How should maritime traffic be modelled by optimal control theory in order to improve the assessment of safety and capacity in maritime traffic? (model development; chapter 4 and 5 of this thesis)

3. How should the new maritime traffic model based on optimal control be calibrated and validated using AIS data? (model calibration and validation; chapter 4 and 5 of this thesis)

4. To what extent does the new model presented in this thesis reproduce reality? (case study; chapter 6 of this thesis)

To answer the research questions, the new maritime traffic model should (1) be capable to predict vessel speed and course of all traffic within an area during a certain period of time, and (2) include different factors influencing vessel behavior, such as waterway geometry external conditions and vessel encounters.

1.4 Automatic Identification System and data

As is expressed by the first research question, investigating vessel behavior and factors influencing vessel behavior requires data including vessel speed, course and path. Automatic Identification System (AIS) data is such a potential data source. In recent decades, AIS has been developed due to the fast development of information and communication technologies. As AIS could be used to improve the maritime safety and efficiency by at short interval transferring vessel dynamic, voyage and safety related data between encountering vessels and from vessels to shore stations, it is required to be installed on almost all vessels.

In the 1990s, the AIS was proposed by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) to the International Maritime Organization (IMO) (Eriksen et al., 2006). The motivation for the system is "to improve the maritime safety and efficiency of navigation, safety of life at sea and the protection of the marine environment" (IALA, 2003). The implementation plan and requirements for AIS are regulated in Regulation 19 of Chapter V of the International Convention for the Safety of Life at Sea (SOLAS): the AIS is mandatory on all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and passenger ships by the end of 2004 (IMO, 2002). It was further regulated by SOLAS that the implementation of AIS for all ships would be done by 1 July 2008.

The AIS is an autonomous and continuous broadcast system, operating on the Very High Frequency (VHF) maritime mobile band. The data is exchanged between vessels with an AIS device and also between vessels and shore stations, such as VTS, to improve traffic safety. The exchanged data is called AIS data, which includes 22 data types. These data types are grouped in four categories: static data, dynamic data, voyage related information and short safety messages. The characteristics of these four categories (Harati-Mokhtari et al., 2007) are:

- The static data include IMO and Maritime Mobile Service Identity (MMSI) number, call sign and name, type of vessel (passenger, tanker, etc.), length and beam, location of position fixing antenna such as GPS/DGPS. They are entered into the AIS system during the installation and need be changed if the ship changes its name or undergoes a major conversion. The reporting interval for the static data is 6 minutes.
- The dynamic data consist of ship's position with accuracy indication (for better or worse than 10 m) and integrity status, time in UTC (coordinated universal time), course over ground (COG), speed over ground (SOG), heading, navigational status (e.g., not under command, constrained by draught), rate of turn (where available), angle of heel (optional), pitch and roll (optional). These dynamic data are automatically updated from the ship sensors connected to the AIS system. The reporting interval for dynamic data

varies from 2 seconds to 3 minutes, which is determined by the dynamic conditions of the vessel, as shown in Table 1.1.

Table 1.1: Reporting intervals for dynamic AIS data (Last et al., 2015)

Vessel's dynamic conditions	Interval
At anchor/moored and not moving faster than 3 kn	3 min
At anchor/moored and moving faster than 3 kn	10 s
Speed 0-14 kn	10 s
Speed 0-14 kn and changing course	3.3 s
Speed 14-23 kn	6s
Speed 14-23 kn and changing course	2s
Speed >23 kn	2s
Speed >23 kn and changing course	2s

- The voyage related data include ship's draught, type of cargo, destination and estimated time of arrival, route plan-waypoints (optional), number of persons on board (on request). These data are manually entered and updated during the voyage by the bridge team. The reporting interval for these data is 6 minutes.
- The short safety related data (text) are messages with important navigational safety related information and shown in an extra window. They are sent as required and are therefore specific to events or incidents.

The accuracy of AIS data is investigated by some researchers. A dataset consisting of 400,059 AIS data reports from 1st March to 17th March 2005 including MMSI number, IMO number, position, COG and SOG was analyzed (Harati-Mokhtari et al., 2007). It was found that the error rate is about 8%, which means 1 in every 14 AIS transmissions in the sample contained at least one piece of erroneous data. The analyses for AIS data of one week in the Dover Straits in three different years (2004, 2005 and 2007) showed that the percentage of errors of AIS data is improved from 10.4% in 2004 to 3.5% in 2007 (Bailey et al., 2008). In addition, it was found that most errors occurred in the message "destination" and "draught". In the last decade, the quality of AIS data has been significantly improved (Felski et al., 2015; Felski et al., 2013). So it can be concluded that the incorrect information appears mostly in aspects which are not so important for utilization of the AIS data in this thesis.

In recent years, AIS data are frequently used to analyze vessel movement and then investigate the maritime traffic risk (Aarsæther & Moan, 2009; Goerlandt & Kujala, 2011; Mou et al., 2010; Ristic et al., 2008; Xiao et al., 2015; Zhang et al., 2016). In these researches, AIS data have been proven to be a useful tool to investigate maritime traffic.

In this thesis, we mainly focus on vessel behavior including vessel speed over ground, course over ground and positions, which are included in the dynamic data.

1.5 Research approach

The main research approach used in this thesis is to apply the optimal control theory, which is successfully applied for pedestrians (Hoogendoorn & Bovy, 2004) and vehicle traffic (Wang et al., 2015), to maritime traffic modelling. Similar to pedestrians and vehicles, vessel speed and course are determined by human (the bridge team) choice. Especially for pedestrians, vessel behavior is very similar: both vessels and pedestrians (1) have specific origin and destination; (2) are constrained by boundary (bank for vessels, and wall or other infrastructures for pedestrians); (3) can influence each other; (4) are influenced by external conditions, such as weather conditions. The many similarities between vessels and pedestrians motivate the use of optimal control for maritime traffic in this thesis. For pedestrians, pedestrian behavior is distinguished into three levels: strategic level, tactical level and operational level (Hoogendoorn & Bovy, 2004). The route choice model was developed for tactical level, while the operational model was applied at operational level. The optimal control theory was applied in both the route choice model and the operational model. To apply the optimal control theory for maritime traffic, vessel behavior is categorized into two levels: the tactical level and the operational level. Each level has a corresponding model: the route choice model and the operational model, and the optimal control theory could be used by these two models.

To establish an empirically underpinned simulation model for maritime traffic, four research steps are conducted in this thesis. Figure 1.1 outlines these steps.

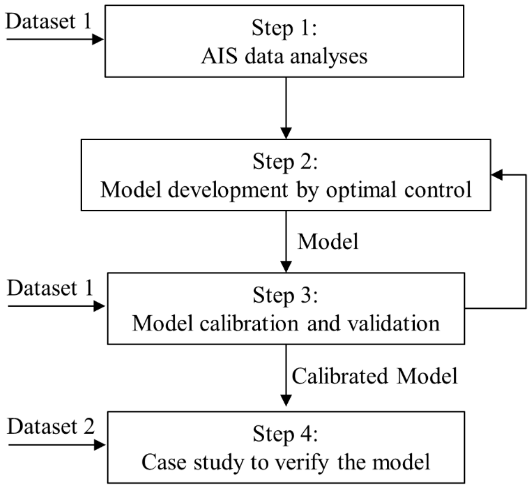


Figure 1.1: Research steps of the thesis.

1.5.1 AIS data analysis

Firstly, the AIS data are analyzed to clarify the influence of different factors on vessel behavior, such as vessel type and size, waterway geometry and external conditions (wind, visibility and current). In this thesis, the AIS data are provided by the Maritime Research Institute Netherlands (MARIN), which is one of the institutes in the Netherlands for hydrodynamic research and maritime technology. To collect the AIS data, the software “ShowRoute” from MARIN is used. The AIS data analyses will support the model development in the next step and research question 1 is answered by the Step 1.

1.5.2 Model development

In the second step, optimal control theory is applied to develop the two sub-models, one at each behavior level: the route choice model and the operational model as mentioned before. To solve the optimal control problem, dynamic programming approach, numerical solution approach and Pontryagin’s method are used in this thesis. Research question 2 is answered in the second step.

1.5.3 Model calibration and validation

In the third step, the models developed in Step 2 are calibrated and validated using AIS data. The calibration and validation provide feedback to Step 2 to improve the model development, and thus improve the quality of the models. As the result of Step 3, the calibrated model is produced and serves to the next step. Research question 3 is answered in the third step.

1.5.4 Case study

In the fourth step, the new maritime traffic model is applied using the optimized parameters from the calibration in another situation (dataset) than it has been calibrated for. This case study is carried out to verify the new maritime traffic model. This step answers research question 4.

1.6 Research scope

As described above, this thesis is devoted to developing a new maritime traffic model, considering the vessel characteristics (type and size), waterway geometry and external conditions, which could be used to predict the vessel behavior including vessel speed, course and path.

Firstly, the AIS data analyses presented in this thesis focus on vessel behavior including speed, course and path, without considering berthing behavior. The motivation for this choice is that the berthing behavior is influenced by the distance to the final destination (berth), which is considered to be outside the research scope.

Secondly, the desired speed in the operational model, which is the optimal speed when the vessel is not influenced by external conditions and other vessels, is generated by the historical data. This could imply that the model cannot be applied in different ports and waterways, where historical data is not available, such as in new ports or port extensions. Normally, “good seamanship” is applied for different areas, but it is subjective and qualitative. Locally manoeuvring and navigation are governed by specific local rules and regulations, which are often dependent on the local situation.

Thirdly, the operational model is used to optimize the longitudinal acceleration and angular speed, which are considered as the control output, since the bridge team maneuvers the vessel in longitudinal and angular direction by the propulsion and rudder system. The drift angle, which is the difference between vessel heading and course, is not considered in both the AIS data analyses and model development in this thesis. This choice is motivated by the fact that the calculation of drift angle is normally related to the hydrodynamics, which would make the model unduly complicated.

1.7 Main contributions

In this section, the contributions of the research in this thesis are presented. In this respect we distinguished two categories: scientific contributions and practical contributions.

1.7.1 Scientific contributions

Firstly, the main scientific contribution is the new maritime traffic model including two sub-models, being the route choice model and the operational model (Chapter 4 and 5), based on the results of AIS data analyses and the optimal control theory. The route choice model is used to derive the desired course in continuous space, considering the waterway geometry, such as width and alignment. Based on the desired speed and desired course generated by the route choice model, the operational model is developed and calibrated using the AIS data from the same vessel category. This research shows the *successful application of optimal control theory in this new maritime traffic model.*

Secondly, the new maritime traffic model is calibrated and validated using AIS data in this thesis (Chapter 4 and 5). To calibrate the route choice model, the AIS data for the small General Dry Cargo (GDC) vessel category are used. For the operational model, the AIS data of vessel encounters are used for the same vessel category. The combined model could be used to predict vessel behavior and simulate maritime traffic to investigate the safety and capacity of the maritime traffic. *The calibration and validation procedures produce a predictively valid model.*

Thirdly, the new maritime traffic model is verified by a case study, that applied the models in a situation other than what it had been calibrated for (Chapter 6). Based on the optimized parameters from the calibrations, the model is applied in the entrance channel to the Maasvlakte I in the port of Rotterdam. The results show a good prediction of the vessel behavior. The contribution of this case study is *the application of the model in a real scenario, which shows the model is generic for different situations*.

Lastly, AIS data analyses are performed in this thesis (Chapters 2 and 3). The data analyses provide *a better understanding of the vessel behavior and the influence of* different *factors on the vessel behavior*, including vessel characteristics (type and size), waterway geometry and external conditions (wind, visibility and current), as well as vessel encounters.

1.7.2 Practical contributions

The newly developed maritime traffic model serves as a new method to predict and investigate the vessel traffic in ports and inland waterways. For the designer of ports and waterways, it is possible 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 and serve as a port and waterway design support tool.

As mentioned before, the data analyses provide insights into vessel behavior in ports and inland waterways. These insights also lead to *recommendations to the port authority or administrative departments*, such as on improvements of bottle necks in ports and waterways or speed limits in crossing areas.

1.8 Outline of the thesis

The remainder of this thesis is organized in 6 chapters. Figure 1.2 shows the schematic overview of these chapters and their relationships. Chapter 2 presents the AIS data analyses, in which the influence on vessel behavior of vessel type and size, waterway geometry and external conditions (wind, visibility and current) is clarified (Shu et al., 2013b). As a further step to analyze AIS data, Chapter 3 investigates the influence of external conditions and vessel encounters on vessel behavior (Shu et al., 2017). The research question 1 is answered in these two chapters.

Chapters 4 and 5 describe the development of the new maritime model, which includes two sub-models: the route choice model and the operational model. In Chapter 4, the route choice model is developed by the optimal control theory and calibrated using the AIS data of small GDC vessels (Shu et al., 2015b). Then, Chapter 5 describes the improved operational model, which is calibrated and validated using the AIS data of encountering vessels (Shu et al., 2018). The research questions 2 and 3 are answered in these two chapters.

In Chapter 6, a case study is carried out to verify the integrated model by applying the new maritime model in another situation than it has been calibrated for (Shu et al., 2016). The research question 4 is answered in this chapter. Finally, Chapter 7 presents the findings and conclusions of this thesis, the implications for practice, as well as the recommendations for future research.

In addition, it should be noted that this thesis is written in a format of a collection of articles. Chapter 2, 3, 4, 5 and 6 correspond to articles that have been published already in scientific journals. Therefore, some information has been repeated in these chapters, especially in the respective introduction sections.

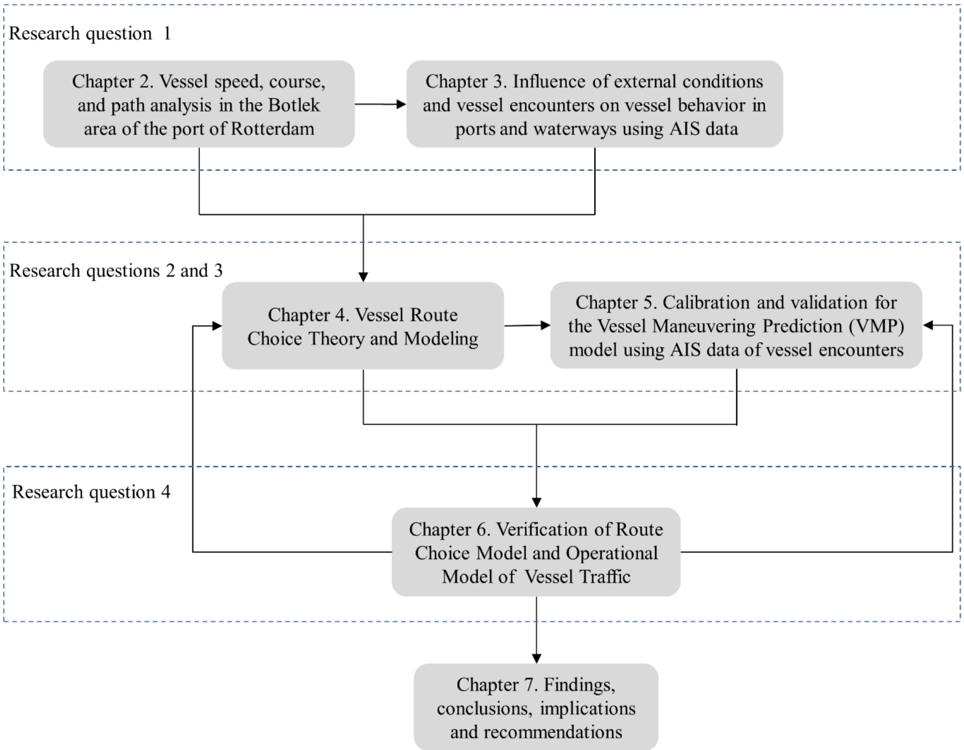


Figure 1.2: Schematic overview of the thesis structure.

Chapter 2

Vessel speed, course, and path analysis in the Botlek area of the Port of Rotterdam, Netherlands

This chapter is an edited version of the article:

Shu, Y., W. Daamen, H. Ligteringen, & S. P. Hoogendoorn (2013) 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*, 2330, pp. 63-72.

Abstract

Because vessel traffic in ports and waterways is growing quickly, much attention has been given to maritime traffic safety and port capacity. Many simulation models have been used for predicting traffic safety and port capacity in ports and waterways. However, maritime traffic models have considered only a few aspects; the influence on safety of human behavior and external factors has not been included. An analysis based on data from an automatic identification system was performed under various external conditions in an investigation of vessel behavior and external influencing factors. The study area included a junction and a slight bend with high maritime traffic density within the port of Rotterdam, Netherlands. Vessels were classified according to type and gross tonnage. Equidistant cross sections approximately perpendicular to the navigation direction were used for investigation of vessel behavior, including speed, course, and path for each vessel category. The influence of external factors (wind and visibility) on vessel behavior was identified through a comparison with the behavior of unhindered vessels. In the analysis, specific thresholds were set for selecting external conditions and eliminating the influence of encounters. The analysis of unhindered vessels for each vessel category provided insight into vessel behavior. The results revealed that wind had an influence on vessel speed and that visibility affected vessel speed, course, and path. Analysis

results can be used as input for the development of a new maritime traffic model, as well as for its verification and validation.

2.1 Introduction

Maritime traffic is growing in importance because international shipping carries about 90% of world trade on more than 50,000 merchant vessels (Dolivio, 2007). The rapid growth of maritime traffic jeopardizes the balance between maritime traffic safety and capacity: when use of waterways increases, safety usually decreases. Maritime traffic safety is a big issue in port areas in particular because of the possible serious consequences of accidents, such as personnel and property losses, traffic congestion, and environmental influence on both the water and the surroundings.

Maritime traffic models have been developed for investigating this complex system consisting of elements such as hydrodynamics, vessel interactions, external conditions, and human factors. Current maritime traffic models are developed only for open seas and are not applicable in constrained waterways such as ports. Researchers have established many mathematical models that consider the hydrodynamics of vessels and the influence of external factors on vessel behavior (Sariöz & Narli, 2003; Sutulo et al., 2002). Others have investigated models for calculating the maritime traffic safety index (Degre et al., 2003; Fowler & Sørgård, 2000; Pedersen, 1995). However, external factors that could affect maritime traffic safety have been considered only as probability parameters in these models, and it remains unclear how external factors affect vessel behavior. Hence, a new maritime traffic model is needed that can describe the relationships between individual vessel behavior, influence of external factors, and maritime traffic safety.

In this study, data analysis was performed at the Maritime Research Institute, Netherlands (MARIN), one of the leading institutes for hydrodynamic research and maritime technology. The research area is the Botlek area of the port of Rotterdam, Netherlands. Botlek is an ideal area in which to conduct this research because it comprises a waterway of high traffic density that has a bend and a junction. In this area, complex navigation situations and high traffic density offer enough data for the analysis of various vessel categories and the identification of the influence of factors including wind and visibility, as well as navigation direction and waterway geometry.

All the data used in this study were collected from the automatic identification system (AIS) in MARIN. The AIS is an onboard autonomous and continuous broadcast system that transmits vessel data between nearby vessels and shore stations on the VHF maritime mobile band (Bailey et al., 2008). By the end of 2004, the AIS system was required to be installed on all ships of 300 gross tonnage and more that are engaged in international voyages, cargo ships of 500 gross tonnage and more that are not engaged in international voyages, and all passenger ships regardless of size.

AIS has been proved to be a useful tool for investigating maritime traffic (Aarsæther & Moan, 2009; Mou et al., 2010; Ristic et al., 2008). Combined with data on wind, current, and visibility, AIS data such as vessel speed, course, and position can be used to investigate influence of external factors on vessel behavior. In this study, historical AIS data from January 2009 to April 2011 for the Botlek area at MARIN were analyzed. Thresholds were set for selection of external conditions and elimination of the influence of encounters. Investigation of unhindered vessel behavior, that is, the behavior of a single vessel without encounters and strong external influence, used the thresholds to eliminate the influence of external factors and encounters. Then, the influence of individual external factors was investigated by addition of these elements to the vessel behavior with opposite thresholds. For example, wind was set as less than 8 m/s (weaker than Beaufort wind force scale 5) in unhindered vessel behavior, and the opposite selection (larger than 8 m/s) was chosen for investigation of the influence of wind on vessel behavior. This nonideal state was compared with unhindered vessel behavior so the influence of external factors could be identified.

Because AIS data are signal-based data corresponding to all points on each vessel track, cross sections are used to extract vessel behavior from raw AIS data in ShowRoute, dedicated software developed by MARIN and used for investigation of AIS data. For each vessel track, linear interpolation is used on cross sections based on the first point after the cross section and the last point before the cross section. In this way, different behaviors of vessles, including unhindered vessel behavior, are shown on these cross sections.

As a basis of the new maritime traffic model, this data analysis identifies behavior of unhindered vessels and the influence of external factors (wind and visibility) on vessel behavior. The AIS data description and the analysis setup are given. Then the unhindered vessel behavior for each vessel category by type and size is investigated. The influence of external factors (wind and visibility) on vessel behavior is analyzed through comparison with the behavior of unhindered vessels. Finally, further recommendations are given. Current is used only as a data selection condition but is not investigated in detail in this paper.

2.2 Description of AIS data

The types of data recorded in the AIS system include static data (Maritime Mobile Service Identity number, type of vessel, length, beam, etc.), dynamic data (vessel position, time instant, speed, course, etc.), voyage-related information (draught, cargo, destination, etc.), and short safety messages (Bailey et al., 2008). The dynamic information, which is automatically updated from the ship sensors to the AIS system, includes most of the data regarding vessel behavior, such as vessel speed, course, and position. In this paper, this dynamic information is used as input for the analysis.

The AIS data come from ship-borne machines that are used by different bridge teams on different vessels. Although the accuracy has been improved in recent years, AIS data are not reliable in many cases (Harati-Mokhtari et al., 2007). However, incorrect information appears mostly in static aspects, such as length and beam, which are not included in the data analysis presented here.

For analysis of the data, the time interval of AIS signals must be known. In the research area, most vessels navigate with a speed of 0 to 14 knots (1 knot = 1.852 *km/h* = 0.514 *m/s*), and they send AIS messages at 10 *s* intervals. When vessels sail at a greater speed of 14 to 23 knots, they send AIS messages every 6 s (Eriksen et al., 2006). Thus, a good way is needed to extract and compare speed, course, and path between tracks. In this paper, cross sections are used, illustrated in the section on AIS data analysis methodology, for comparing vessel behavior in various vessel tracks.

2.3 AIS data analysis setup

In the remainder of the paper, behavior of unhindered vessels and the influence of the external factors of wind and visibility on vessel behavior are investigated. Cross sections are proposed for calculating vessel behavior and identifying the influence of external factors.

Vessel behavior parameters including speed, course, and path are investigated. To structure the analysis, the following research questions are posed about unhindered vessel behavior and influence of external factors for each vessel category:

- Question 1. Which factors influence average speed of unhindered vessels?
- Question 2. Which factors influence average course of unhindered vessels?
- Question 3. Which factors influence average path of unhindered vessels?
- Question 4. Does wind influence average vessel speed, course, and path of unhindered vessels?
- Question 5. Does visibility influence average vessel speed, course, and path of unhindered vessles?

2.4 Methodology for AIS data analysis

The period from January 2009 to April 2011 was selected for AIS data analysis. This gives more than 2 years of the most recent data. In addition, more vessels in the research area had AIS installed compared with previous years. Although more data was desired, the data set depends on the size of the Access file, which should be less than 2 GB and will become slower as the file gets larger.

The research area is shown in Figure 2.1; Figure 2.1*b* zooms in on the area. The Nieuwe Maas, flowing east to west, connects the older port basins of the Waalhaven and Eemhaven with the sea. The Oude Maas joins the Nieuwe Maas from the south and forms the main connection for vessel traffic to the hinterland. The following four main vessel flows are used in the analysis:

- Sea to Nieuwe Maas,

- Nieuwe Maas to sea,
- Sea to Oude Maas, and
- Oude Maas to sea.

Figure 2.1: Research area: (a) overview and (b) close-up.

There are many vessel types in the research area, including container vessels, tankers, and general dry cargo vessels. Different types of vessels may have different unhindered vessel behavior because maneuverability and sensitivity to danger will differ. The influence of vessel type on a vessel's behavior is investigated in this paper.

Table 2.1: Vessel Classification for the Five Most Occurring Types

Vessel type		Category 1	Category 2	Category 3	Category 4	Category 5
Container	Size [GT]	<5100	5100-12000	12000-20000	20000-38000	>=38000
	number of data	44,848	198,523	30,852	49,634	13,194
GDC	Size [GT]	<3600	3600-12000	12000-20000	>=20000	na
	number of data	99,680	47,501	6,737	4,015	na
Dredger	Size [GT]	<3600	3600-6500	>=6500	na	na
	number of data	3,027	16,563	4,418	na	na
RoRo	Size [GT]	<7500	7500-17500	>=17500	na	na
	number of data	4,676	3,483	13,058	-	-
Tanker	Size [GT]	<7500	7500-17500	>=17500	-	-
	number of data	6,802	3,878	3,289	-	-

Note: Size is in gross tonnage. GDC = general dry cargo; na = not applicable; RoRo = roll-on-roll-off.

To some extent, a vessel's size determines its maneuverability. For example, compared with larger vessels, smaller vessels have greater freedom in restricted waterways. This implies that vessel size is expected to affect the vessel's behavior as well. As a key index of vessel size, the gross tonnage (GT) could be obtained directly from the AIS data, thus it is used to classify vessels into different categories.

The existence of many berths in the area could create special maneuvering and vessel berthing paths. Although berthing vessels show special behaviors, the data analysis mainly investigated sailing behavior without berthing. In this research, berthing behavior is thus filtered from the data set by the boundary defined in ShowRoute.

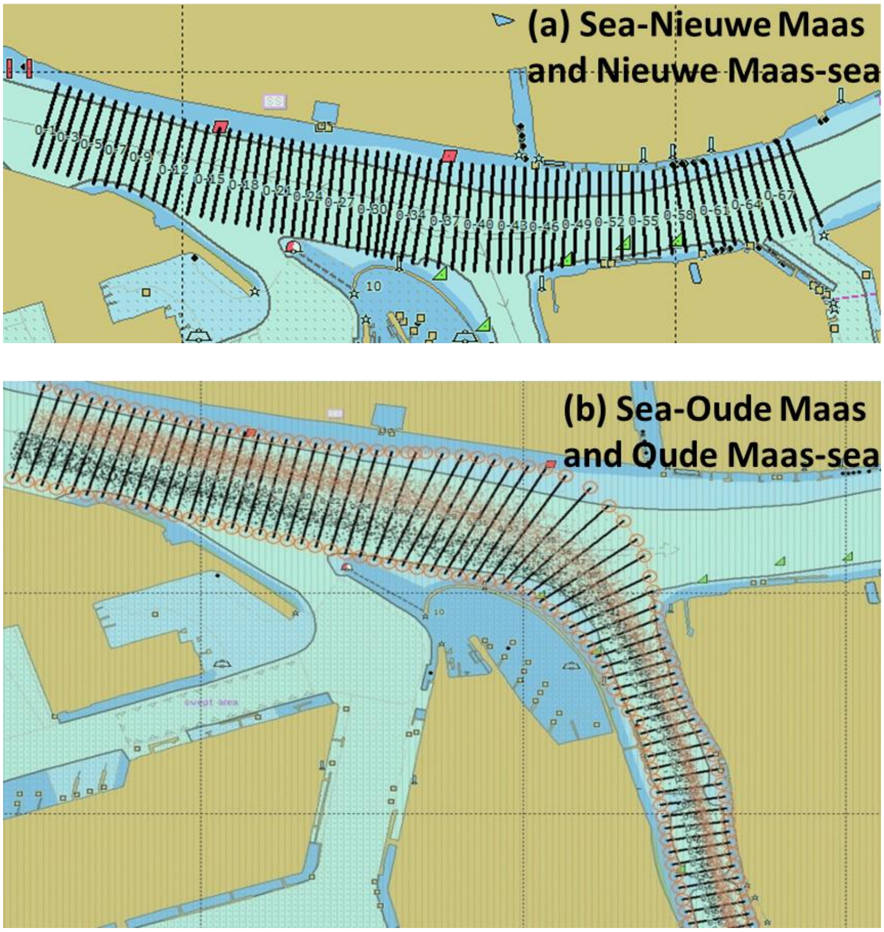


Figure 2.2: Cross-sections for the study area (a) between sea and Nieuwe Maas and (b) between sea and Oude Maas.

For the five vessel types with the greatest occurrence in the AIS data (container, general dry cargo, dredger, roll-on–roll-off, and tanker), vessels are classified into several categories on the basis of their size distribution. As shown in Table 2.1, the criterion for this classification is to classify vessels with expected similar behavior into the same group. The size categories are chosen so that in every data set, approximately the same amount of data points is available. Here, 3,000 data points is the minimum for distinguishing a separate category. Container vessels have five categories because they have the largest amount of AIS data and enough data for each category. General dry cargo vessels are classified into four categories. Dredger, roll-on–roll-off, and tanker vessels are divided into three categories because less data for these vessels are available.

Cross sections are proposed for investigating vessel behavior based on AIS data. Figure 2.2*a* shows 69 cross sections for the navigation directions sea to Nieuwe Maas and Nieuwe Maas to sea, and Figure 2.2*b* shows 68 cross sections for the navigation directions sea to Oude Maas and Oude Maas to sea. All cross sections are formed by linking two points at 5-m depth contours on two sides of the waterway. Usually, water depth is an important factor for the bridge team to take into account when considering vessel draught. Buoys are set in some places to indicate shallow water in waterways, but there are only two buoys in this area (red diamonds in Figure 2.2). The bridge team bases the choice of vessel path on the buoys, the maritime chart, and experience. As a result, sailing vessels normally do not pass the 5-m depth contour. Therefore, this is chosen as the reference line for calculation of the distance between vessels and the bank. There is no 5-m depth contour in the junction area on one side of the waterway, so a smooth curve is defined between the adjacent 5-m depth contours.

Most vessels in this area navigate at a speed of 0 to 14 knots. A vessel sailing at 10 knots, which is about the average speed in the research area, should be able to send at least one AIS message between two cross sections. Thus, 50 *m* is used as the distance between two cross sections. The cross sections between the 5-m depth contours are approximately perpendicular to the navigation direction.

For each navigation direction, a vessel’s sailing information including vessel position, speed, and course is interpolated on each cross section with information from the last record before and the first record after the cross section. In this way, AIS data on cross sections are calculated and are used for analysis in the following research. This data set can be combined with wind, current, and visibility data for describing vessel behavior depending on these external conditions. This combination is used in the next section to investigate the behavior of unhindered vessels.

2.5 Behavior of unhindered vessels

Unhindered vessel behavior including vessel speed, course, and path without influence of external factors (wind and visibility) and encounters is calculated on each cross section for the four navigation directions. The current varies over time and space: the speed of current varies from -1.5 m/s and 1.5 m/s in longitudinal direction in the research area, while the current decreases from the center of the waterway to both banks. In this chapter, the approximate current was used only for investigating vessel behavior on a specific cross section in unhindered conditions. The analysis was carried out for all vessel types, but the results presented here are related to container vessels, unless otherwise indicated.

First, the AIS data set was combined with wind and visibility data so vessel data without influence of wind (less than 8 m/s), visibility (more than 2,000 m), and encounters (a minimum distance from other vessels larger than 1,000 m) could be selected. These thresholds permitted enough data for investigation of unhindered vessel behavior and influence of external factors. This data set was used to calculate behavior of unhindered vessels for all vessel categories in four navigation directions. In this section, the influence of vessel type and size (gross tonnage) on vessel behavior is investigated.

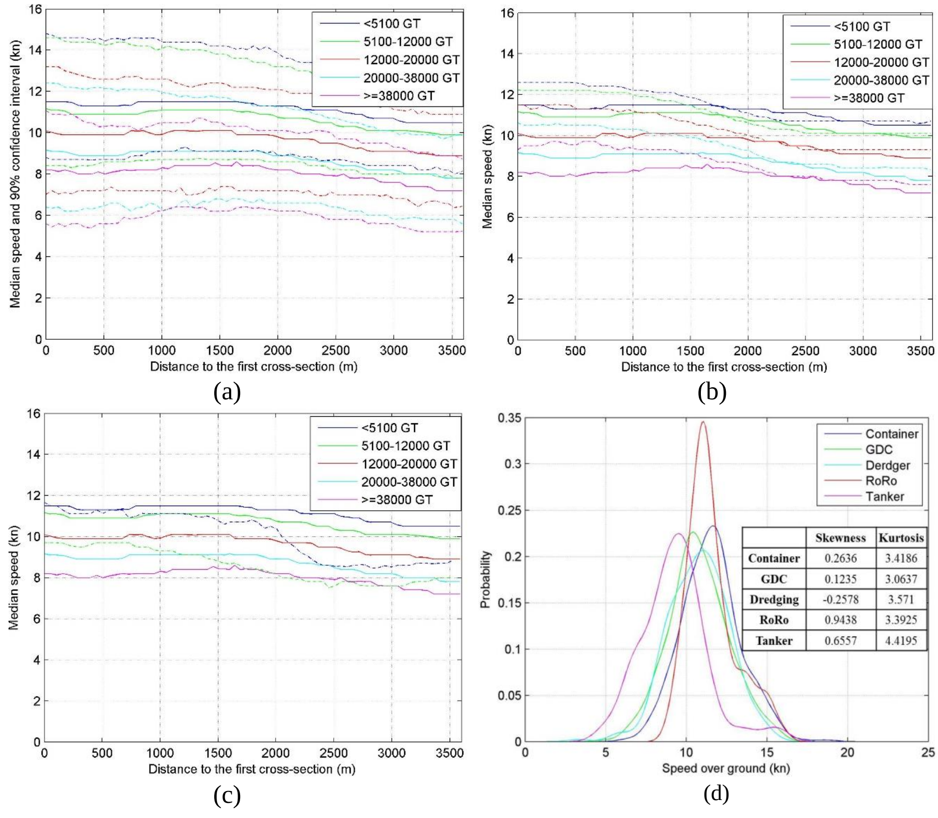


Figure 2.3: Unhindered vessel speed: (a) median speed of container vessels as function of waterway geometry (solid lines) and 90% confidence interval (dotted lines) in sea–Nieuwe Maas direction, (b) median speed of container vessels in sea–Nieuwe Maas direction (solid lines) and Nieuwe Maas–sea direction (dotted lines), (c) median speed of container vessels in sea–Nieuwe Maas direction (solid lines) and sea–Oude Maas direction (dotted lines), and (d) speed distributions for five vessel types in Nieuwe Maas–sea direction on Cross Section 2 (GT = gross tonnage).

2.5.1 Influence on unhindered vessel speed (Question 1)

Figure 2.3 shows median speed of container vessel as a function of waterway geometry and vessel speed distribution for five vessel types on Cross Section 2.

Figure 2.3a shows the median vessel speed (solid lines) and the 90% confidence interval (dotted lines) along the waterway for five categories of container vessels for the navigation direction of sea to Nieuwe Maas. Here, the x-axis, distance to the first cross section, indicates the longitudinal distance along the waterway. In the figure, the <5,100 GT category has the greatest speed, and the >35,000 GT category navigates with the lowest speed. The results of other vessel categories show the same trends and their curves are approximately parallel; smaller vessels have greater speeds than do larger vessels. For all categories, vessel speed decreases after the junction along the waterway. This means that vessel speed is influenced by vessel size, as well as waterway geometry, such as waterway bend.

In Figure 2.3*b* median speed from Figure 2.3*a* is compared with the same vessel categories in the direction of Nieuwe Maas to sea (dotted lines). The dotted lines are largely higher than the solid lines; this difference means that incoming vessels have a lower speed than that of outgoing vessels. The waterway to the east zigzags more than the waterway to the west. Thus, vessel speed is influenced by navigation direction, as well as waterway geometry.

In the same way, Figure 2.3*c* shows a comparison of median speed for the directions of sea to Nieuwe Maas (solid lines) and sea to Oude Maas (dotted lines) for the two smallest categories (the larger categories do not have sufficient passing of vessels). Compared with vessels in the direction of sea to Nieuwe Maas, vessels in the direction of sea to Oude Maas decrease their speed by about 20% after the bend. A reasonable explanation is that vessels have lower speed in a narrower waterway and decrease their speed when they pass the bend area.

Vessel groups with similar gross tonnage of 3,500 to 6,500 GT from different vessel types were chosen for a comparison of speed distribution, shown in Figure 2.3*d.* This range was chosen because in this category the largest number of vessels is observed for each vessel type. The figure shows the probability density functions of speed for five vessel types on Cross Section 2. The skewness and kurtosis for each vessel type are listed in the figure, where the skewness is always within the interval [−1, 1] and the kurtosis is around 3, except for the value for tanker vessels (4.42). Thus it can be concluded that vessel speeds are approximately normally distributed. The MATLAB statistical test function ttest2 shows acceptance of means are equal between container and roll-on/roll-off vessels, as well as between general dry cargo and dredger vessels. This means that vessel speed is influenced by vessel type in most cases. The 95% confidence level is used in the rest of this paper.

2.5.2 Influence on unhindered vessel course (Question 2)

The results for the unhindered vessel course are shown in Figure 2.4. Figure 2.4*a* (sea to Nieuwe Maas) and Figure 2.4*b* (Nieuwe Maas to sea) show that the median course for the different container vessel categories in both directions is approximately equal.

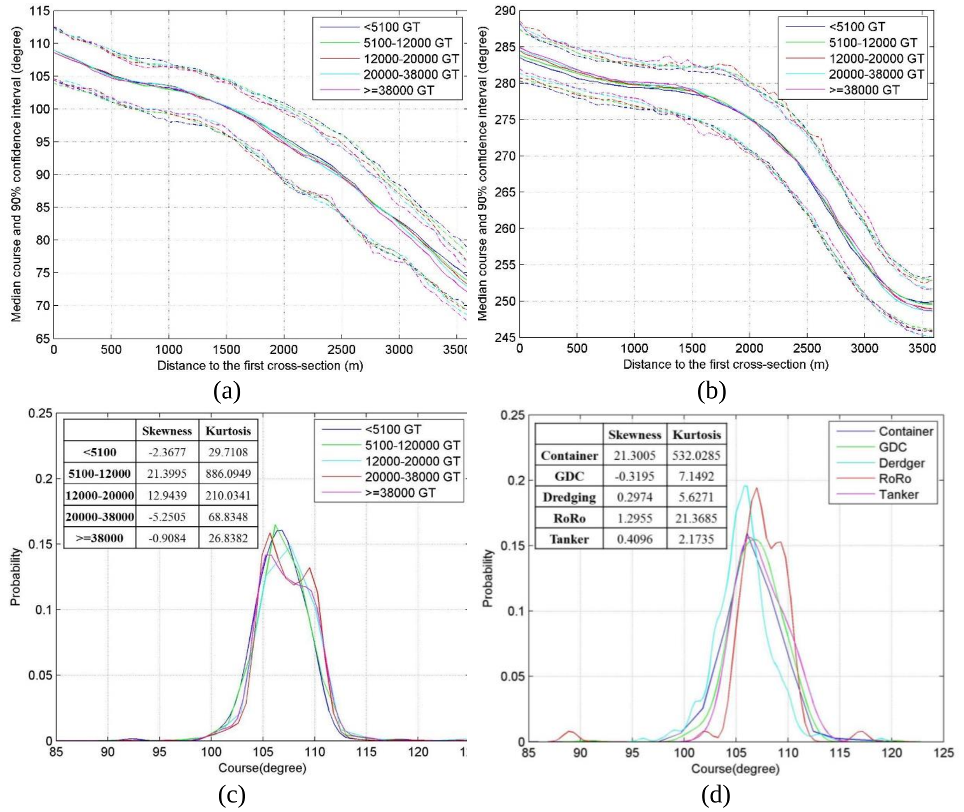


Figure 2.4: Unhindered vessel course: (a) median course of container vessels as function of waterway geometry (solid lines) and 90% confidence interval (dotted lines) in sea–Nieuwe Maas direction, (b) median course of container vessels as function of waterway geometry (solid lines) and 90% confidence interval (dotted lines) in Nieuwe Maas–sea direction, (c) comparison of vessel course of container vessels in sea–Nieuwe Maas direction on Cross Section 2, and (d) comparison of vessel course for five vessel types in sea–Nieuwe Maas direction on Cross Section 2.

Figure 2.4*c* shows the vessel course distribution of five container categories on Cross Section 2. According to skewness and kurtosis, the vessel course does not follow a normal distribution. In the statistical tests, means are equal is mostly accepted. This means that vessel course does not depend on vessel size.

Figure 2.4*d* shows course distributions for vessels of 3,500 to 6,500 GT from different vessel types on Cross Section 2. In the statistical test, means are equal is accepted in most cases. Thus it can be concluded that the mean course value is approximately equal for different vessel types, which means that vessel course is not influenced by vessel type.

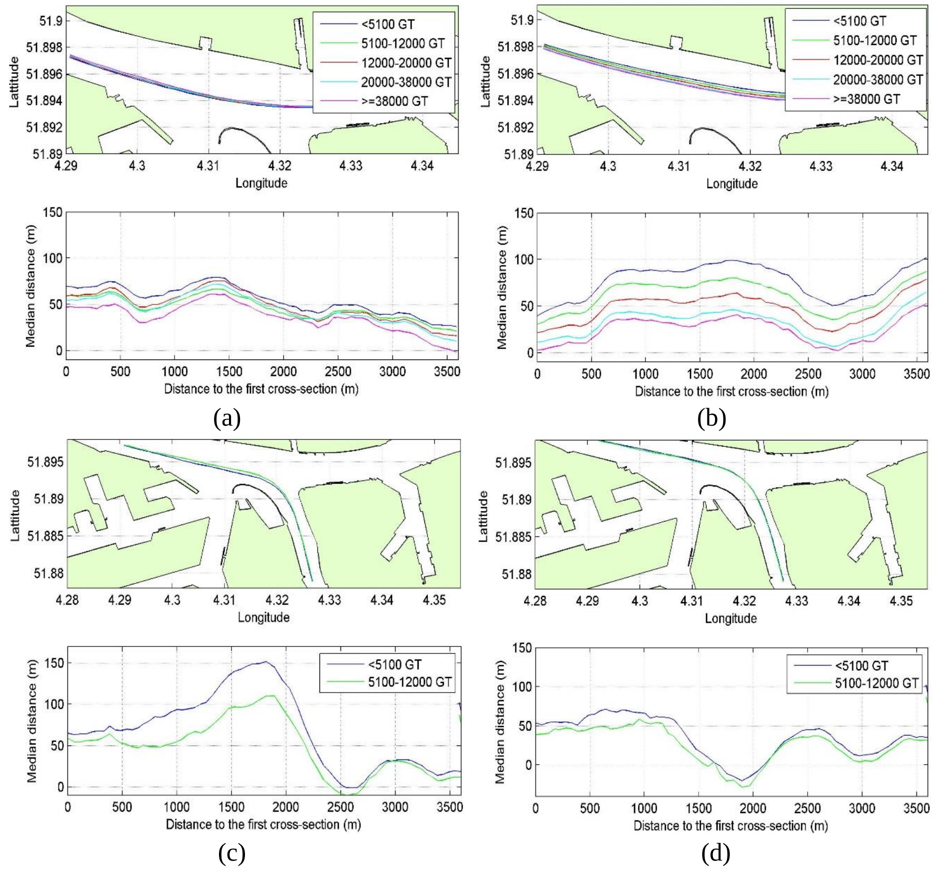


Figure 2.5: Unhindered median path of container vessels as a function of waterway geometry in four directions: (a) sea to Nieuwe Maas, (b) Nieuwe Maas to sea, (c) sea to Oude Maas, and (d) Oude Maas to sea.

2.5.3 Influence on unhindered vessel paths (Question 3)

Smaller vessels usually have a smaller beam and draught, so they can sail closer to the starboard bank. With the centerline formed by the middle points of all cross sections as a reference, Figure 2.5 shows vessel distance to the centerline of the waterway.

Figure 2.5*a* shows that the smallest vessels keep the largest distance to the centerline and the largest vessels keep the lowest distance to the centerline on all cross sections. For other vessel categories, some curves overlap in the middle of the figure. This could be caused by berthing vessels, which have influence on calculated vessels. For example, a vessel sails to the berths at the south side of the waterway. The behavior of this vessel is not included in the database for unhindered vessel behavior. However, the influence of this vessel on other sailing vessels cannot be eliminated in the calculation. Especially for sea to Nieuwe Maas, vessel behavior is affected by vessels arriving at and departing from the berths at the south bank of the waterway.

As shown in Figure 2.5*b*, compared with the direction of sea to Nieuwe Maas, the path for the direction Nieuwe Maas to sea is not strongly affected by berthing vessels, which makes the distance to the centerline throughout inversely proportional to vessel size. Thus, the vessel path is influenced by vessel size and waterway geometry.

Figure 2.5, *c* and *d*, shows the path for the directions sea to Oude Maas and Oude Maas to sea, respectively. Because of the relatively low amount of data for the larger vessel sizes, only two categories are analyzed. For sea to Oude Maas, the distance to the centerline decreases with increasing vessel size; for Oude Maas to sea, very little influence can be observed, probably because vessels all keep to port in anticipation of the turn to be made toward the sea.

2.6 External factors

In this section, unhindered vessel behavior calculated as in the last section is used to identify the influence of wind and visibility. Opposite thresholds for external conditions are used in the selection of AIS data, and the influence of each factor is investigated individually. Vessel behavior appears not to significantly differ when more than two categories are distinguished for both wind and visibility. Therefore, the analysis in this paper looks only at the extremes.

For both wind and visibility, the investigation includes only container vessels in Category 2 (5,100 to 12,000 GT) on Cross Section 2, which has the largest amount of AIS data (3,505 records) in all categories. Table 2.2 gives the mean values of vessel speed, course, and distance to the bank for an unhindered container in Category 2 on Cross Section 2. These values are used here for comparison and statistical tests.

2.6.1 Influence of wind on vessel behavior (Question 4)

Wind speeds greater than 8 m/s were chosen for investigation of influence of wind, cross wind, and against wind in comparisons to unhindered vessel behavior (Table 2.2). The shaded values in Table 2.2 indicate a significant difference compared with unhindered behavior. The table shows that with wind and cross wind affect vessel speed, but against wind does not influence vessel behavior. In other words, vessel speed is enhanced under a strong wind that has the same direction as the vessel, and vessel speed is decreased under a strong cross wind.

Table 2.2: Comparison between hindered and unhindered behavior for Container Category 2 on Cross-section 2

	Unhindered		Mean			
Parameters	Mean	Std	With wind	Cross Wind	Against wind	Visibility
Speed (kn)	11.38	1.95	11.9	10.85	11.9	10.45
Course (degree)	107.93	2.68	107.9	107.95	108.61	109.35
Distance (m)	140.28	35.23	135.36	136.52	124.06	125.87

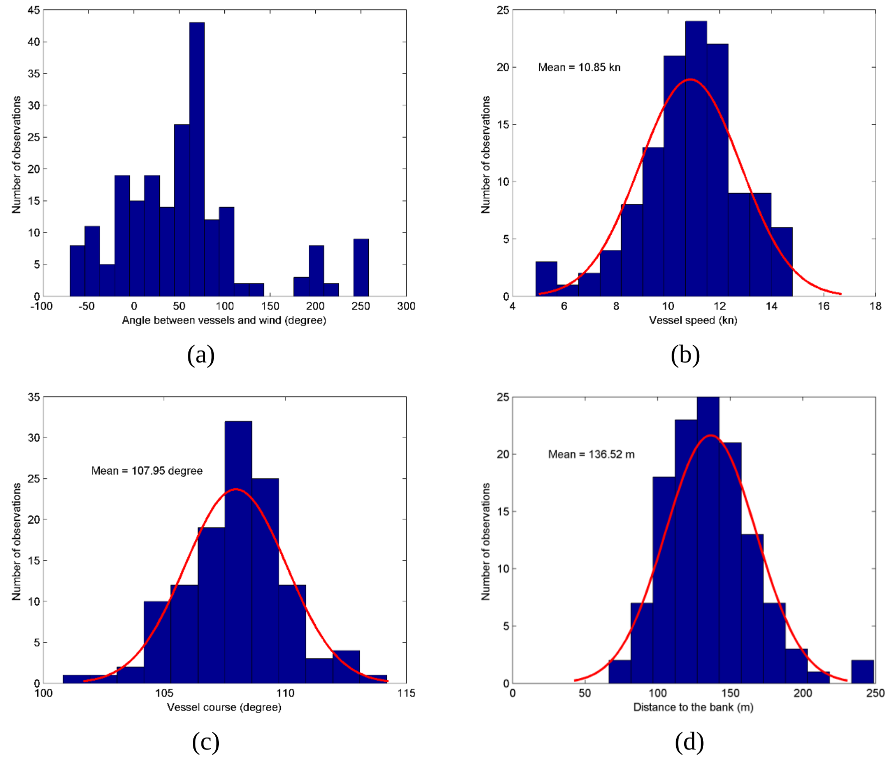
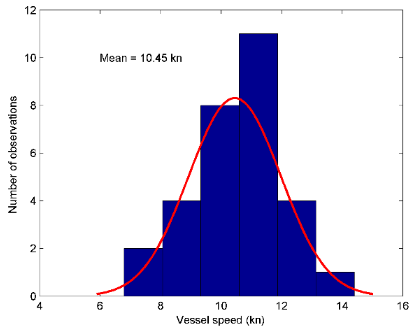


Figure 2.6: Effects of wind: (a) distribution of angle difference between vessels and strong wind; distribution and mean value under cross wind influence of (b) vessel speed, (c) vessel course, and (d) vessel distance to bank.

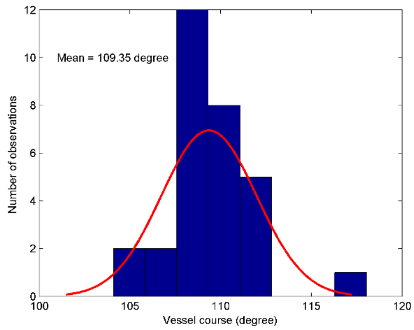
As an example, the results of this comparison for cross wind are shown in Figure 2.6. Figure 2.6*a* shows the distribution of the angle between vessels and strong wind, where 0 means that the wind and the vessel have the same direction. The figure illustrates that west is the dominant wind direction in this area and is vessel direction. The remaining three graphs of the figure show distributions of vessel speed, course, and distance to the bank under influence of a cross wind.

2.6.2 Influence of visibility on vessel behavior (Question 5)

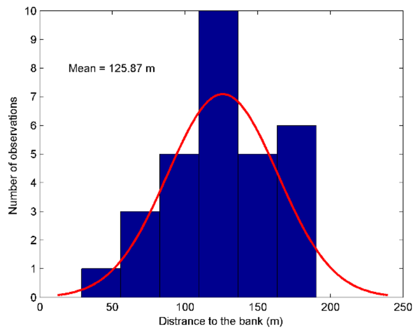
The method used to investigate the influence of wind was also used to investigate the influence of bad visibility, which here means less than 2 *km*. As shown in Table 2.2, all values under the visibility influence show significant differences compared with unhindered behavior. This is because the bridge team decreases the vessel speed and sails closer to the bank when visibility is poor. In this case the vessel course is changed as well. Distributions of vessel speed, course, and distance to the bank under the visibility influence are shown in Figure 2.7.



(a)



(b)



(c)

Figure 2.7: Distribution and mean value under visibility influence of (a) vessel speed, (b) vessel course, and (c) vessel distance to bank.

2.7 Conclusions and recommendations

This paper presented the results of an analysis of AIS data for behavior of unhindered vessels and the influence of external factors in the Botlek area of the port of Rotterdam in the Netherlands. Vessel categories were based on vessel type and size. Vessel behavior was characterized by three parameters: speed, course, and path (lateral position). Through analysis of these parameters under strong wind and bad visibility, the influence of these external factors was identified.

The results show different vessel behavior for different vessel categories. First, vessel speed is influenced by waterway geometry, navigation direction, vessel type, and vessel size. Smaller vessels have larger speeds in the Botlek area, where outgoing vessels navigate at greater speed than do incoming vessels. In addition, vessels in wide waterways sail faster than vessels in a narrow waterway. Second, vessel course depends little on vessel size and vessel type, but it does depend on waterway geometry and navigation direction. Third, vessel path is influenced by vessel type, vessel size, and waterway geometry. Smaller vessels keep a larger distance from the waterway centerline.

An analysis of the influence of external factors showed that wind has an effect on vessel speed but not on vessel course and path. In addition, visibility has a significant impact on vessel speed, course, and path. A bridge team decreases a vessel's speed and deviates to the bank when visibility decreases. Consequently, vessel course is changed as well.

Apart from supporting the new maritime traffic model, the findings of this research could be used to enhance maritime traffic safety for both port authorities and bridge teams. For example, the vessel traffic service center could send more frequent and more specific notices to passing vessels during high winds or reduced visibility, such as a notice of strong (dangerous) wind reminder.

In this paper, a limited number of factors was investigated. However, more factors exist that could affect vessel behavior, such as current, encounters, and tugs. Future research will add these elements, starting with current and encounters. In the next chapter, influence of external conditions including wind, visibility, current and encounters on vessel behaviour will be investigated.

The analysis results should be compared with those of other port areas to obtain a generalized set of parameter distributions, as boundary conditions for the new maritime traffic model, and for verification and validation of this model.

Chapter 3

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

This chapter is an edited version of the article:

Shu, Y., W. Daamen, H. Ligteringen, & S. P. Hoogendoorn (2017) Influence of external conditions and vessel encounters on vessel behavior in ports and waterways using Automatic Identification System data, *Ocean Engineering*, 131, pp. 1-14.

Abstract

The impact of many external factors, such as wind, visibility and current, on the behavior of vessels in ports and waterways has not been investigated systematically in existing maritime traffic models. In order to fill the current knowledge gap and provide a basis for developing a new model to effectively simulate maritime traffic, the influences of wind, visibility and current as well as vessel encounters on vessel behavior (vessel speed, course and relative distance to starboard bank) have been investigated in this study by analyzing Automatic Identification System data collected from the port of Rotterdam. It is found that wind, visibility, current and encounters have significant impact on the vessel speed and relative distance to starboard bank, while vessel course is mainly affected by current and encounters. The results also showed that the vessels would adapt their speed, course and relative distance to starboard bank during encounters. These findings showed the importance of considering external factors and

encounters in simulating vessel behavior in restricted waterways and provide a starting point for building up more comprehensive maritime traffic models.

3.1 Introduction

As one of the important modes of international freight transportation, the scale of maritime transportation has been expanding sharply in recent decades. The increase of both vessel number and size draws more and more concerns for the balance between safety and capacity of maritime traffic: when measures are taken to increase capacity, usually the safety decreases, and vice versa. This holds even stronger for ports and inland waterways, where vessel encounters and external conditions can significantly influence vessel behavior, such as vessel speed and course. In those areas, vessel collisions and groundings occur more often because of the confined space (Darbra & Casal, 2004). As maritime traffic accidents may have serious consequences, such as personnel and property losses, traffic congestion and environmental impacts both in the water and in the surrounding area, it is desirable to properly address the safety and capacity of the maritime traffic system in restricted waterways.

Currently, various simulation models are available to investigate the maritime traffic system. Some of these models have been developed to assess risk of collisions and groundings (Goerlandt & Kujala, 2011; Montewka et al., 2010; Qu et al., 2011),while other models have been built to investigate the effect of vessel hydrodynamics and vessel maneuverability (Sariöz & Narli, 2003; Sutulo et al., 2002). However, most models focus on maritime traffic in open seas while only few investigate the traffic in ports and waterways (Xiao, 2014). And all these models consider only a limited number of external factors.

Initial studies qualitatively showed that the wind and current can effect vessel speed and course in ports (De Boer, 2010). However, the influence of external factors, either wind or current, on vessel behavior was investigated without eliminating the impact of other factors on vessel behavior in this study and the influence of external factors on vessel behavior has not been quantified. A recent maritime traffic simulation study showed that vessel characteristics (type and size) can also significantly influence the vessel behavior in ports (Xiao et al., 2015). Notwithstanding these studies, the influence of external conditions (including wind, visibility and current) and vessel encounters on vessel behavior is not yet fully understood and quantified.

The aim of this paper is to systematically investigate and quantify the influence of external conditions and vessel encounters on vessel speed, course and vessel path in ports and waterways. For vessels sailing in the confined waterways of the port, the vessel path is described by the relative distance to the starboard bank (the distance to starboard bank divided by waterway width). So, vessel speed, course and relative distance to starboard bank are three parameters considered in this paper. As currently no other research specifically focuses on this aspect, the results of this paper are seen as an essential basis for improvement of maritime traffic models and investigations on maritime traffic. In addition, this research also shows a method how to utilize Automatic Identification System (AIS) data and cross sections to extract useful information, such as vessel encounters.

Based on this aim, the following research questions were proposed:

Research question 1: How does wind influence vessel behavior (vessel speed, vessel course and relative distance to starboard bank)?

Research question 2: How does visibility influence vessel behavior (vessel speed, course and relative distance to starboard bank)?

Research question 3: How does current influence vessel behavior (vessel speed, course and relative distance to starboard bank)?

Research question 4: How do vessel encounters (head-on and overtaking) influence vessel behavior (vessel speed, course and relative distance to starboard bank)?

In this paper, the research data and approach are introduced in Section 3.2. Then, the influences of wind, visibility, current and vessel encounters on vessel behavior are presented, respectively, in Section 3.3 to 3.6. Finally, this paper ends with conclusion and discussions in Section 3.7.

3.2 Research area, data and approach

In this section, the research area is introduced, followed by the introduction of the research data and research approach. Then, the statistical analysis method used in this paper is described.

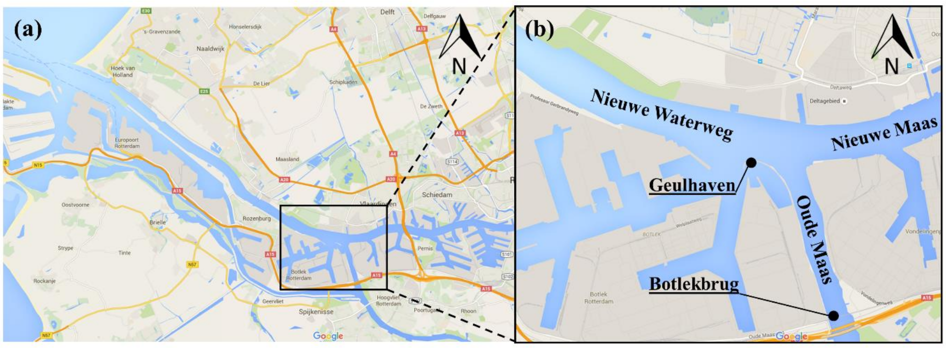


Figure 3.1: (a) Location of research area: the Botlek area in the port of Rotterdam; (b) the zoom-in view of the Botlek area, comprising three parts: “Nieuwe Waterweg”, “Nieuwe Maas” and“Oude Maas”. The locations of the measuring station “Geulhaven” for wind and visibility and the measuring station “Botlekbrug” for current are also specified.

3.2.1 Research area

The research area used in this study is the Botlek area in the port of Rotterdam, as shown in Figure 3.1. This area is chosen because of its high traffic density and the availability of historical data of wind, visibility and current from measuring stations located in this area. The research area comprises three navigation channels: “Nieuwe Waterweg”, “Nieuwe Maas” and “Oude Maas”. As the main waterways connecting the older port basins with the Sea, the “Nieuwe Maas” and the “Nieuwe Waterweg” have a width of around 400 meters and a minimum depth of 13.8 meters below Mean Lower Low Water (MLLW), which is the average height of the lowest tide recorded at a tide station in the port area. The vessel traffic in these two waterways mainly consists of commercial vessels including container vessels (59.6%) and General Dry Cargo (GDC) vessels (29.3%). 75% of these are small vessels less than 10,000 gross tonnage (GT). The “Oude Maas” joins the “Nieuwe Maas” from the south and forms the main connection for vessel traffic from the port of Rotterdam to the hinterland. The “Oude Maas” has a width of around 200 meters and a minimum depth of 9.6 meters MLLW. This condition in the “Oude Maas” restricts vessels, so 95% of the vessels in the “Oude Maas” are small vessels less than 10,000 GT. Among these vessels, 63.7% are GDC vessels and 26% are tankers. In these analyses, the following four navigation directions are distinguished according to main vessel traffic flows:

- Sea-Nieuwe Maas: vessels sail from Sea to the “Nieuwe Maas”
- Nieuwe Maas-Sea: vessels sail from the “Nieuwe Maas” to the Sea
- Sea-Oude Maas: vessels sail from the Sea to “Oude Maas”
- Oude Maas-Sea: vessels sail from the “Oude Maas” to the Sea

3.2.2 Research data

The research data consists of two parts. Firstly, the vessel behavior is collected from the AIS data, which are provided by the Maritime Research Institute Netherlands (MARIN), using “ShowRoute”. The “ShowRoute” is a dedicated software developed by MARIN used for investigation of AIS data. AIS data have turned out to be a useful tool to investigate maritime traffic (Aarsæther & Moan, 2009; Hansen et al., 2013; Meng et al., 2014; Mou et al., 2010). Secondly, the wind, visibility and current data collected from two measuring stations in the research area are provided by the Port of Rotterdam Authority. In this section, AIS data and cross sections used to collect the AIS data are introduced firstly. Then, the available wind, visibility and current data are described.

AIS data and cross sections

In the 1990s, the International Association of Maritime Aids to Navigation and Lighthouse Authorities (IALA) presented to the International Maritime Organization (IMO) the first proposal for AIS, in which the AIS system is designed to identify other vessels including their positions (Eriksen et al., 2006). The purpose of the AIS system is “to contribute to improved situational awareness for shore-side authorities and ships’ officers” (Bailey et al., 2008). The AIS system works on Very High Frequency (VHF), so it is possible to detect other AIS-equipped vessels when the radar detection is confined, such as under influence of strong rain or tall buildings. In the International Convention for the Safety of Life at Sea (SOLAS), IMO made AIS mandatory for vessels of 300 GT and more by 2004, and now it is mandatory for small vessels as well.

The AIS system records the following types of data: static vessel data (Maritime Mobile Service Identity (MMSI) number, type of vessel, length, beam, etc.), dynamic vessel data (vessel position, time instant, speed, course, etc.) and voyage related information (draught, cargo, destination, etc.). The static vessel data are entered into the AIS system when the AIS unit is installed on vessels. It needs to be changed only if the ship type changes or if her name or MMSI changes. The dynamic information contains the vessel behavior information and serves as input for the analyses in this research. The voyage related data is entered manually by the vessel’s crew (Eriksen et al., 2006).

The accuracy of AIS data has been improved a lot in the last decade. It was found that the percentage of vessels that transmitted errors decreased from 10.4 % in 2004 to 3.5 % in 2007, and most errors are about destination and draught, which includes misspelling, empty data fields, incomprehensible abbreviations and references to the previous port (Bailey et al., 2008; Harati-Mokhtari et al., 2007). It was also found that errors occur in Estimated Time of Arrival (ETA) (21.7 % of the observations were wrong), IMO number (14.1 %), Destination (11.0 %), Rate of turn (8.9 %), Heading (7.1 %), Dimensions (6.2 %), Draught (5.7 %), Course over ground (0.8 %), Speed over ground (0.8 %) and a missing ship name (0.04%) (Solvsteen, 2009). It can be concluded that dynamic vessel data are more accurate.

To reduce the data set size and to easily derive and compare the lateral position per ship, cross sections were defined and used to extract AIS data. As shown in Figure 3.2, 69 cross sections in Sea-Nieuwe Maas and Nieuwe Maas-Sea and 68 cross sections in Sea-Oude Maas and Oude Maas-Sea are defined (Shu et al., 2013b). The systematic approach to make the cross sections perpendicular to waterway centerline is preferable. When we analyzed the AIS data, we have drawn the cross sections manually in “ShowRoute” in a more pragmatic manner. We have found that the results, in terms of vessel speed, course and relative lateral position, are not sensitive to the precise choice of the cross sections. Thus, these cross sections are not strictly perpendicular to waterway direction. The interval between cross sections is approximately equal to 50 meters, which is similar to the distance in which vessels send one AIS record, as the average speed of vessels in this area is around 10 knots (5.14 m/s) and the reporting interval for most vessels is 10 seconds. Each cross section is formed by linking two points at the 5-meter depth contours on two sides of the waterway, which are the dividing lines between light blue and dark blue area. The light blue indicates the area where the water depth is larger than 5 meters, while the dark blue is corresponding to the area shallower than 5 meters. These two points are chosen such that the cross section is approximately perpendicular to the waterway axis. The 5-meter depth contours are used because vessels normally do not pass the 5-meter depth contour to avoid groundings. Therefore, the 5-meter depth contours are considered as part of the bank in our research. It should be noted that there is no 5-meter depth contour in the junction area and entrances to the basins on one side of the waterway, so there a smooth curve is defined to link the adjacent 5-meter depth contours, as described previously (Shu et al., 2013).

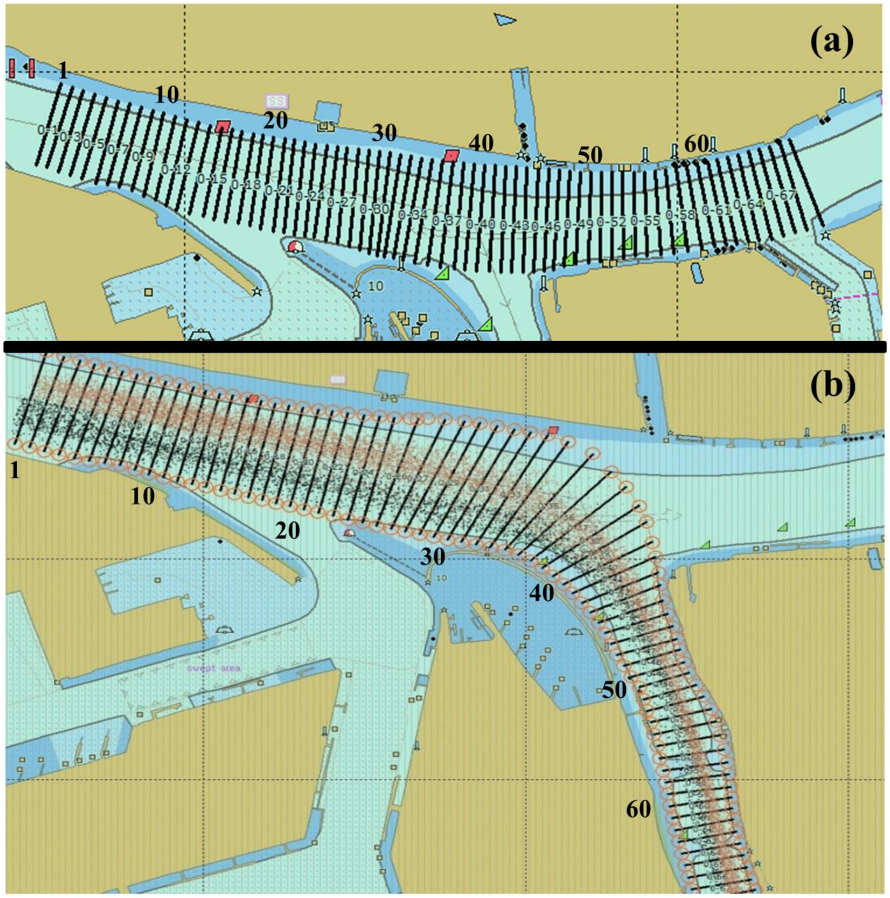


Figure 3.2: (a) 69 cross sections in Sea-Nieuwe Maas and Nieuwe Maas-Sea, the cross sections are numbered from the west to the east as cross section 1 to 69; (b) 68 cross sections in Sea-Oude Maas and Oude Maas-Sea, the cross sections are numbered from the west to the southeast as cross section 1 to 68 (Shu et al., 2013).

Using these cross sections, AIS data in the time period from January 2009 to April 2011 are extracted in the four aforementioned directions and will be used for the analyses. To calculate vessel speed, course and position on a cross section, the data from the nearest point before and after the cross section is used to extrapolate the values on the cross section, based on the function of time using linear interpolation. In this way, each vessel path will have one data record on each cross section.

Wind, visibility and current data

The wind, visibility and current data are collected by two measuring stations in the research area. The wind and visibility data are recorded every 5 minutes by the measuring station “Geulhaven” (Figure 3.1), which is located in the center of the research area. As the research area is relatively small and there are no obstructions, wind and visibility are considered to be homogeneous in this area.

In order to investigate the influence of current on vessel behavior, it is important to have reliable current data in the research area. In this study, the current data are available from the measuring station “Botlekbrug” (Figure 3.1), which is located in “Oude Maas”, and in the south of the research area. Because the measured current data from one measuring station cannot represent the current in the whole area, it is essential to identify the applicable area of the measured current data. These data are recorded every 10 minutes and velocity is taken at 5 meters depth to the local datum - Amsterdam Ordnance Datum (in Dutch “Normaal Amsterdams Peil”, NAP). As the current is influenced by river discharge, the tidal condition and waterway geometry, the current may vary at different locations as well as over the water depth. However, for most of the vessels that pass along Oude Maas, the current speed at 5m below NAP represents the average conditions fairly well (for which reason this depth has been chosen by the authorities). In order to link the recorded current data to currents in other parts of the research area, a numerical simulation model called Delft3D (Roelvink & Van Banning, 1995) has been applied by the Port of Rotterdam Authority to simulate the currents along the stretch Sea-Oude Maas under different tidal conditions within one day. The annual average discharge of 2300 m3/s is applied as input for this model and both the neap and spring tide are simulated for tidal conditions. It is assumed that the variability of real current is similar to the variability of simulated current along the waterways.

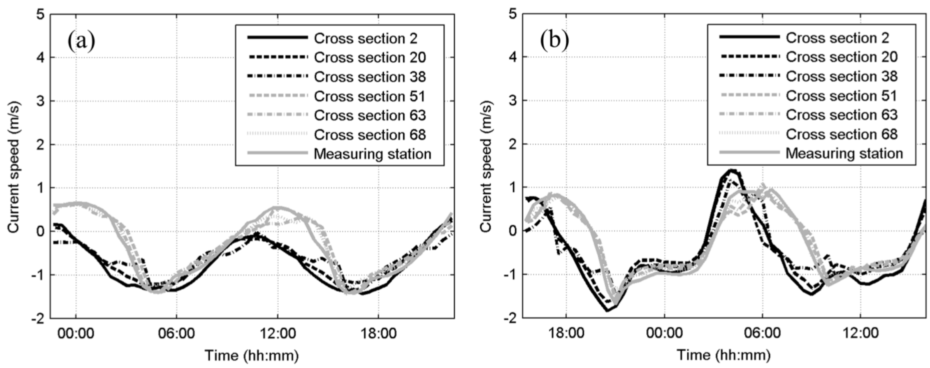


Figure 3.3: The simulated current speed at the condition of (a) neap-average discharge and (b) spring-average discharge, at different cross sections and at the measuring station over one day, simulated by the model Delft3D.

The simulated current during the simulation period at the measuring station and at cross sections 2, 20, 38, 51, 63 and 68 are presented as examples in Figure 3.3. Here, cross sections 2, 20, 38, 51, 63 and 68 are chosen as representative situations, which are clearly distinct from each other. These cross sections are selected from both straight stretches and the bend. Cross sections 2 and 20 represent the situation in the straight stretch “Nieuwe Waterweg”; cross section 38 is selected because it is located in the middle of the bend area; cross section 51, 63 and 68 represent the situation in the straight stretch “Oude Maas”. It is shown that the simulated current at the measuring station and at the cross sections 51, 63 and 68, which are all located in the “Oude Maas”, do not show substantial differences. The absolute difference between the simulated current at the measuring station and the values at cross sections 51, 63 68 is 0.21, 0.16 and 0.18 m/s for neap-average discharge and 0.19, 0.11 and 0.14 m/s for spring-average discharge, respectively. In comparison, the absolute difference between the simulated current at the measuring station and the value on cross sections 2, 20, 38 (located on “Nieuwe Waterweg”) is much larger (0.62, 0.56 and 0.62 m/s for neap-average discharge and 0.5, 0.49, 0.39 m/s for spring-average discharge, respectively). This result implies that the current data collected from the measuring station in “Oude Maas” can be used to represent the current on cross sections 51-68. This finding enables us to investigate the influence of current on vessel behavior in this area.

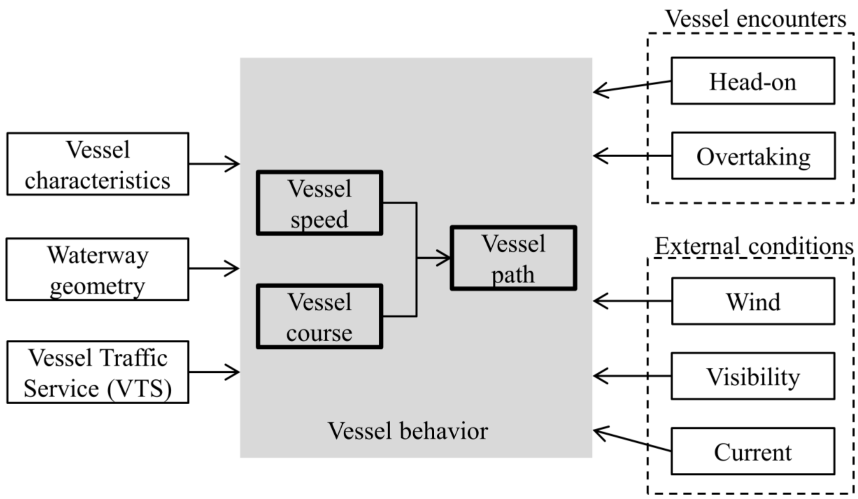


Figure 3.4: Vessel behavior and potential factors influencing vessel behavior.

3.2.3 Research approach

In our research, the bridge team is considered as the “brain” of the vessel and covers the intelligence and decision making for the vessel. Based on this assumption, the bridge team and the vessel are considered as an integrated entity. The vessel behavior discussed in this paper is governed by this entity and is defined by the vessel speed, course and path. The vessel behavior and potential factors influencing vessel behavior are shown in Figure 3.4. It can be seen that vessel behavior can be affected by different factors, such as vessel characteristics and waterway geometry. In this paper, external conditions (wind, visibility and current) and vessel encounters (head-on and overtaking) are investigated, while specific vessel categories classified by vessel type and size (Shu et al., 2013) are used to eliminate the influence of vessel characteristics.

It is hypothesized that vessel behavior changes in different external conditions and encounters. This hypothesis is tested by the comparison between different data sets with different thresholds, which are determined according to the local external conditions. On the one hand, these thresholds should be used to distinguish different vessel behavior. On the other hand, appropriate thresholds should be made to keep enough data for studying both influenced and uninfluenced vessel behavior. The research approach is to directly compare the vessel speed, course and relative distance without the influence of external conditions with the situations under which the vessel behavior is influenced by an individual factor. To this aim, the uninfluenced behavior, for vessels that are not influenced by external conditions (below or above certain threshold value) and by the presence of other vessels (the distance to other vessels is larger than a certain threshold) and the influenced behavior, where external conditions and/or vessel encounters play a substantial role to affect vessel behavior, were defined in a recent study (Shu et al., 2013).

Table 3.1: Conditions for uninfluenced and influenced vessel behavior

	Conditions for uninfluenced behavior	Conditions for influenced behavior
Wind All cross sections	Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m	Wind > 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m
Visibility All cross sections	Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m	Wind < 8m/s Visibility < 2,000 m Distance to other vessels > 1,000 m
Current Cross sections 51-68	Current < 0.8 m/s Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m	Current > 0.8 m/s Wind < 8m/s Visibility > 2,000 m Distance to other vessels > 1,000 m

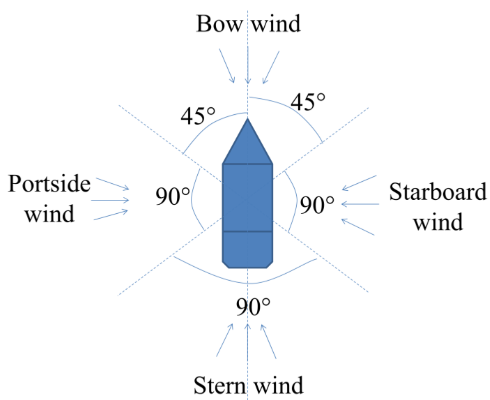


Figure 3.5: Four wind categories based on the angle between vessel course and wind direction.

In this research, the AIS data are combined with historical data of wind, visibility and current by linearly interpolation based on time and coupling the time records of the individual AIS messages and the data sets for wind, visibility and current. The combined data set is divided into two groups corresponding to the uninfluenced and influenced vessel behavior according to the conditions listed in Table 3.1. The thresholds for selecting uninfluenced vessel behavior are the same as we used in the previous paper: for wind < 8 m/s, for visibility > 2,000 meters and for encounters a distance to other vessels including moored vessles < 1,000 meters (Shu et al., 2013). The extra condition for uninfluenced vessel behavior is for current < 0.8 m/s. It should be noted that current is not considered when the influences of wind and visibility are investigated, because the current data only cover cross section 51-68.

For the influenced behavior listed in Table 3.1, different categories for influenced behavior by wind and current are investigated. For wind, it is assumed that the wind has main influence on the side of the vessel where the wind comes from (bow, portside, stern or starboard), every side comprising directions within an arc of 90 degrees. As shown in Figure 3.5, four wind categories are defined (Stern wind, Starboard wind, Bow wind and Portside wind) according to the angle between the wind and the course of vessels. For current, two categories “Against current” and “With current”, are chosen.

To compare the influence of wind and visibility on vessel behavior, the vessel categories for container vessels with 5,100-12,000 GT and general dry cargo (GDC) vessels with gross tonnage less than 3,600 GT on all cross sections in Sea-Nieuwe Maas are investigated in this paper (Shu et al., 2013). These two vessel categories in this direction are investigated since they are the most common vessel categories in the research area and Sea-Nieuwe Maas is the direction with the main vessel traffic flow. For current, GDC vessels with gross tonnage less than 3,600 GT on cross sections 51-68 in Sea-Oude Maas and in Oude Maas-Sea are investigated, since GDC vessels are the most common vessels in these two directions.

For encounters, three main types of vessel encounters have been distinguished according to the International Regulations for Preventing Collisions at Sea (COLREG): head-on, overtaking, and crossing encounters. Compared to head-on and overtaking encounters, cross encounters are more complicated for navigators to deal with and more difficult to be analyzed. In an early stage of this study, we have chosen to focus on head-on and overtaking encounters, which are more common in our research area, leaving crossing encounters as subject of future research. The AIS data on each cross section are used to select head-on and overtaking encounters according to the time in each AIS message. For head-on encounters, two vessels sail in different directions. These vessels are selected from the AIS data set according to the moment they pass adjacent cross sections. For vessel A sailing from cross sections n to cross section $n+1$. If vessel B appears between these two cross sections during this period, a head-on encounter occurs. In overtaking encounters, overtaking and overtaken vessels sail in the same direction. Similar to head-on encounters, these vessels are selected based on the moment they pass adjacent cross sections. For example, vessel A passes cross section n later than vessel B and it passes the next cross section $n+1$ earlier than vessel B. Then, vessel A overtakes vessel B between these two cross sections. It should be noted that the influences of wind, visibility and current are not considered in these analyses.

The influences of encounters on vessel behavior are investigated in Sea-Nieuwe Maas and Nieuwe Maas-Sea, which are the waterways with the main vessel traffic flow. Using the algorithm above, 948 head-on encounters are selected in Sea-Nieuwe Maas and Nieuwe Maas-Sea, while 146 and 106 overtaking encounters are selected respectively in Sea-Nieuwe Maas and in Nieuwe Maas-Sea.

It should be noted here that vessel type and size is not considered when we investigate the influence of vessel encounters on vessel behavior. To investigate average vessel behavior in encounters, the cross section nearest to the Closest Point of Approach (CPA) is defined as the relative cross section 0. Then, the cross sections located ahead and behind the relative cross section 0 are defined as the relative cross sections with negative ids and positive ids ranging in [-68,68], respectively. However, it is important to mention that the research area was divided into 69 cross sections. If the relative cross section is located close to the border of the research area, some relative cross sections would be located out of the research area, i.e. there is no data available. Therefore, the data availability on the relative cross sections decreases with the increasing distance to the relative cross section 0. To ensure that the average vessel behavior on each relative cross section is supported by enough data, the minimum requirement for data number on each relative cross section is 30 in these analyses. Then, the uninfluenced and influenced vessel behavior at each relative cross section is calculated and compared for both vessels in encounters, and the uninfluenced behavior is calculated according to the vessel categories in our previous research (Shu et al., 2013).

3.2.4 Statistical analysis method

As it was found that vessel behavior is influenced by waterway geometry (Shu et al., 2013), comparison between uninfluenced and influenced vessel behavior should be performed on each cross section. In this paper, the Kolmogorov-Smirnov test (K-S test) is used to test if uninfluenced and influenced vessel behavior come from the same distribution. The null hypothesis of the K-S test is that “the uninfluenced and influenced vessel behavior are drawn from the same distribution”. In this method, a threshold for the p-value, called the significance level of the test, is used as 5%. To represent the results of K-S test, the parameter p_r is the percentage of cross sections, on which the null hypothesis of K-S test is rejected.

In addition, Mean Absolute Percentage Error (MAPE) is used to represent the average of percentage errors by which influenced behavior differs from the uninfluenced behavior. The MAPE in this paper is defined as:

$$\mathrm{MAPE} = 1/n \sum_{i=1}^{n} |\mu_i - \mu_i^*|/\mu_i^* \tag{3.1}$$

where n is the number of cross sections, and μ_i and μ_i^* denote the average influenced and uninfluenced behavior on cross section i, respectively. If n equals to 1, the MAPE will become Absolute Percentage Error (APE), which will be used to investigate the vessel behavior at the relative cross section 0 during encounters in Section 3.6.1 and Section 3.6.2.

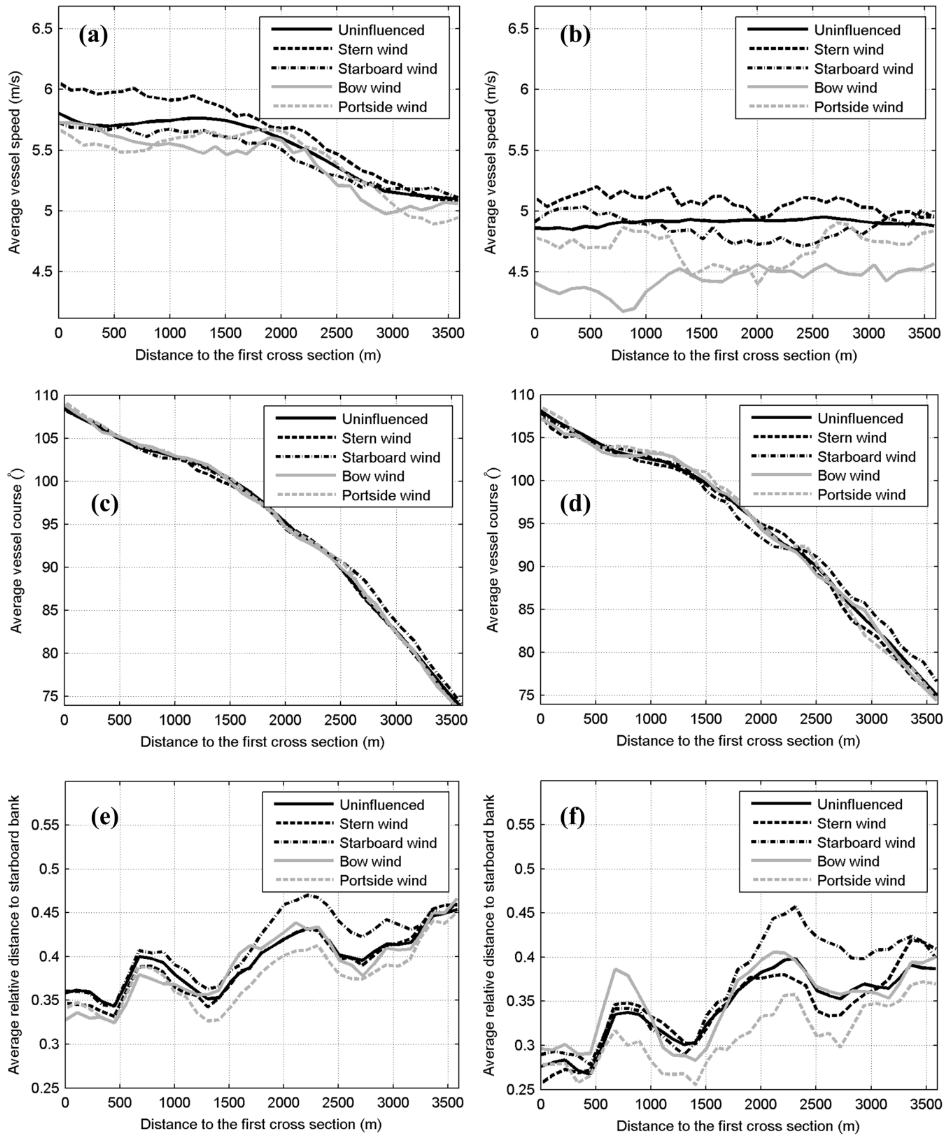


Figure 3.6: Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by wind for container vessels in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by wind for GDC vessels in Sea-Nieuwe Maas.

3.3 Influence of strong wind on vessel behavior (Research question 1)

Fig 3.6 shows the average uninfluenced and influenced vessel behavior by stern wind, starboard wind, bow wind and portside wind for the two vessel categories. Here, the x-axis "distance to the first cross section" represents the longitudinal distance along the centerline of the waterway.

As shown in Figure 3.6 (a) and Figure 3.6 (b), vessel speed is influenced by strong wind for both container and GDC vessels, especially under stern wind and bow wind. It is in line with our expectations that vessel speed increased under stern wind and decreased under bow wind, which is caused by the wind force added on the vessels. For starboard wind and portside wind, a small drop is observed on most cross sections and can be explained by the anticipation of dangerous situations by the bridge team. In Figure 3.6 (c) and Figure 3.6 (d), it is shown that the influenced vessel course is similar to uninfluenced vessel course for both container and GDC vessels. However, the larger fluctuations of vessel course for GDC vessels than for container vessels also indicate that GDC vessels are more easily affected by wind than container vessels. Figure 3.6 (e) and Figure 3.6 (f) show that the relative distance to starboard bank under stern wind and bow wind are comparable with uninfluenced behavior, while the relative distance is decreased under portside wind and it is increased under starboard wind. It also can be found that the deviation of relative distance under portside wind and starboard wind from the uninfluenced behavior is larger for GDC vessels than for container vessels. In addition, the deviation between uninfluenced and influenced relative distance is larger in the eastern part of the waterway than in the western part. This might be caused by the influence of the waterway geometry.

As mentioned before, p_r represents the percentage of cross sections, on which the null hypothesis of K-S test is rejected. To compare the average difference between uninfluenced and influenced behavior along the waterway, the values of p_r and MAPE for different wind categories are shown in Table 3.2.

Table 3.2: Statistical results of p_r and MAPE between uninfluenced and influenced vessel behavior by wind in Sea-Nieuwe Maas

		Speed		Course		Relative distance	
		$p_r(\%)$	$MAPE(\%)$	$p_r(\%)$	$MAPE(\%)$	$p_r(\%)$	$MAPE(\%)$
Container 5,100-12,000 GT	Stern	39.1	2.3	7.2	0.3	2.9	1.6
	Starboard	1.4	1.4	30.4	0.6	37.7	4.2
	Bow	11.6	2.5	4.3	0.4	1.4	3
	Portside	2.9	2.1	2.9	0.3	11.6	4.9
GDC <3,600 GT	Stern	10.1	3.4	10.1	0.6	17.4	3.3
	Starboard	0	2.2	30.4	0.9	30.4	7.3
	Bow	97.1	9.6	0	0.5	0	4.5
	Portside	13	4.3	13	0.7	20.3	9.4

As shown in Table 3.2, the null hypothesis of the K-S test for container vessel speed is rejected at 39.1% and 11.6% of cross sections for stern wind and bow wind, respectively. The values of MAPE indicate that the speed is increased by 2.3% and decreased by 2.5% under stern wind and bow wind, respectively. For GDC vessels, stronger influence is observed for bow wind and the null hypothesis is rejected on 97.1% of cross sections, where vessel speed is decreased by 9.6%. Although vessel speed is only influenced by stern wind at 10.1% of cross sections, the value of MAPE shows vessel speed is increased by 3.4%. The null hypothesis of the K-S test is accepted for starboard and portside wind at most cross sections for both container and GDC vessels. This means that the starboard and portside wind do not influence vessel speed.

For vessel course, the null hypothesis of K-S test is accepted in most cases, except for starboard wind, under which the null hypothesis is rejected at around 30% of cross sections for both vessel categories. Such results imply that only starboard wind has influence on vessel course.

Similarly, the strongest influence on the relative distance to starboard bank is also observed for starboard wind, under which the null hypothesis is rejected for more than 30% of cross sections for both vessel categories, and the relative distance is increased by 4.2% and by 7.3% for container and GDC vessles, respectively. The strong influence is also observed for portside wind, under which the relative distance is decreased by 4.9% and by 9.4% for both vessel categories. This indicates that starboard and portside wind lead to lateral deviation to portside and starboard bank, respectively.

It can be concluded that stern wind and bow wind influence vessel speed, starboard wind affect vessel course, and starboard and portside wind has influence on the relative distance to starboard bank. Furthermore, the influence of wind on GDC vessels is stronger than the influence on container vessels. This might be caused by the different superstructure and different size of these two vessel types.

3.4 Influence of bad visibility on vessel behavior (Research question 2)

The results of visibility for the two vessel categories in Sea-Nieuwe Maas are presented in Figure 3.7. In Figure 3.7 (a), it can be found that vessel speed is decreased under bad visibility for container vessels. Compared to Figure 3.7 (b), the difference between uninfluenced and influenced vessel speed for container vessels is much larger than for GDC vessels. This might be caused by the different perception of danger for different vessel categories. Figure 3.7 (c) and Figure 3.7 (d) show strong resemblance of uninfluenced and influenced vessel course, which means the vessel course is barely influenced by bad visibility. In Figure 3.7 (e) and Figure 3.7 (f), the relative distance for influenced behavior is observed to be smaller than for uninfluenced behavior on most cross sections. This means that vessels sail closer to the bank in bad visibility, although they may have radar system onboard. The statistical results of p_r and MAPE are presented in Table 3.3.

The statistical results show different influence on vessel speed for container and GDC vessels. For container vessels, the null hypothesis is rejected on most cross sections (58%) and the MAPE shows that vessel speed is decreased by 4.9%. However, p_r shows that the null hypothesis is accepted for GDC vessels on all cross sections and the value of MAPE is very small (1.7%). For vessel course, it is found that bad visibility almost does not influence vessel course for both container and GDC vessels. Although the null hypothesis is rejected for relative distance on 24.6% and 11.6% of cross sections for container and GDC vessels, the values of MAPE are 3.6% and 5.1%. This means that vessels will deviate to starboard bank under bad visibility and the influence for GDC vessels is stronger than for container vessels. This can be explained by the perception of danger for the bridge team and thus they sail closer to the bank.

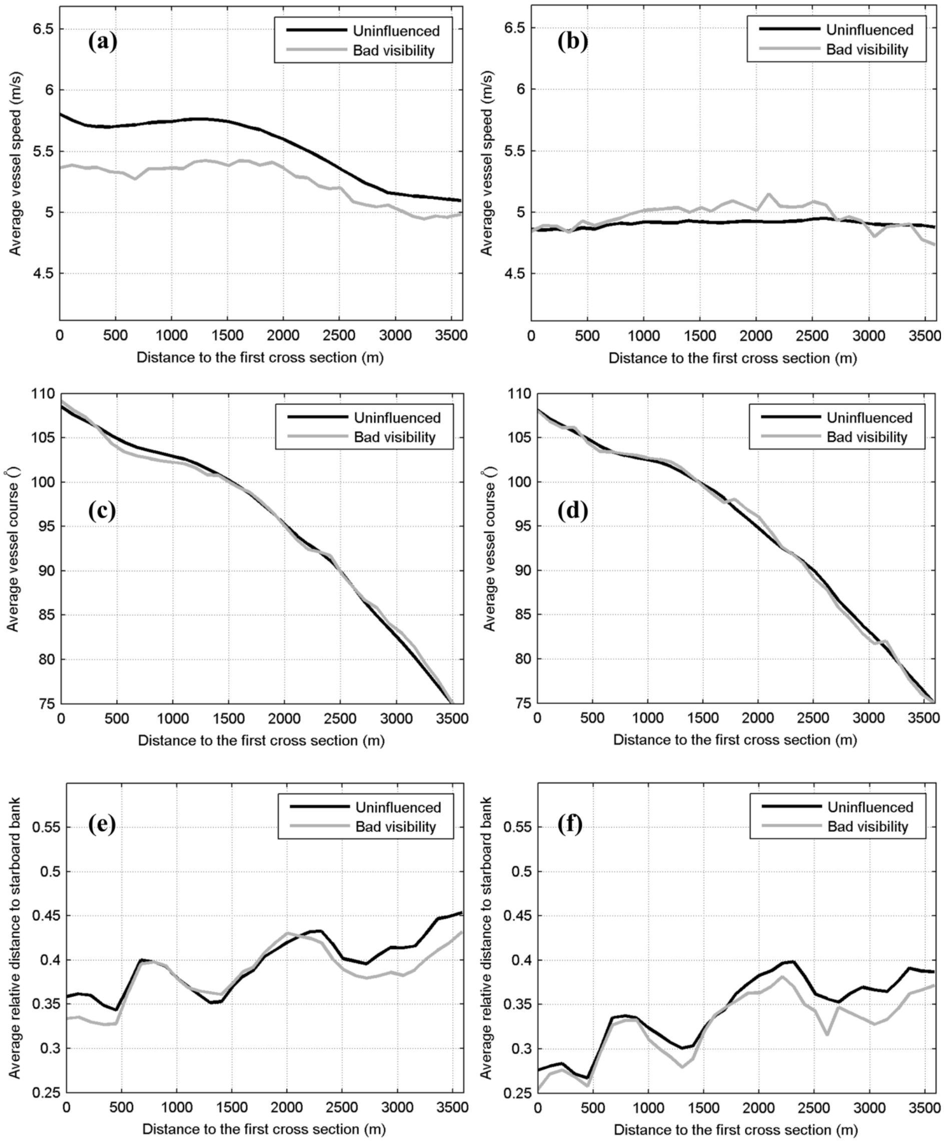


Figure 3.7: Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by visibility for container vessels in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by visibility for GDC vessels in Sea-Nieuwe Maas.

Table 3.3: Statistical results of p_r and MAPE between uninfluenced and influenced vessel behavior by visibility in Sea-Nieuwe Maas

	Speed		Course		Relative distance	
	p_r(%)	MAPE(%)	p_r(%)	MAPE(%)	p_r(%)	MAPE(%)
Container 5,100-12,000 GT	58	4.9	11.6	0.5	24.6	3.6
GDC <3,600 GT	0	1.7	0	0.5	11.6	5.1

To conclude, bad visibility has a negative influence on container vessel speed, but it does not influence GDC vessel speed. It is also found that vessel course is barely influenced by visibility. For the relative distance, both container and GDC vessels will deviate to starboard bank under bad visibility, where the GDC vessels will deviate more than container vessels. This could be explained by the smaller draught of GDC vessels, which allows these vessels sail closer to the starboard bank.

3.5 Influence of strong current on vessel behavior (Research question 3)

Figure 3.8 shows the average uninfluenced and influenced vessel behavior for GDC vessels in Sea-Oude Maas and Oude Maas-Sea. Figure 3.8 (a) and Figure 3.8 (b) show both that vessel speed is decreased under “Against current” and is increased under “With current” in two directions, which means the vessel speed is influenced by current. Figure 3.8 (c) and Figure 3.8 (d) show that vessel course under strong current deviates from uninfluenced behavior. In Figure 3.8 (e) and Figure 3.8 (f), the relative distance to starboard bank changes along the waterway depending on current direction. The statistical results of p_r and MAPE are presented in Table 3.4.

Table 3.4: Statistical results of p_r and MAPE between uninfluenced and influenced vessel behavior by current in Sea-Oude Maas and in Oude Maas-Sea

		Speed		Course		Relative distance	
		p_r(%)	MAPE(%)	p_r(%)	MAPE(%)	p_r(%)	MAPE(%)
Sea-Oude Maas	Against current	100	11.6	61.1	0.3	94.2	6.2
	With current	0	6.1	33.3	0.5	22.2	5.3
Oude Maas-Sea	Against current	0	5.3	61.1	0.3	27.8	8.4
	With current	100	12.9	88.9	0.3	100	9.7

It can be found that vessel speed is decreased under “Against current” by 11.6% in Sea-Oude Maas and by 5.3% in Oude Maas-Sea, and is increased under “With current” by 6.1% in Sea-Oude Maas and by 12.9% in Oude Maas-Sea. The value $p_r = 0$ in Sea-Oude Maas under “With current” indicates that incoming vessels are unwilling to enhance their speed as they are approaching the destination even they sail with the current. On the contrary, the value $p_r = 0$ for “Against current” in Oude Maas-Sea represents that outgoing vessels prefer to counteract the influence of against current and thus keep a large speed to the sea. Although the values of MAPE for vessel course are very small, the values of p_r show that the uninfluenced and influenced vessel course are different at most cross sections. Finally, two strong influences on relative distance are observed for “Against current” in Sea-Nieuwe Maas and “With current” in Oude Maas-Sea, but values of MAPE are all more than 5%, which means relative distance is influenced by bad visibility.

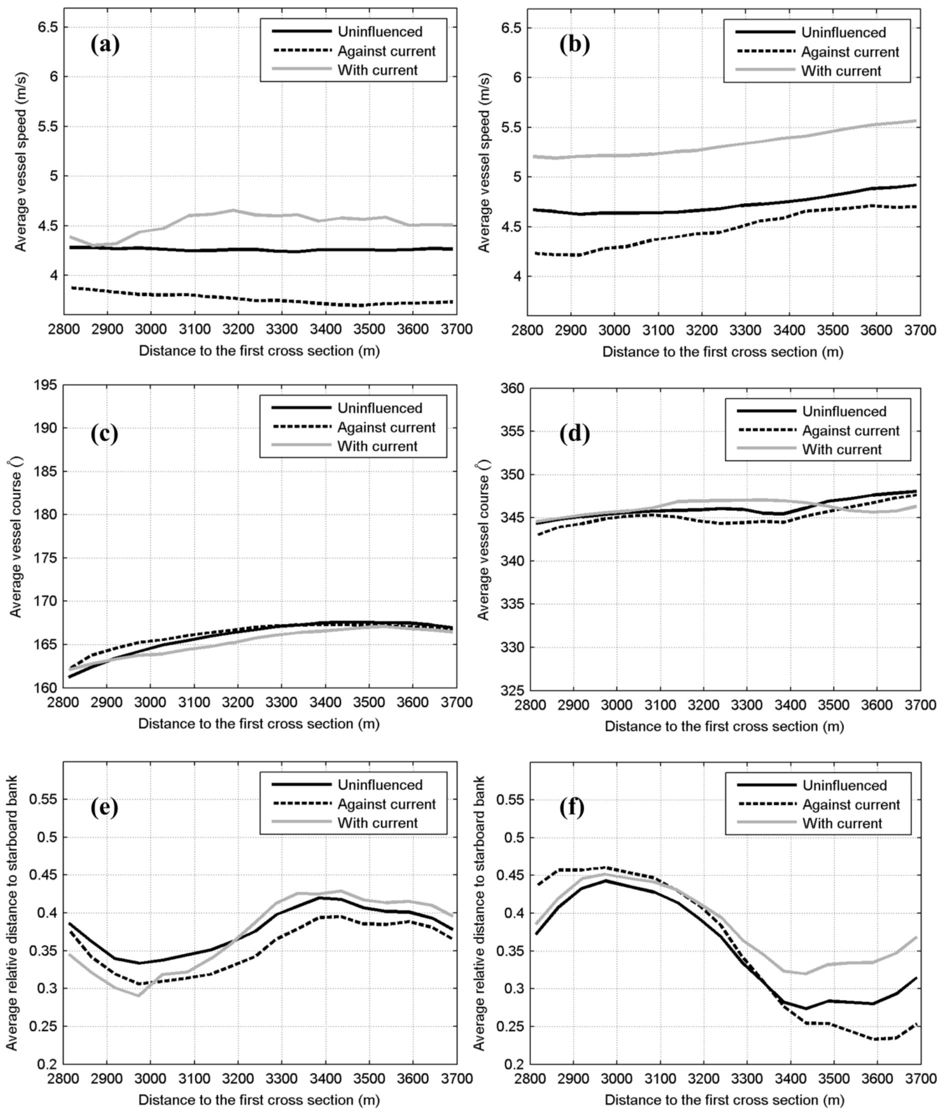


Figure 3.8: Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by current for GDC vessels at cross section 51-68 in Sea-Oude Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by current for GDC vessels at cross section 51-68 in Oude Maas-Sea.

To sum up, vessel speed is decreased by “Against current” and increased by “With current”. Vessel course and relative distance to starboard bank are also influenced by strong current, but the pattern of the influence needs further research using the real time data and considering the influence of waterway geometry. This is a interesting direction, but it is not investigated in this thesis.

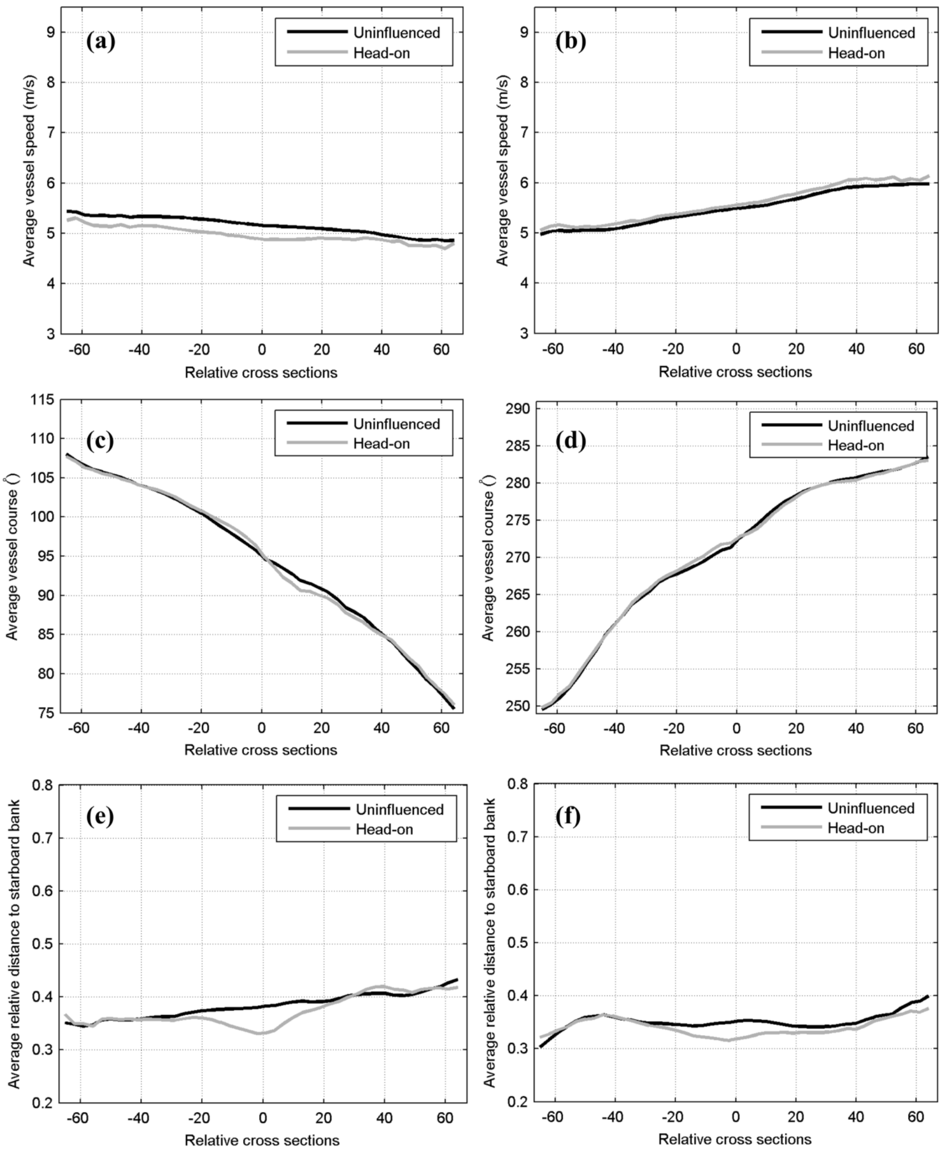


Figure 3.9: Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by head-on encounters in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by head-on encounters in Nieuwe Maas-Sea.

3.6 Influence of encounters (Research question 4)

In this section, the results of comparison between uninfluenced and influenced vessel behavior on the relative cross sections for head-on and overtaking encounters are shown, respectively. In this research, the K-S test will only be applied for the relative cross section 0 to test if the uninfluenced and influenced vessel behavior are equal. The result of K-S test equals to 0 (accepted) or 1 (rejected). Similarly, the Absolute Percentage Error (APE) will be applied at the relative cross section 0 as well. As the relative cross section 0 can be at different locations in the research area, the difference attributed to the location is not considered in this paper.

3.6.1 Head-on encounters

Figure 3.9 shows the comparison between uninfluenced and influenced vessel behavior for 948 head-on encounters in Sea-Nieuwe Maas and in Nieuwe Maas-Sea. Figure 3.9 (a) and Figure 3.9 (b) show that vessel speed in Sea-Nieuwe Maas is decreased and vessel speed in Nieuwe Maas-Sea does not strongly change in head-on encounters. This might be caused by the fact that incoming vessels are more likely to decrease their speed than outgoing vessels, as incoming vessels are approaching their destination in the resear area. In Figure 3.9 (c) and Figure 3.9 (d), vessel course is observed to be changed during the encounters between relative cross sections -20 and 20, although the difference at the relative cross section 0 is very small. This is the course change related to the maneuver during encounters. For relative distance to starboard bank, Figure 3.9 (e) and Figure 3.9 (f) show the similar phenomenon that vessels will deviate to starboard bank during head-on encounters, especially between relative cross sections -20 and 20. It can be concluded that the entire maneuver is completed within about 40 cross sections, which means that our investigation area is sufficient to analyze vessel head-on encounters. This finding indicates that the influence distance is around 2 *km*, in which the bridge team should start the maneuvering for head-on encounter. Furthermore, it can be concluded that the lateral distance between head-on vessels (on cross section 0) in the research area is around 0.35 times the width of the waterway, which means vessels keep about the same distance to the bank than to the other head-on vessels.

The statistical results of K-S test and APE between uninfluenced and influenced vessel behavior at the relative cross section 0 are shown in Table 3.5.

Table 3.5: Statistical results of K-S test and APE between uninfluenced and influenced vessel behavior at the relative cross section 0

		Speed	Course	Relative distance
Sea-Nieuwe Maas	K-S test result	1	0	1
	APE (%)	5.3	0.2	13.3
Nieuwe Maas-Sea	K-S test result	1	0	1
	APE (%)	1.2	0.2	9.7

It is found that vessel speed and relative distance are considered to be different for uninfluenced and influenced behavior at the relative cross section 0. The values of APE for relative distance in two directions are 13.3% and 9.7%, which imply the strong deviation to starboard bank at the relative cross section 0 for vessels in head-on encounters. The vessel course at the relative cross section 0 is considered to be uninfluenced, but it should be noted that vessels adapt their course before and after the relative cross section 0.

3.6.2 Overtaking encounters

In this section, 146 and 106 overtaking encounters respectively in Sea-Nieuwe Maas and in Nieuwe Maas-Sea are investigated. Since there is no regulation on which side vessels shall overtake each other, the bridge team can choose which side is the best for two vessels according to their experience, waterway geometry, on-coming traffic, etc. Before investigating the vessel behavior at the relative cross section 0, it is important to know on which side vessels overtake each other in the research area. In Figure 3.10, histograms of relative lateral position difference of overtaken and overtaking vessels at the relative cross section 0 in Sea-Nieuwe Maas and Nieuwe Maas-Sea are shown. The positive and negative value of relative lateral position difference represents the portside and starboard overtaking, respectively. It can be found that most vessels overtake other vessels on their portside in Sea-Nieuwe Maas in Figure 3.10 (a). However, Figure 3.10 (b) shows that around one third of vessels overtake other vessels on their starboard in the opposite direction. Then, the analysis will focus on portside overtaking in Sea-Nieuwe Maas, and both portside and starboard overtaking in Nieuwe Maas-Sea.

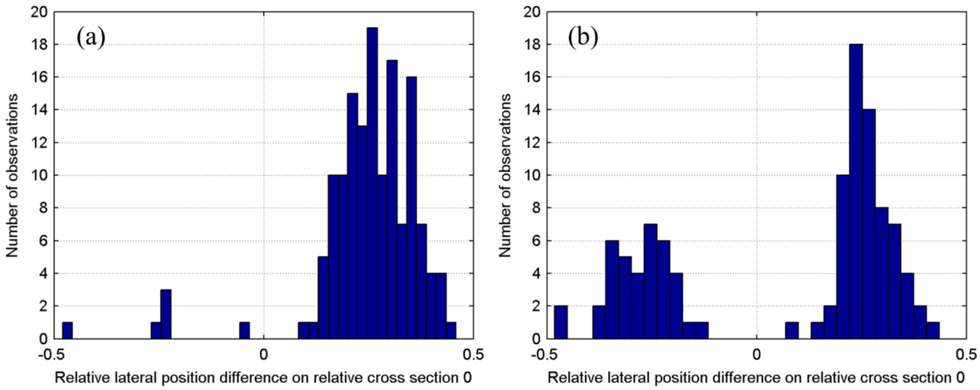


Figure 3.10: Histograms of relative lateral position difference of overtaken and overtaking vessels at relative cross section 0 in Sea-Nieuwe Maas (a) and Nieuwe Maas-Sea (b).

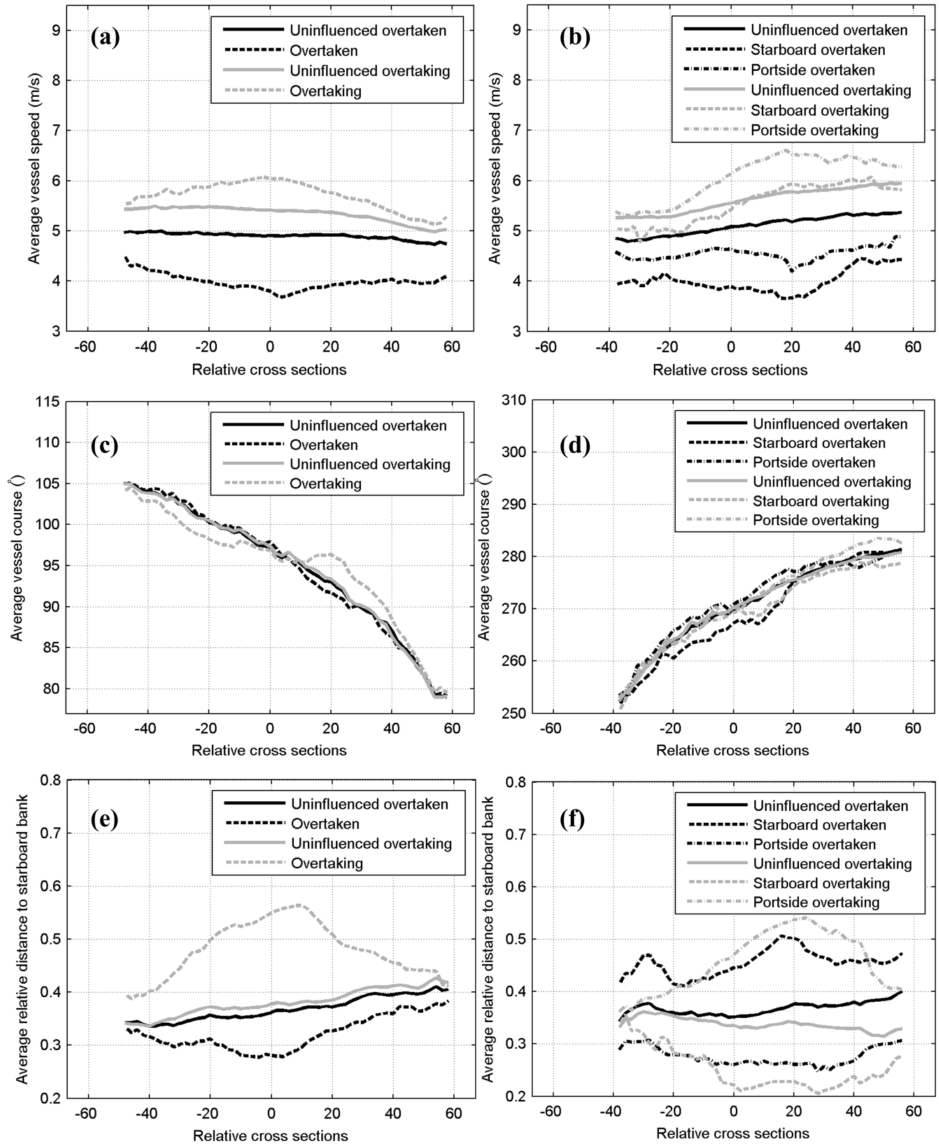


Figure 3.11: Uninfluenced and influenced vessel speed (a), course (c) and distance to starboard bank (e) by overtaking encounters in Sea-Nieuwe Maas; uninfluenced and influenced vessel speed (b), course (d) and distance to starboard bank (f) by overtaking encounters in Nieuwe Maas-Sea.

The average uninfluenced and influenced vessel behavior in Sea-Nieuwe Maas and in Nieuwe Maas-Sea is shown in Figure 3.11. Figure 3.11 (a) and Figure 3.11 (b) show that overtaking vessels increase their speed and overtaken vessels decrease their speed in overtaking encounters. This cooperative procedure could shorten the encounter period and thus increase the safety. Figure 3.11 (c) and Figure 3.11 (d) show that both overtaking and overtaken vessels will deviate from uninfluenced vessel course between relative cross section [-40, 40], which also show the cooperation between overtaking and overtaken vessels. Figure 3.11 (e) and Figure 3.11 (f) show the changes of relative distance for overtaking and overtaken vessels, which implies that during the overtaking the vessel on portside moves away from the bank and the vessel on starboard towards the bank. And the deviation of overtaken vessels in lateral direction is less than that of overtaking vessels. In this situation, the maximum lateral distance between overtaking vessels equals to 0.28 times the width of the waterway, which is smaller than between head-on vessels.

It also can be seen that the overtaking maneuver is not completed within the research area. Since both vessels sail in the same direction, overtaking encounters take more time and a longer distance than head-on encounters. This finding indicates the distance, in which the bridge team starts the maneuvering for overtaking, is larger than 2 *km*.

Then, the statistical results of the K-S test and APE between uninfluenced and influenced vessel behavior at the relative cross section 0 for overtaking encounters in Sea-Nieuwe Maas and in Nieuwe Maas-Sea are shown in Table 3.6 and Table 3.7, respectively.

Table 3.6: Statistical results of K-S test and APE between uninfluenced and influenced vessel behavior at the relative cross section 0 for overtaking encounters in Sea-Nieuwe Maas

	Speed	Course	Relative distance
K-S test - overtaken	1	0	1
APE (%) - overtaken	23.2	0.8	23.1
K-S test - overtaking	1	0	1
APE (%) - overtaking	11.6	0.5	45.6

Table 3.7: Statistical results of the K-S test and APE between uninfluenced and influenced vessel behavior at the relative cross section 0 for overtaking encounters in Nieuwe Maas-Sea

	Starboard overtaking			Portside overtaking		
	Speed	Course	Relative distance	Speed	Course	Relative distance
K-S test - overtaken	1	0	1	1	0	1
APE (%) - overtaken	29.3	0.8	37	14.8	0.8	28.4
K-S test- overtaking	1	0	1	1	0	1
APE (%) - overtaking	1.9	0.9	33	14.4	0.3	55.8

It is found that vessel speed and relative distance are significantly different than the uninfluenced behavior at the relative cross section 0 for both starboard overtaking and portside overtaking. Vessel speed is decreased by around 20% for overtaken vessels and is increased for around 10% for overtaking vessels. The relative distance is significantly changed between 23%

- 37% for overtaken vessels and changed between 33% - 55% for overtaking vessels during encounters. However, vessel course is not influenced at the relative cross section 0, although it was found that vessel course changes before and after cross section 0. All these changes of vessel behavior can be considered as the cooperative behavior of the vessels in overtaking encounters. The overtaking vessels increase their speed and deviate from their original course, while the overtaken vessels will decrease the speed and deviate to the opposite direction. These maneuvers are performed by both vessels to shorten the overtaking period and increase the safety during encounters.

To conclude, vessel speed and relative distance to starboard bank are decreased during head-on encounters, but vessel course is influenced before and after CPA (relative cross section 0). In overtaking encounters, speed of overtaken vessels is decreased and speed of overtaking vessels is increased. In both starboard overtaking and portside overtaking, vessels will deviate to keep a larger lateral distance between overtaking and overtaken vessels. These behavior changes are performed by the bridge team to shorten the overtaking period and increase the safety during encounters.

3.7 Conclusion and discussions

In this paper, the influences of external conditions (wind, visibility and current) and vessel encounters (head-on and overtaking) on vessel speed, course and relative distance to starboard bank are analyzed by comparing uninfluenced and influenced vessel behavior using AIS data and historical data of wind, visibility and current.

Stern wind and bow wind mainly influence vessel speed, while starboard wind and portside wind can affect the relative distance to starboard bank. It was found that vessel speed is on average increased by 2.3% for container vessels and by 3.4% for GDC vessels under stern wind, but it is decreased by 2.5% and 9.6%, respectively by bow wind. Vessel course is barely influenced by wind, except for starboard wind. The relative distance to starboard is increased by 4.2% and 7.3% and is decreased by 4.9% and 9.4% respectively for the two vessel types. It is also can be seen that GDC vessels are easier to be influenced by wind than container vessels. Bad visibility has negative influence on vessel speed for container vessels (4.9%), but is does not influence GDC vessels. Vessel course is not influenced by visibility. The relative distance to starboard bank is decreased by bad visibility by 3.6% and 5.1% for container vessels and GDC vessels, respectively. For current, it is clear that GDC vessel speed is decreased by 11.6% and 5.3% under “Against current” and is increased by 6.1% and 12.9% under “With current”. That means current has significant influence on vessel speed. In addition, the influences of current on vessel course and relative distance to starboard are observed to be significant. But further research on the influence of current and waterway geometry is required.

For head-on encounters, it was found that vessel speed is decreased by 5.3% and 1.2%, and relative distance to starboard bank is decreased by 13.3% and 9.7% at the relative cross section 0 in two directions, respectively. Although vessel course at the relative cross section 0 is observed to be uninfluenced, it changes before and after CPA (relative cross section 0). It was also found that the research area is sufficient to cover the head-on encounters, which are approximately completed between relative cross sections -20 and 20. In overtaking encounters, it was firstly found that vessels can overtake each other either by portside or starboard side. Furthermore, vessel speed and relative distance to starboard bank are influenced during overtaking encounters. Vessel speed is decreased around 20% for overtaken vessels and is increased around 10% for overtaking vessels. The relative distance is decreased by around 25% for overtaken vessels and is increased by 50% for overtaking vessels in portside overtaking, while 37% and 33% in starboard overtaking. In addition, it was found that overtaking maneuver is not completed within the research area. It can be concluded that overtaking encounters take more time and a longer distance than head-on encounters since both vessels sail in the same direction, and the maximum lateral distance between overtaking vessels is smaller than between head-on vessels in this research. For both head-on and overtaking encounters, two vessels show the cooperative behavior during the encounters. For example, both vessels will deviate from their original path, and vessel speed for overtaking vessel is increased and speed of overtaken vessels is decreased. This cooperative behavior should be considered when vessel encounters are simulated.

The results of these analyses could benefit both port authority and the bridge team. For port authority, these results could be used to improve the maritime traffic management and risk assessment in ports and waterways, such as the risk grading for different external conditions and encounters or waterway expansion. For the bridge team, the results could serve as the guidance for vessel maneuvering. On the other hand, the analysis results also provide direction for the new maritime traffic model (Hoogendoorn et al., 2013) or risk assessment model development.

Although the influence of each individual factor is investigated in this paper, the combined influence of these factors needs to be further investigated. In addition, vessel behavior is only investigated on part of the waterway due to the limit of available current data. A real-time measured current data in different locations could provide more insight into the influence of current on vessel course and relative distance to starboard bank. Furthermore, it is recommended to investigate the relation between safe lateral distance and vessel dimensions, which is more practicable for the bridge team.

Acknowledgment

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Chapter 4

Vessel route choice theory and modeling

This chapter is an edited version of the article:

Shu, Y., W. Daamen, H. Ligteringen, & S. P. Hoogendoorn (2015b) Vessel route choice theory and modeling, *Transportation Research Record: Journal of the Transportation Research Board*, 2479, pp. 9-15.

Abstract

A new maritime traffic model describes vessel traffic in ports and inland waterways better. In this research, vessel behavior is categorized into a tactical level (route choice) and an operational level (dynamics of vessel behavior). This new maritime traffic model comprises two parts. The route choice model resulting in the vessel's preferred route and the operational model describing the maneuvering behavior, including interactions between vessels. This paper presents the vessel route choice model, which is based on disutility or cost minimization. The cost is determined by characteristics of the infrastructure, such as expected sailing time and distance to the bank. It is assumed that the bridge team will try to follow a preferred route that minimizes the cost to the destination. To calculate this preferred route, the so-called "value function" is defined as the minimum disutility function in continuous time and space. Subsequently, the value function is solved with dynamic programming and a numerical solution approach. Data of unhindered vessel behavior in the Port of Rotterdam, Netherlands, collected with an automatic identification system, are used to calibrate the vessel route choice model. The calibrated results of the route choice model show plausible preferred routes in the research area, which aid understanding of the desired vessel behavior (route). These results could be used to improve vessel traffic management and provide a basis for predicting vessel behavior at the operational level.

4.1 Introduction

Because of the globalization of trade of products, the use of vessels for transportation has increased all over the world. A balance is needed between safety and capacity in busy ports and inland waterways: when measures are taken to increase capacity, usually safety is decreased. Modeling tools can be used to optimize ports and waterway design and improve maritime traffic management.

Vessel behavior, including its speed and path, is difficult to predict, especially in ports and inland waterways, because many factors influence vessel behavior, such as the waterway's geometry, human factors, and external conditions, including wind and visibility. Some maritime models focus on calculating the risk probability of collisions or groundings (Degre et al., 2003; Fowler & Sørgård, 2000; Pedersen, 1995); other models mainly consider the hydrodynamics of vessels (Sariöz & Narli, 2003; Sutulo et al., 2002; Yoon & Rhee, 2003) or simulate the routing in a shipping network (Hsu & Hsieh, 2007; Kosmas & Vlachos, 2012; Norstad et al., 2011). In addition, most maritime simulation models focus on vessel dynamics and traffic for open seas. These models cannot be applied in constrained ports and waterways because different factors affect sailing behavior in ports and waterways and that in open seas (e.g., influence of banks or water depth). Little research has been performed into vessel route choice in inland waterways, interaction between vessels, and human factors influencing maritime traffic. To optimize ports and waterway design and improve maritime traffic management, a new model is needed that describes vessel traffic in ports and inland waterways.

In the presented research, vessel behavior is categorized into a tactical level and an operational level (Hoogendoorn, 2001). The tactical level includes vessel route choice in inland waterways without external influences. The vessel route choice at the tactical level serves as the basis for vessel behavior at the operational level. The operational level includes the external influences and dynamics of the vessel behavior, such as all decisions related to sailing made for the coming short time period. In other words, at the operational level, it is hypothesized that vessels follow the preferred route generated at the tactical level as much as possible, while taking into account external influences and human factors. Hence, the new maritime traffic model will comprise two parts: a route choice model, resulting in preferred routes, and an operational model, describing the sailing behavior, including interactions between vessels, which was proposed in previous research (Hoogendoorn et al., 2013). This paper presents the vessel route choice model at the tactical level.

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

In recent research, automatic identification system (AIS) data have been proved to be a powerful tool for investigating maritime traffic (Aarsæther & Moan, 2009; Mou et al., 2010). An AIS is an onboard system that transmits vessel information (position, velocity, destination, etc.) between nearby vessels and shore stations. AIS data in the Port of Rotterdam, Netherlands, are provided by the Maritime Research Institute Netherlands (the leading institute for hydrodynamic research and maritime technology in that country). These data are used for model calibration in this paper.

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

4.2 Vessel behavior at the tactical level

This research focuses on the vessel behavior in the two-dimensional space, including vessel position and velocity. Previous research showed that many factors influence vessel behavior, such as vessel characteristics (e.g., vessel type and size), waterway geometry, and external conditions (e.g., wind, visibility, and current)(Shu et al., 2013a; Shu et al., 2013b).

Here, vessel route choice is investigated at the tactical level. In this approach, the bridge team is considered to be the brain of the vessel. In vessel route choice theory, it is assumed that disutility or cost of each route for the vessel is determined by characteristics of the infrastructure, which will be proposed and included in the running cost in the next section. To identify the preferred route, the bridge team will predict and minimize this expected disutility, or cost C.

This research investigates vessel behavior in a waterway stretch, which is defined by two cross sections. These two cross sections can be considered as the entrance and the destination for vessels sailing in this direction. The vessel route $x(\cdot)$ is a continuous function, uniquely determined by the velocity trajectory $v(\cdot)$ through the waterway. Since the position is the derivative of the velocity, optimizing the velocity also optimizes the route. Then, the utility optimization for the vessel route will yield the optimized velocity choice at the tactical level.

Both vessel course and vessel speed are included in this optimized velocity. Vessel speed is affected by external influences (e.g., wind and visibility) and is determined by the bridge team according to the traffic situation and the infrastructure at the operational level. Hence, the vessel route choice model will mainly consider vessel course, rather than vessel speed.

In Equation (4.1), the optimal course (over a period) is defined as that which minimizes the cost, given the current time and position of the vessel:

$$v^*(\cdot) = \arg\min C\ (v(\cdot)|t_0, x_0) \tag{4.1}$$

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

The next section discusses the expected disutility and the solution for optimization of the vessel route choice.

4.3 Optimal route choice for vessels

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

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

Vessels sometimes deviate from their planned path when they encounter other vessels. To flexibly adapt vessels to other routes, the expected minimum perceived disutility for all locations *x* and instants *t* is proposed. The so-called "value function *W(t, x)*" is defined as the expected minimum perceived disutility function in continuous time and space (Fleming & Soner, 2006). From the solution of *W(t, x)*, the optimal route choice for vessels can be determined.

4.3.1 Vessel kinematics under uncertainty

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

$$dx = vdt + d\varepsilon \quad subject\ to\ x(t) = \hat{x} \tag{4.2}$$

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

This research investigates vessels sailing in ports and waterways, where they sail at relatively low speed, around 10 knots, which is normally far below the physical limitation of the vessel. This physical limitation is not considered in the research.

4.3.2 Generalized expected utility

In vessel route choice, vessel velocity and position in waterways are investigated. Consider a part of waterway between two cross sections, which are set as the origin and the destination, respectively. Let $[t, t_t)$ denote the planning period of the bridge team, where t and t_t are, respectively, the current time and the terminal time (planning horizon). The vessel is expected to reach its destination during this time period. Let 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 in the trajectory $x_{[t,T)}$, the expected disutility or cost C is defined as

$$C\left(T, v_{[t,T)}\right) = \int_t^T L(\tau, x(\tau), v(\tau))d\tau + \phi(T, x(T)) \tag{4.3}$$

where L and ϕ respectively denote the so-called running cost and the terminal cost. The running cost $L(\tau, x(\tau), v(\tau))$ reflects the cost incurred in a small time period $[\tau, \tau + d\tau)$, given the location $x(\tau)$ at time τ and control velocity $v(\tau)$. The terminal cost $\phi(T, x(T))$ reflects the penalty incurred due to the vessel ending up at position $x(T)$ at the terminal time T, but not at the destination. This expected utility is input into the dynamic programming problem identified later.

4.3.3 Specification of terminal cost

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

$$\phi(T, x(T)) = \begin{cases} 0, & T < t_t \\ \phi, & T = t_t \end{cases} \tag{4.4}$$

The terminal cost ϕ thus reflects the penalty for not having arrived at the destination at the end of the prediction horizon. When the vessel arrives at the destination in time, the penalty is zero. Hence the vessel will aim to reach the destination within the prediction horizon.

4.3.4 Specification of running cost

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

$$L(t, x, v) = \sum_{k=1,2,\ldots} c_k L_k(t, x, v) \tag{4.5}$$

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

The data analysis showed that both banks and the vessel characteristics influence vessel route choice (Shu et al., 2013b). In the approach here, the following characteristics of the infrastructure are considered in the running costs for a specific vessel category: expected sailing time, counteracting the bend waterway effect, and discomfort caused by proximity to banks and sailing at a certain speed. These running costs are described below.

Expected sailing time

For the expected sailing time, L_1 is defined as follows:

$$L_1(t, x, v) = 1 \tag{4.6}$$

This definition results in the route cost

$$\int_t^T c_1 \cdot L_1(\tau, x(\tau), v(\tau))d\tau = \int_t^T c_1 d\tau = c_1(T - t) \tag{4.7}$$

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

Waterway bend effect

Including the sailing time assumes that vessels prefer to sail in a straight line toward their destinations. In bended waterways, this implies that vessels will cut corners. However, previous AIS data analysis showed that vessels normally sail along the centerline of the waterway in the bend area of the waterway (Shu et al., 2013b). In the route choice model, a term is therefore added to the running cost to counteract the bend waterway effect to make sure vessels are sailing along the waterway in the bend area. An example of a bend waterway is shown in Figure 4.1, where the bend area is shaded. In the figure, θ denotes the change of waterway direction before the bend and after the bend. S denotes the average arc length, which approximately equals the length of the middle line of the bend waterway. Then, θ/S reflects the direction change in unit distance, which could be defined as strength of the bend. d_{cv} is the distance to the convex bank.

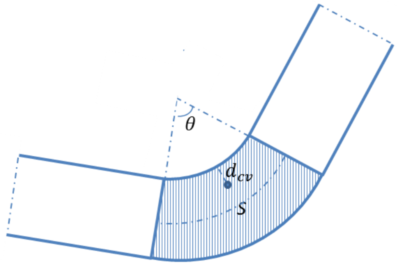

Figure 4.1: Example of bend waterway and it's parameters.

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

$$L_2 = -\frac{\theta}{S} \cdot d_{cv}(x) \tag{4.8}$$

This cost is added only in the bend area of the waterway. Then, in the bend area, L_2 reflects the cost contribution from the convex bank.

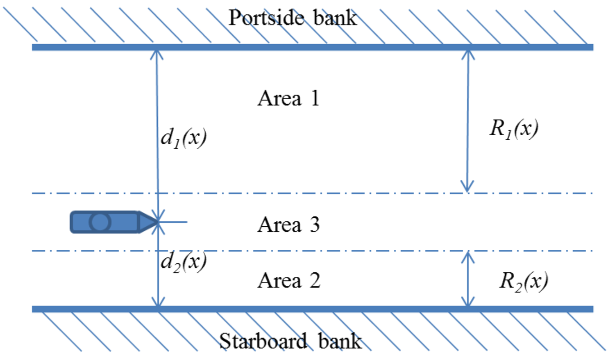

Figure 4.2: Waterway area division according to portside and starboard bank.

Discomfort caused by proximity to banks

As we know from AIS data analysis, sailing vessels normally keep a certain distance to the bank, which in the present case has been defined as the five meter water depth line. The bridge team will adjust its course to make sure that their vessel is not too close to either portside bank or starboard bank. In our approach, it is assumed that a vessel is influenced by the bank when it is closer to the bank than a certain threshold distance. As shown in Figure 4.2, a 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 and the starboard bank respectively, R_1 and R_2 describe how far both banks can influence the vessel. The vessel is 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 bank influences the vessel in a similar way. In Area 3, the vessel is not influenced by either bank, which means the contribution for cost function is zero.

The influence of the two banks is added in the expected route cost as a monotonously decreasing (linear) function of the distance to the bank in the corresponding area. Running cost components L_3 and L_4 denote the contributions from the portside and starboard bank, respectively. They are defined as

$$L_3(t,x,v) = \begin{cases} 0, & d_1(x) > R_1 \\ \dfrac{R_1 - d_1(x)}{R_1}, & d_1(x) \le R_1 \end{cases} \tag{4.9}$$

$$L_4(t,x,v) = \begin{cases} 0, & d_2(x) > R_2 \\ \dfrac{R_2 - d_2(x)}{R_2}, & d_2(x) \le R_2 \end{cases} \tag{4.10}$$

The scaling parameters R_1 and R_2 are defined as

$$R_1 = [d_1(x) + d_2(x)] \cdot r_1 \tag{4.11}$$

$$R_2 = [d_1(x) + d_2(x)] \cdot r_2 \tag{4.12}$$

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

Sailing at a certain speed

To arrive at the destination in time, an appropriate speed is needed. However, high speed means high energy consumption, which will result in high cost. Speed choice is thus a trade-off between the time remaining to sail to the destination and the energy consumed in sailing at a certain speed. For simplicity, the energy consumption is assumed to be a quadratic function of the vessel speed as follows:

$$L_5(t,x,v) = \frac{1}{2}v^2 \tag{4.13}$$

4.3.5 Dynamic programming and numerical solution modeling

To solve the route choice problem in continuous time and space, the so-called value function $W(t,x)$ is defined as the expected minimum perceived disutility function. To solve the value function, a dynamic programming approach and a numerical solution approach are used in the model. The solution of $W(t,x)$ describes the minimum cost to the destination for a vessel located at position x at instant t. Based on this solution, the optimal course and speed can be determined. For details, we refer to previous work (Hoogendoorn & Bovy, 2004).

4.4 Calibration of route choice model

In this section, the vessel route choice model is calibrated with AIS data. The AIS data and unhindered vessel behavior, that is, vessel behavior without the influence of other vessels, are introduced. Vessel encounters are considered at the operational level but not at the tactical level. Hence only unhindered vessel behavior should be used to calibrate the vessel route choice model at the tactical level. Then, the calibration setup and the objective function for calibration are described. Finally, calibration results are presented.

4.4.1 AIS Data and unhindered paths

In this research, the class of small general dry cargo vessels of less than 3,600 gross tonnage is used. AIS data for these vessels in the Botlek area in the Port of Rotterdam from January 2009 to April 2011 were selected. Figure 4.3 shows the research area, called Sea-Nieuwe Maas, which corresponds to vessels sailing from the sea (in the west) to the Nieuwe Maas river (in the east). For comparing lateral positions of these tracks and easily calculating the average path, 69 cross sections with intervals of about 50 *m* are defined in the research area. These cross sections are approximately perpendicular to the waterway axis and are used for selecting AIS data. End points of these cross sections are located at the 5-*m* water depth line, because it was found in the data analysis that vessels will not pass this line. For areas without a 5-*m* water depth line, such as entrances to basins or waterway branches, end points are created such that the boundary remains smooth. In the model, these 5-*m* water depth lines will form the effective waterway for vessel sailing.

In previous research, AIS data analysis provided insight into vessel behavior (Shu et al., 2013a). It was found that vessels deviate from their planned path when they encounter other vessels, especially during overtaking.

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

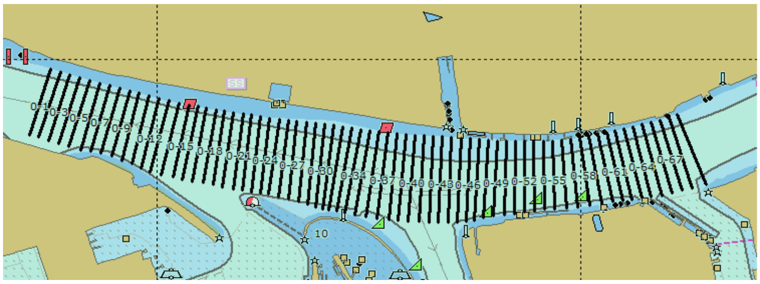

Figure 4.3: Waterway of Sea-Nieuwe Maas and 69 cross sections.

However, these unhindered paths concentrate in the right part of the waterway. For estimating the influence of the banks, more data are needed that describe the vessel route choice in the areas close to banks. To provide more data in these areas, parts of hindered vessel paths are used. For hindered vessel paths, vessels normally deviate from their planned path and sail into the area closer to the banks. It is assumed that the influence of other vessels ends after the encounter. At that moment, both vessels have the largest deviation when they are closest to each other. Hindered vessel paths after the encounter can then be considered as unhindered and used for calibration as well. Including these, the tracks of the AIS data set used for calibration cover most of the waterway. In Figure 4.4, longitude and latitude coordinates are transformed into coordinates of the Rijksdriehoeksstelsel, which is the national grid of the Netherlands. This national grid is used as a basis for geographical indications and files, such as geographic information systems.

The definitions of the parameters of the bend waterway are given in Figure 4.1. According to bend strength θ/S, the waterway is divided into two parts: the area from Cross Section 1 to Cross Section 42 and the area from Cross Section 42 to Cross Section 69. Because of differing bend strengths, vessels in these two parts will have different contributions to cost from the bend effect.

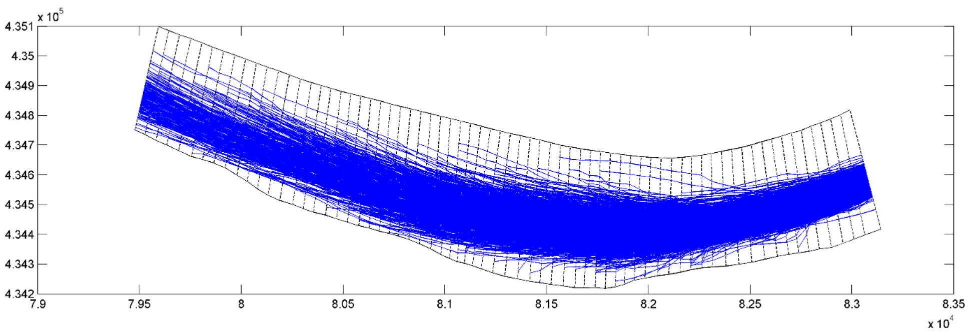

Figure 4.4: AIS data used for vessel route choice calibration from Sea to Nieuwe Maas.

4.4.2 Calibration setup and objective function

Only the ratio between the weights can be determined with AIS data. Without loss of generality, $c_1 = 1$. Then, the parameters that need to be calibrated are in the vector $\beta^T = (c_2, c_3, c_4, r_1, r_2, c_5)$.

In this research, vessels have a two-dimensional motion that includes vessel speed and course. Vessel speed is determined at the operational level by the bridge team according to the vessel engine power or influence of other vessels and external influences (such as wind and visibility), but not at the tactical level. Hence, only vessel course is considered in the objective function in calibration of route choice model. The calibration process aims at minimizing the difference between vessel course measured from AIS data and vessel course predicted by the vessel route choice model.

As shown in Figure 4.4, vessel paths concentrate in the right part of the waterway and they are not uniformly distributed. Overlapping paths provide similar inputs to the calibration. To combine a lot of repetitive inputs, a mesh grid of $10 \times 10\ m$ is used to generate a velocity field, which will be used to determine the difference. Figure 4.5 shows the generated velocity field based on the mesh grid and AIS data in Figure 4.4. This velocity field will be compared with the simulated results based on the route choice model.

In the simulation model, the part of Cross Section 69 (the rightmost), where 99% of the unhindered vessels pass, is defined as the destination. To use the numerical solution approach, the waterway is discretized into cells $5 \times 5\ m$ and the time step is defined as $0.5\ s$. Then, the value function can be solved for the whole research area, as well as the optimal course field. Again, only vessel course is considered in the calibration of the route choice model. This optimal course field will be used to compare with the velocity field in Figure 4.5.

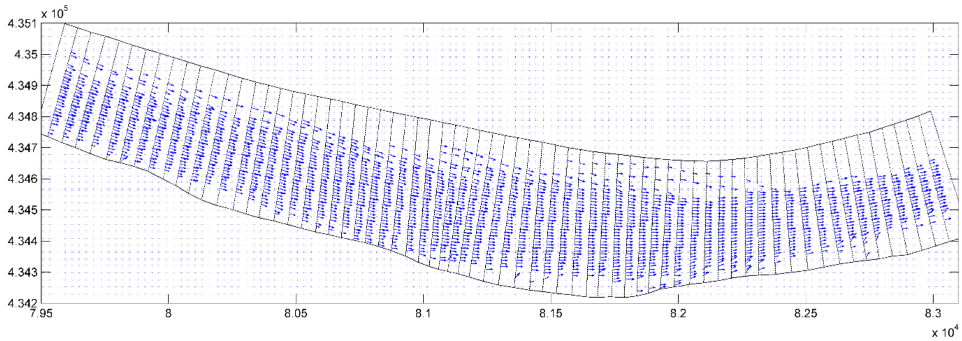

Figure 4.5: Velocity field based on AIS data in the meshgrid of $10\ m \times 10\ m$.

Let α_{data} denote vessel course in the velocity field in Figure 4.5. Correspondingly, αsim is the optimized course for the same point in the mesh grid calculated by the route choice model based on a given β. For these m mesh grid points, the average square error is defined as

$$E(\beta) = \frac{1}{m}\sum_{i=1}^{m}(\alpha_{data} - \alpha_{sim})^2 \tag{4.14}$$

Hence the calibration problem becomes a multivariable nonlinear optimization problem as follows, which could be solved with the fminsearch function in MATLAB:

$$\beta^* = arg\, min\, E(\beta) \tag{4.15}$$

4.4.3 Calibration results

Through application of the described optimization method, the best fit of the vessel route choice model to the AIS data is found. The calibration results are summarized below:

• Optimized parameters:

c_2 = 0.0211,
c_3 = 0.0122,
c_4 = 0.0215,
r_1 = 0.5414,
r_2 = 0.2305, and
c_5 = 0.0218 and

• Error = 19.92.

In the model, the values of parameters c_3 and c_4 reflect the cost when the vessel is very close to the portside bank and starboard bank. c_3 and c_4 also have the largest influence from both banks, since the influence of banks is a linear decreasing function of the distance to the bank in equations (4.9) and (4.10). That means that banks contribute to the cost function between 0 ~ 0.02. Compared to the contribution of sailing time (equals to 1), these two values seem small, but they cannot be neglected as they provide the repellence of both banks.

The parameters r_1 and r_2 describe the percentage of the waterway width, in which both banks contribute to the cost function. Calibration results show that portside bank have influence when the distance between the vessel and the portside bank is less than 54% of the waterway width. For the starboard bank, the influence area is 23% of the waterway width. The rest area around 23% of the waterway is the area where banks do not have influence on vessel behavior. This area could be considered as unhindered area, where the vessels will concentrate. This is corresponding to the fact that ships in a two-way channel have to navigate on the right hand side of the channel, which could be observed in Figure 4.4.

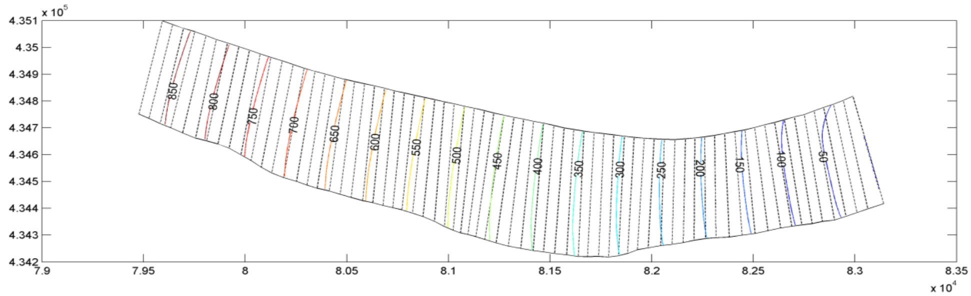

Figure 4.6: Contour lines for value function.

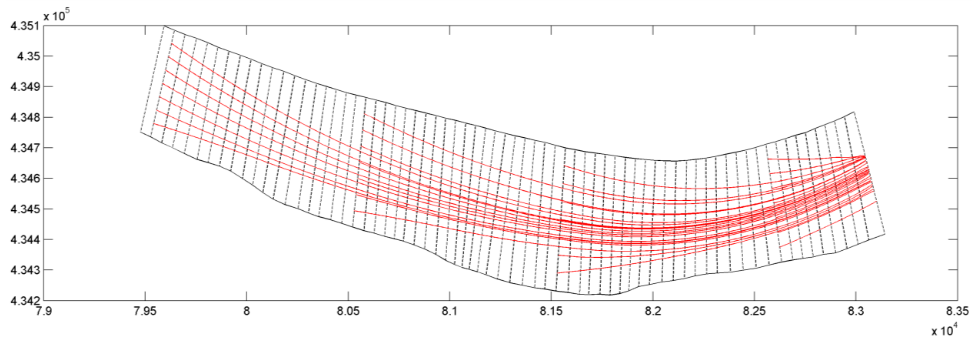

Figure 4.7: Example tracks on cross sections 2, 20, 40 and 60.

When the calibrated results shown in the list above are applied, the expected minimum disutility function is generated in the research area. The contour lines and corresponding value for this value function are shown in Figure 4.6. Vessels will follow the preferred route, which is perpendicular to these contour lines. The shape of the contour lines indicates that vessels will be pushed away from the bank when they are too close to the bank.

For Cross Sections 2, 20, 40, and 60, several example tracks of route choice are generated as shown in Figure 4.7. When vessels are too close to the bank, they will be pushed away from the bank and sail toward the unhindered area, which corresponds to the phenomenon in Figure 4.4; this result is as expected.

4.5 Conclusions and recommendations

An approach was proposed with which to generate vessel route choice in continuous time and space for ports and inland waterways. A dynamic programming approach and a numerical solution approach were used to solve the value function, which can be used to generate optimal course and speed. This vessel route choice model was calibrated according to AIS data on unhindered paths and hindered paths.

The calibrated results show that vessels keep a distance of 54% of the waterway width from the portside bank and keep a distance of 23% of the waterway width from the starboard bank, which corresponds to the observation in AIS data. Hence vessels concentrate in the right part of the waterway. The results also show plausible example preferred routes in the research area, which aid understanding of the desired vessel behavior (route). In the model, the waterway geometry is input, so the route choice model is also applicable in other parts.

The vessel route choice model provides the preferred routes for vessels, which could be used as a reference guide for both the bridge team and vessel traffic services and hence can help to improve waterway traffic management. In addition, the preferred routes generated by the route choice model could be used to indicate the dangerous area for vessels by considering vessel maneuverability. Hence at the decision-making level, the model can be used to control vessel traffic, design new ports, or extend existing ports and inland waterways.

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

Also, the vessel route choice model will serve as input to the maneuvering model at the operational level. The route choice model and the maneuvering model form the new maritime traffic model, which describes maritime traffic by predicting single vessel behavior.

Acknowledgments

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Chapter 5

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

This chapter is an edited version of the article:

Shu, Y., W. Daamen, H. Ligteringen, M. Wang, & S. P. Hoogendoorn (2018) Calibration and validation for the vessel maneuvering prediction (VMP) model using AIS data of vessel encounters, *Ocean Engineering*, 169, pp. 529-538.

Abstract

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

5.1 Introduction

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

To address this need, a new maritime traffic operational model was developed recently by applying differential game theory (Hoogendoorn et al., 2013). The approach of this model was adapted from an approach that was successfully applied to predict the behavior of pedestrians (Hoogendoorn & Bovy, 2003; Hoogendoorn & Bovy, 2004) as there are many similarities between vessels and pedestrians: both vessels and pedestrians (1) have specific origin and destination; (2) are constrained by boundary (bank for vessels, and wall or other obstacles for pedestrians); (3) can influence each other; (4) are influenced by external conditions, such as weather conditions. In this model, vessel behavior is described at two levels: a tactical level and an operational level. The tactical level includes vessel route choice (the desired course) and desired speed, which serve as the reference (guide) at the operational level. The desired course and desired speed represent the optimal course and speed when the vessel is not influenced by extreme external conditions and other vessels. The operational level includes the dynamics of the vessel sailing behavior, e.g. longitudinal acceleration and angular speed of the vessel. Although the route choice model is assumed to be very simple in the previous work (Hoogendoorn et al., 2013), the framework for the model was created. Based on this framework, the route choice model at tactical level was further developed (Shu et al., 2015b). The results of this study serve as an input into the operational model, which is called Vessel Maneuvering Prediction (VMP) model in this paper. The VMP model was introduced by considering the influence range in different directions of the vessel to be homogeneous and the model was only calibrated for unhindered vessel behaviour (Shu et al., 2015a), in which the influence between encountered vessels is not considered.

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

This paper starts with an introduction of the improved VMP model in Section 5.2. Then, the calibration and validation approaches are presented in Section 5.3, followed by the results of the calibration and validation in Section 5.4. Finally, this paper ends with discussion and conclusions in Section 5.5.

5.2 The improved VMP model of vessel traffic

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

$$\dot{x} = v\,cos\left(\frac{\pi}{2} - \psi\right) \tag{5.1}$$

$$\dot{y} = v\,sin\left(\frac{\pi}{2} - \psi\right) \tag{5.2}$$

$$\dot{v} = u_1 \tag{5.3}$$

$$\dot{\psi} = u_2 \tag{5.4}$$

where the state of the vessel is defined as $\vec{\xi} = (x, y, v, \psi)$, in which *x* and *y* denote the position, and *v* and ψ denote vessel speed and course, respectively. In this coordinate system, Equations (5.1-5.2) represent the vessel speed in *x*-*y* coordinates and Equations (5.3-5.4) show the longitudinal acceleration and angular speed.

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

$$J = \int_t^{t+H} L\big(s, \vec{\xi}, \vec{u}\big) ds + \Phi(t + H, \vec{\xi}(t + H)) \tag{5.5}$$

where H denotes the prediction horizon, which is assumed to be a time period in which the bridge team could predict the vessel behavior; L denotes the running cost (cost incurred in a small time interval $[\tau, \tau + d\tau)$); $\vec{u} = (u_1, u_2)$ 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 $t + H$. The terminal cost is assumed to be zero.

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

$$L = L^{stray} + L^{effort} + L^{prox} \tag{5.6}$$

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

$$L^{stray} = \frac{1}{2}\left(c_2^v(v^0(\vec{x}) - v)^2 + c_2^\psi(\psi^0(\vec{x}) - \psi)^2\right) \tag{5.7}$$

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

The propulsion and steering costs are defined by:

$$L^{effort} = \frac{1}{2}\left(c_3^v u_1^2 + c_3^\psi u_2^2\right) \tag{5.8}$$

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

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

$$L^{prox} = \begin{cases} c_1\left(e^{-d/R} - e^{-1}\right), d < R \\ 0, \qquad d \geq R \end{cases} \tag{5.9}$$

where c_1 is the weight factor for this proximity cost, d denotes the distance between the simulated vessel and the encountered vessel, and R is the scaling parameter, which indicates the range within which the simulated vessel is influenced by the other vessel and this parameter is determined by the relative position between the simulated vessel and the encountered vessel. As shown in Equation (5.9), the proximity costs increase when the encountering vessels approach each other, and the proximity costs equal to zero when the distance is larger than the scaling parameter. In the data analysis of vessel encounters, it was found that the influence distance between encountering vessels in longitudinal direction is much larger than in lateral direction (Shu et al., 2017). This results in an elliptical influence area. As an example, the elliptical influence area of an overtaking vessel is shown in Figure 5.1.

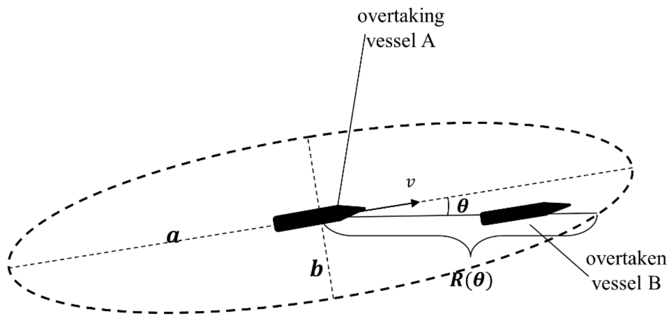

Figure 5. 1: Elliptical influence area of overtaking vessel and the definition of scaling parameter for the overtaking vessel.

As shown in Figure 5.1, the elliptical influence area has a semi-major axis a and a semi-minor axis b. The scaling parameter R could be interpreted as the radius of the ellipse, which is a function of the parameters a, b and the angle θ (the angle between the course of the own vessel and the line connecting the locations of the two encountering vessels):

$$R(\theta) = \frac{ab}{\sqrt{a^2 \, sin^2\,\theta + b^2 \, cos^2\,\theta}} \tag{5.10}$$

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

$$a = p * (L_A + L_B)/2 \tag{5.11}$$

$$b = q * (B_A + B_B)/2 \tag{5.12}$$

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

5.3 Research approach

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

In this paper, the AIS data of 146 overtaking encounters and 162 head-on encounters are used. These data are provided by Maritime Research Institute Netherlands (MARIN) and analyzed using dedicated software called "ShowRoute", which is developed by MARIN and used to investigate AIS data. These data were selected in the Botlek area in the port of Rotterdam and used to analyze the vessel behavior in previous studies (Shu et al., 2017). The waterway stretch is around 2.5 *km* and the sailing time in the research area approximately equals 500 seconds, given the average vessel speed of 5 *m/s* (Shu et al., 2013b).

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

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

5.3.1 Calibration approach

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

Calibration set-up

The parameters of the VMP model, consisting of weight factors $c_1, c_2^v, c_2^\psi, c_3^v$ and c_3^ψ, and the scaling coefficients p and q need to be calibrated. It should be noted that all weight factors cannot be uniquely determined from the data, since only the relative importance of the weights can be determined. Without loss of generality, we set $c_1 = 1$. Then, the parameters to be calibrated are $\beta^T = (c_2^v, c_2^\psi, c_3^v, c_3^\psi, p, q)$.

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

To run the VMP model, the desired speed and desired course serve as inputs, while the vessel speed, course and path are the outputs. We assume that the desired course generated by the Route Choice model (Shu et al., 2015b) is applicable for all vessels in the research area, because it was found that vessel course is hardly influenced by vessel size and type (Shu et al., 2013b). In terms of the desired speed, it was found that overtaking vessels increase their speed before the CPA (Closest Point of Approach) and decrease the speed after the CPA (Shu et al., 2017). Therefore, the desired speed is set as the maximum speed v_{max} before the CPA and set as the end speed v_{end} after CPA, as shown in Figure 5.2. This way, the variability of the desired speed is considered, which is closer to reality than setting a constant desired speed.

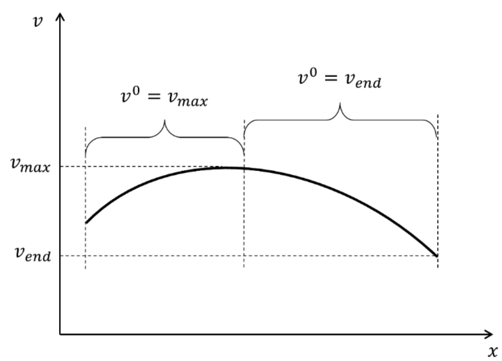

Figure 5.2: Definition of desired speed v^0 for an overtaking vessel. The curve indicates the speed track of overtaking vessel in overtaking encounters. Axis x and y represent the longitudinal distance and vessel speed, respectively.

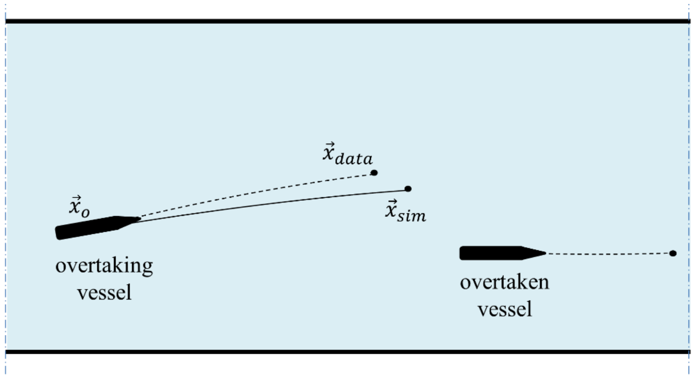

Figure 5.3: Vessel path of overtaking and overtaken vessel from AIS data (solid line) and simulation path of overtaking vessel (dashed line) within the prediction horizon.

Objective function for calibration

The calibration process aims at minimizing the difference between the vessel path predicted by the VMP model and the observed path from AIS data. As shown in Figure 5.3, an overtaking vessel sails from left to right and the observed vessel position at the end of the prediction horizon is $\vec{x}_{data}$. The VMP model predicts that the overtaking vessel is at position $\vec{x}_{sim}$ at the end of the prediction horizon. Then, the parameters should be chosen such that the distance between the position $\vec{x}_{data}$ and the position $\vec{x}_{sim}$ is minimized.

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

$$E(\beta) = \frac{1}{m} * \frac{1}{n_i} * \sum_{i=1}^{m} \sum_{j=1}^{n_i} \left(\vec{x}_{data}^{i,j} - \vec{x}_{sim}^{i,j}\right)^2 \tag{5.13}$$

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

$$\beta^* = arg\,min\,E(\beta) \tag{5.14}$$

Sensitivity analysis

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

5.3.2 Validation approach

The validation is performed to see if the calibrated parameters could be used to predict the vessel path for other datasets accurately (within the allowed error margin). Contrary to the path segments used in the calibration, the validation simulates the whole path using the optimized parameters. In the validation, the optimized parameters are applied for all three scenarios: overtaking vessels, overtaken vessels and head-on vessels. Among these scenarios, the overtaking and overtaken vessels are from the same dataset. Similar as in the calibration, the vessel is simulated while the encountered vessel path is considered as a known input (described by the AIS data). Then, the calibrated parameters are used by the VMP model to predict each vessel path every 10 seconds.

To evaluate the simulation quality, the comparison between the simulated path and the real path focuses on four aspects in both the longitudinal and lateral direction: the final position of the whole path, the maximum absolute deviation, the average absolute deviation and average percentage of good predictions (within the allowed error margin). To quantify how well the simulated path fits the vessel path from AIS data, 8 goodness of fit measures are defined. Considering the overtaking vessel as an example, Figure 5.4 shows the simulated vessel path for the overtaking vessel and the real path from AIS data, as well as the parameters used to formulate the measures. It should be noted that the scheme to determine the port side or starboard overtaking is not included in this VMP model yet, so the simulated overtaking may happen on the other side than the real one, when the whole vessel path is simulated by the VMP model. The results for these overtaking and overtaken paths will not be included in the validation results and the choice of the overtaking side is left for further research.

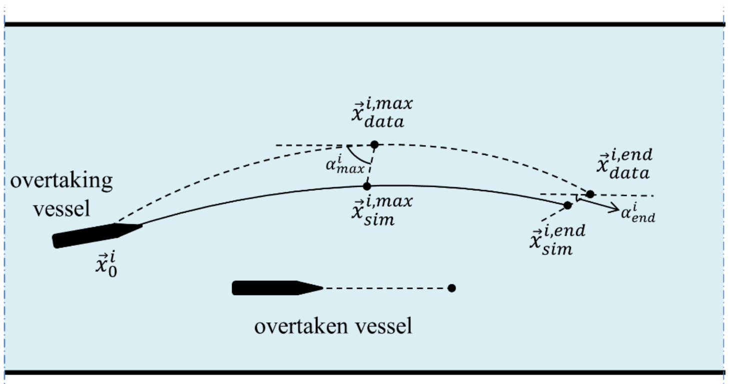

Figure 5.4: Simulated vessel path (solid line) of overtaking vessel and the observed path (dashed line) from AIS data.

As shown in Figure 5.4, the origin of the simulated overtaking vessel is $\vec{x}_0^i$, in which *i* denotes vessel path id. The maximum deviation happens when the overtaking and overtaken vessels are located at positions $\vec{x}_{sim}^{i,max}$ and $\vec{x}_{data}^{i,max}$, while the simulated path and the real path end at $\vec{x}_{sim}^{i,end}$ and $\vec{x}_{data}^{i,end}$, respectively. The deviations E_{lo}^F and E_{la}^F are the average difference for the final position of simulated path and AIS path in the longitudinal and lateral direction, respectively:

$$E_{lo}^F = \frac{1}{m}\sum_{i=1}^{m}(\left|\vec{x}_{data}^{i,end} - \vec{x}_{sim}^{i,end}\right| * \cos\alpha_{end}^i) \tag{5.15}$$

$$E_{la}^F = \frac{1}{m}\sum_{i=1}^{m}(\left|\vec{x}_{data}^{i,end} - \vec{x}_{sim}^{i,end}\right| * \sin\alpha_{end}^i) \tag{5.16}$$

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

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

$$E_{lo}^M = \frac{1}{m}\sum_{i=1}^{m}(\left|\vec{x}_{data}^{i,max} - \vec{x}_{sim}^{i,max}\right| * \cos\alpha_{max}^i) \tag{5.17}$$

$$\mathrm{E_{la}^M} = \frac{1}{\mathrm{m}}\sum_{\mathrm{i}=1}^{\mathrm{m}}(\left|\vec{\mathrm{x}}_{\mathrm{data}}^{\mathrm{i,max}} - \vec{\mathrm{x}}_{\mathrm{sim}}^{\mathrm{i,max}}\right| * \sin\alpha_{\mathrm{max}}^{\mathrm{i}}) \tag{5.18}$$

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

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

$$E_{lo}^A = \frac{1}{m} * \frac{1}{n_i} * \sum_{i=1}^{m}\sum_{j=1}^{n_i}(\left|\vec{x}_{data}^{i,j} - \vec{x}_{sim}^{i,j}\right| * \cos\alpha_{i,j}) \tag{5.19}$$

$$E_{la}^{A} = \frac{1}{m} * \frac{1}{n_i} * \sum_{i=1}^{m} \sum_{j=1}^{n_i} (|\vec{x}_{data}^{i,j} - \vec{x}_{sim}^{i,j}| * sin\,\alpha_{i,j}) \tag{5.20}$$

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

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

$$P_{lo} = \frac{1}{m} * \sum_{i=1}^{m} P_{lo}^{i} \tag{5.21}$$

$$P_{la} = \frac{1}{m} * \sum_{i=1}^{m} P_{la}^{i} \tag{5.22}$$

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

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

5.4 Results

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

Table 5.1: Calibration results for the VMP model for three different datasets

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

5.4.1 Calibration results

By applying the optimization approach, the best fit of the VMP model to the AIS data of overtaking vessels is determined. The optimal model parameters are shown in Table 5.1. The obtained error is 458 m^2, which is the mean square of the distance of the final position between the simulated path and actual path from AIS data. This implies that the prediction error is around 21 meters while the prediction period is 60 seconds.

It can be seen that all parameters have positive values, which is as expected because these parameters are weight factors and scaling parameters. Compared to c_2^v and c_2^ψ, c_3^v and c_3^ψ are much larger. Compared to vessel speed and course, the values of longitudinal acceleration and angular speed are normally very small. This will result in large values of c_3^v and c_3^ψ. The scaling parameters p and q equal to 8 and 3.9, which means that the influence range in longitudinal and lateral direction is around 8 times the vessel length and 3.9 times the vessel width, respectively. They are consistent with our expectation that vessels have stronger influence in the longitudinal direction than in the lateral direction, considering the fact that vessel length is much larger than vessel beam.

Based on the six optimal parameter values in Table 5.1, the relationships between each parameter and the error by varying each parameter while keeping the other parameters constant at their optimal value are shown in Figure 5.5.

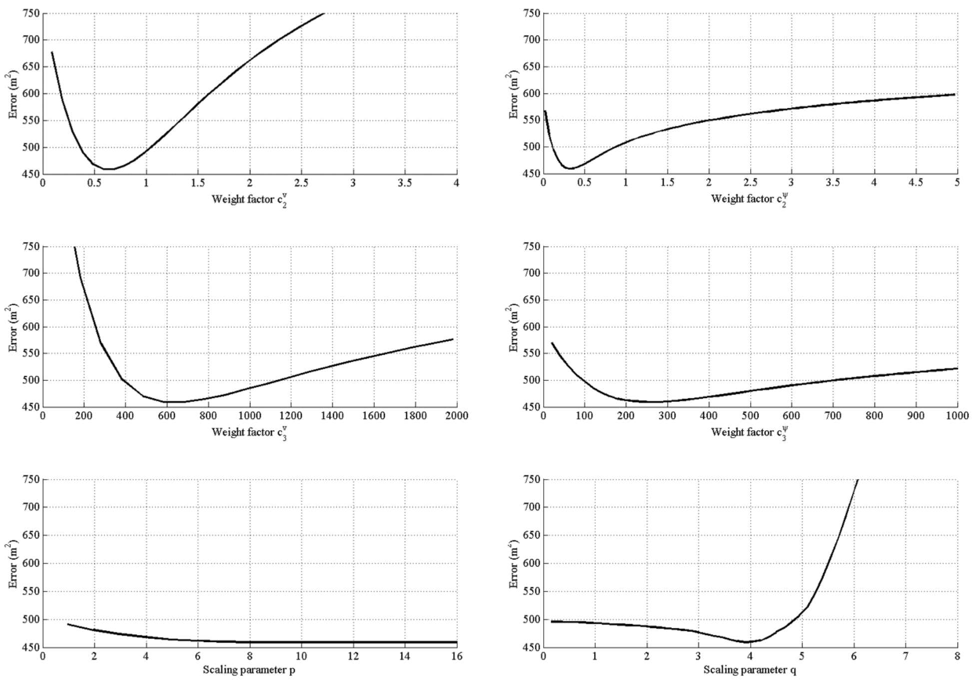

Figure 5.5: The relationships between each parameter and the error by varying each parameter while keeping the other parameters constant at their optimal value.

It is clear that all curves for these parameters are smooth. For parameters c_2^v, c_2^ψ, c_3^v, c_3^ψ and q, the curves have a single and clear minimum, which means the optimal values are taken at the global minimum. Thus, it also means that the calibration method is robust and the optimal values for these parameters are reliable. Regarding the parameter p, the error decreases with the increase of the scaling parameter up to 8, after which the p value remains stable. It means that the model is not sensitive to the p value and the optimal p value is difficult to be determined when the p value is larger than 8. However, it is not meaningful to investigate the situation for larger p value (p > 8), which leads to a unrealistically large influence range in longitudinal direction (exceeding the research area).

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

5.4.2 Validation results and examples

By applying the validation approach, the goodness of fit measures is calculated for overtaking vessels, overtaken vessels and head-on vessels, as shown in Table 5.2. As mentioned in section 3.2, the 23 vessel paths in which overtaking occurred on the other side of the overtaken ship than the actual side are removed from these validation results, and 10 vessel paths of simulated overtaken vessels are filtered in the same way.

Table 5.2: The goodness of fit measures for the validation of different scenarios

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

The deviations in longitudinal direction range from 33 m to 112 m. Considering the waterway stretch of around 2.5 km, all measures representing the error in longitudinal direction are less than the 5% of the waterway stretch. In the lateral direction, the deviations vary from 27 m to 83 m, which is relatively large given the waterway width of around 430 m. However, the deviation in lateral direction is also influenced by the deviation in longitudinal direction, as the vessel path is compared by time line. So it is difficult to judge the simulation quality based on the deviation in lateral direction here.

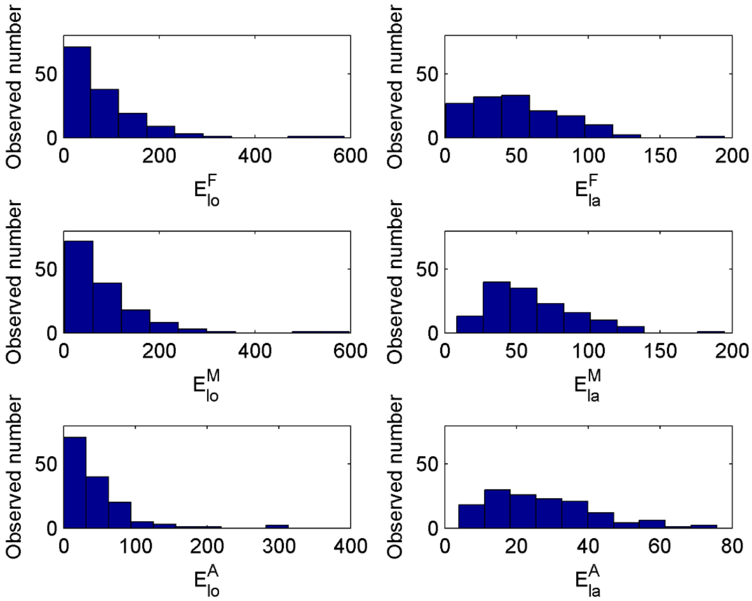

Figure 5.6: Histograms of the deviations from the first six good of fit measures for overtaking vessels.

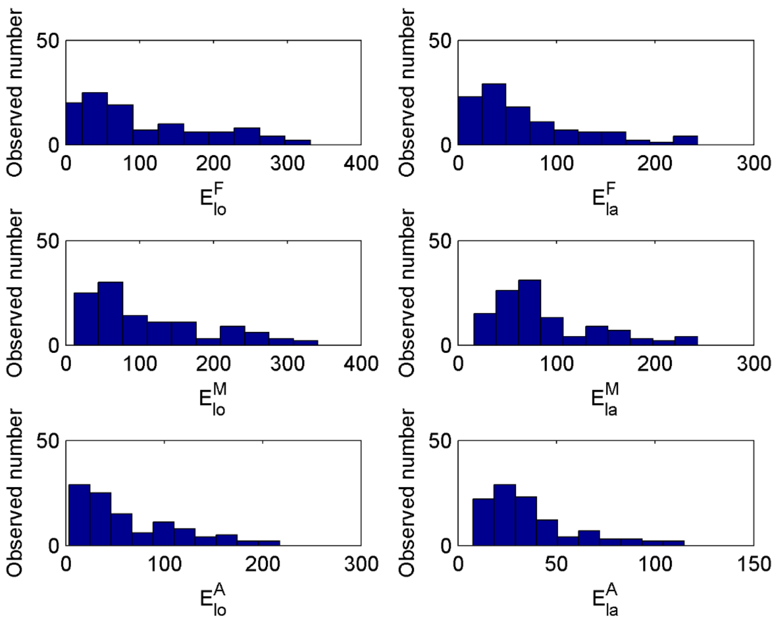

Figure 5.7: Histograms of the deviations from the first six good of fit measures for overtaken vessels.

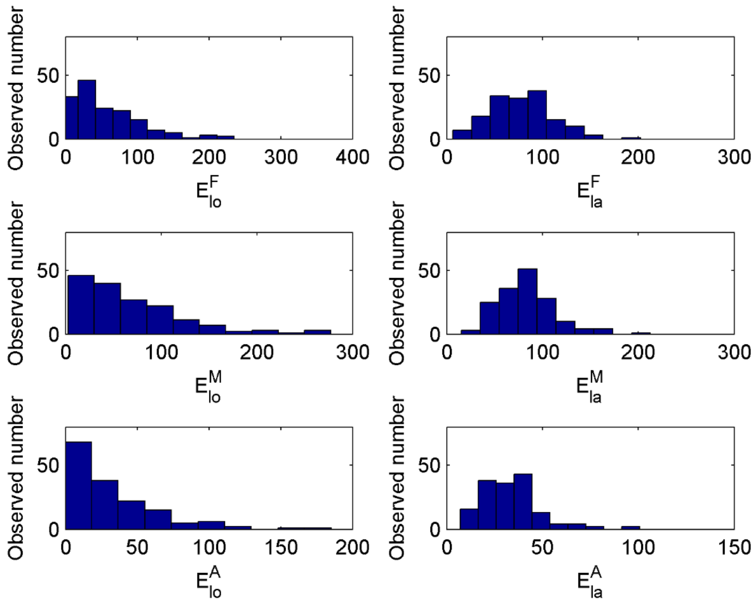

Figure 5.8: Histograms of the deviations from the first six good of fit measures for head-on vessels.

The data clearly showed that the best prediction in longitudinal direction is for head-on encounters, as all the deviations in longitudinal direction for head-on encounters are smaller than other scenarios, and the percentage of good prediction is around 81%, which is better than for the other scenarios as well. This may be caused by the fact that the speed is hardly influenced by the head-on encounters. However, the prediction in lateral direction for head-on encounters is obviously worse than for the other scenarios. This could imply that the elliptical influence area does not work well for head-on vessel encounters. It suggests to improve the cost function for vessel influence in the VMP model in future research, specifically for head-on encounters. As mentioned in Section 6.3.2, the histograms of the deviations for the first six goodness of fit measures are shown in Figure 5.6-5.8.

In the remainder of this section, some example paths have been randomly chosen for each scenario and plotted in Figure 5.9, and compared to the actual path from AIS data and unhindered path (generated by the desired course). The first example is to simulate overtaking vessel sailing from left to right. It can be seen that the predicted path in the middle part of the stretch is closer to the starboard bank, meaning that the influence between two vessels in the VMP model is not strong enough during that period. In the right part of the stretch, the simulated vessel deviates from the desired path and then the simulated path is consistent with the AIS overtaking path, which implies the influence between two vessels is reasonably predicted in this situation. In the remaining two examples, the predicted paths are nearer to the shore, compared to both the AIS path and desired path. This could mean that the influence between vessels, as calibrated for overtaking vessels, is too strong for overtaken and head-on vessels.

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

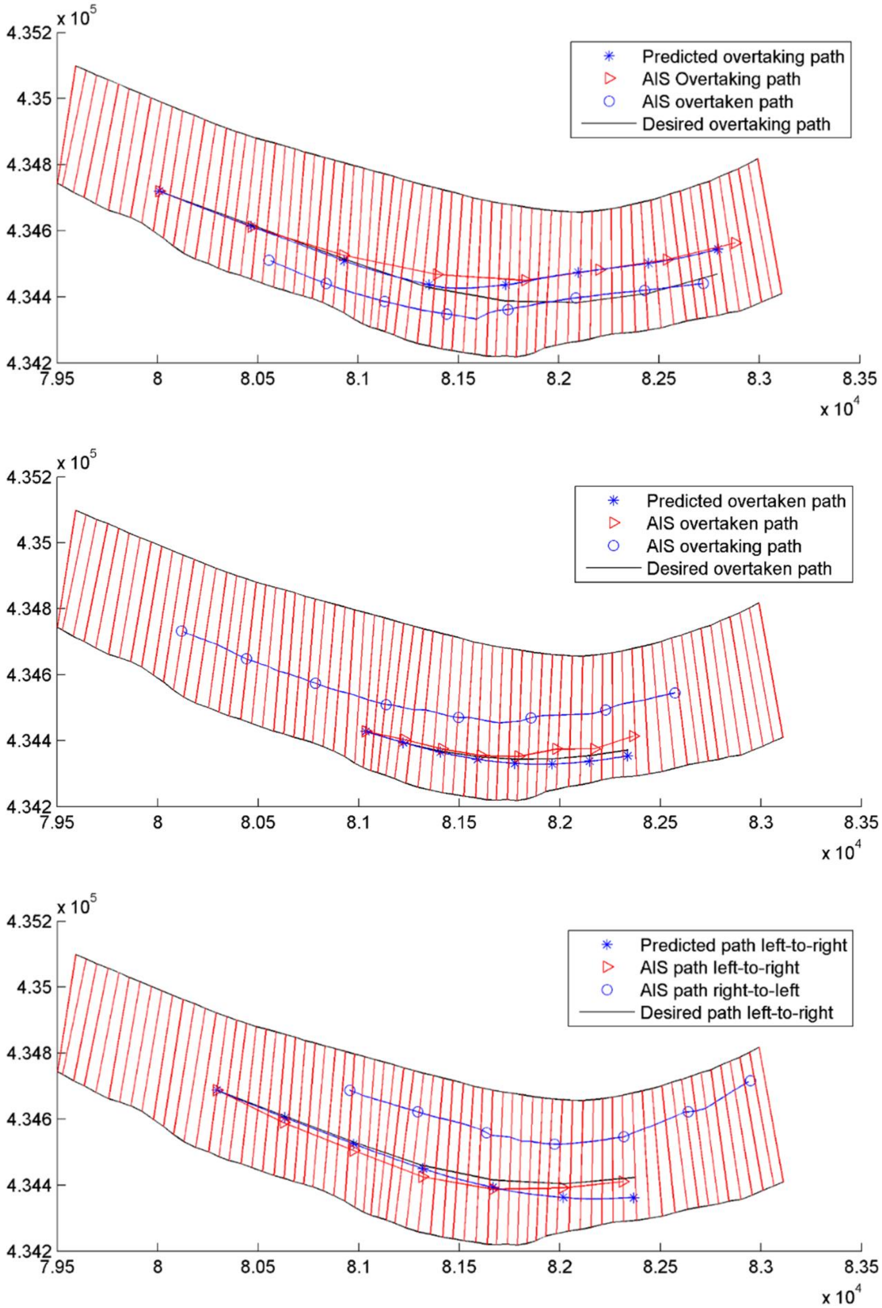

Figure 5.9: Example simulated vessel paths compared to the actual path from AIS data and unhindered path generated by desired course.

5.5 Discussion and conclusions

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

It should be noted that several factors influence the calibration results. Firstly, the calibration results are influenced by the desired speed and desired course, which are important inputs to the model. As we can see in Equation (5.7), the costs for straying from the optimal path were based on the difference between the real speed and the desired speed, as well as the real course and the desired course. In this research, the desired speed is based on empirical data. A better solution would be a derivation of the desired speed based on waterway geometry and vessel characteristics. For the desired course, the results of the Route Choice model for one representative vessel category is used. Since the dataset used for calibration comprises several vessel categories, this contributes to the error in the calibration of the VMP model.

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

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

Acknowledgment

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Chapter 6

Verification of route choice model and operational model of vessel traffic

This chapter is an edited version of the article:

Shu, Y., W. Daamen, H. Ligteringen, & S. P. Hoogendoorn (2016) Verification of Route Choice Model and Operational Model of Vessel Traffic, *Transportation Research Record: Journal of the Transportation Research Board*, 2549, pp. 86-92.

Abstract

Because of ever-increasing economic globalization, it is necessary to simulate vessel behavior for investigating safety and capacity in ports and inland waterways. A new maritime traffic model was developed; it 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. Through prediction and minimization of this disutility, the longitudinal acceleration and angular speed can be optimized and predict individual vessel sailing behavior. To verify the route choice model and the operational model, a case study was carried out; it applied the models to predict individual vessel behavior (path, speed, and course) in the entrance channel to Maasvlakte I at the Port of Rotterdam, Netherlands. The simulation results show a good prediction of the vessel path and vessel course. As no other model has been built specifically to predict vessel behavior in the port area, the current methods provide a fundamental basis for investigating vessel behavior in restricted waterways. In addition, this research showed the potential of the model to increase the safety and capacity of ports and inland waterways.

6.1 Introduction

Because of ever-increasing economic globalization, the scale of transportation through ports and inland waterways has 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 safety decreases, and vice versa. This rule holds even more strongly for ports and inland waterways, where 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 used in three main ways. Some models calculate the collision and grounding probability (Degre et al., 2003; Fowler & Sørgård, 2000; Pedersen, 1995). The second type of model predicts vessel maneuvering by including hydrodynamics of vessels (Sariöz & Narli, 2003; Sutulo et al., 2002; Yoon & Rhee, 2003). The last type of model is related to simulating the routing in a shipping network (Hsu & Hsieh, 2007; Kosmas & Vlachos, 2012; Norstad et al., 2011). 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 factors such as waterway geometry, water depth, and interaction between vessels. For predicting vessel behavior in ports and inland waterways, the influence of these factors on vessel behavior must be included. However, little research has been performed on these factors. Advances in maritime safety in ports and inland waterways mean more effort is needed in developing models, because of the 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 (Hoogendoorn et al., 2013; Shu et al., 2013b; Shu et al., 2014; Shu et al., 2015b). 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 is input for vessel behavior at the operational level. The operational level includes the dynamics of the vessel sailing behavior, such as longitudinal acceleration and angular speed of the vessel.

This paper verifies the applicability of the route choice model and the operational model by using automatic identification system (AIS) data collected from another part of the Port of Rotterdam, Netherlands. These data contain vessel information transmitted between vessels and shore stations, such as vessel speed, course, and position. In recent research, AIS data were proved to be a powerful tool for investigating maritime traffic (Aarsæther & Moan, 2009; Mou et al., 2010) and developing and calibrating simulation models. In the case study, the desired course was generated by the calibrated route choice model. Together with the desired course, the desired speed generated from AIS data was used as an input of the operational model to predict paths, courses, and speeds of individual vessels. The predicted paths and courses were then compared with AIS data to verify whether the model predictions were sufficiently accurate.

The rest of this paper is structured as follows. First, the maritime traffic control framework is presented. Then, the operational model is demonstrated in detail, followed by the case study setup, modeling results, and discussion. Finally, conclusions and recommendations for future research are proposed.

6.2 Maritime traffic control framework

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 termed the "brain" of the vessel. The team observes and predicts the vessel sailing context and then maneuvers the vessel by accelerating, decelerating, or turning. This maneuvering is the control of the vessel.

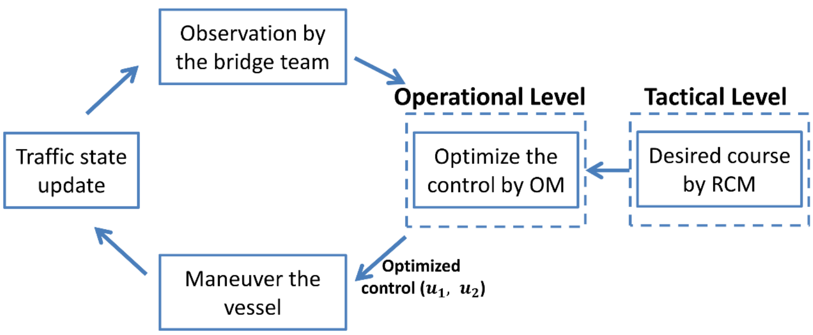


Figure 6.1: Maritime traffic control framework. (OM = operational model; RCM = route choice model).

The control framework is shown in Figure 6.1. The traffic state (sailing context) is observed by the bridge team and is the input to the operational model. With the desired course generated by the route choice model as the starting point, control in the longitudinal direction (longitudinal acceleration u_1) and the angular direction (angular speed 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.

6.3 Operational model

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

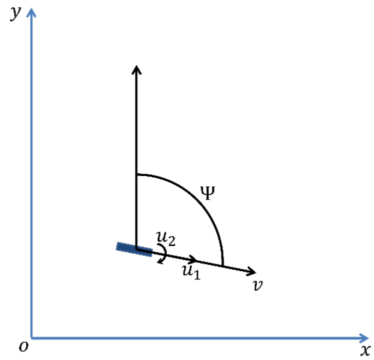


Figure 6.2: Vessel coordinate system and control.

6.3.1 System dynamics

This research considers the vessel's motions in horizontal plane, in which three Degrees Of Freedom (DOF) are considered (surge, sway and yaw). As shown in the vessel coordinate system in Figure 6.2, a vessel is geometrically represented by a rectangle in the *x*–*y* coordinates and sails to the bottom right, under longitudinal acceleration u_1 and the angular speed u_2.

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:

$$\dot{x} = v\,cos\left(\frac{\pi}{2} - \psi\right) \tag{6.1}$$

$$\dot{y} = v\,sin\left(\frac{\pi}{2} - \psi\right) \tag{6.2}$$

$$\dot{v} = u_1 \tag{6.3}$$

$$\dot{\psi} = u_2 \tag{6.4}$$

6.3.2 Model by optimal control

The bridge team controls the vessel according to 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 propulsion and steering costs (accelerating, decelerating and turning).

The control objective functions were used to 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 at the desired speed and on the desired course. In the proposed theory, deviating from the desired speed and course, accelerating, decelerating, and turning provide disutility (cost) to the vessel. Through prediction and minimization of this disutility, the longitudinal acceleration and angular speed can be optimized.

The control objective function *J* is defined by

$$J = \int_{t}^{t+H} L\left(s, \vec{\xi}, \vec{u}\right) ds + \Phi(t + H, \vec{\xi}(t + H)) \tag{6.5}$$

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 $[\tau, \tau + d\tau)$), $\vec{u} = (u_1, u_2)$ 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:

- Costs of straying from the desired speed and course, expressed by

$$L^{stray} = \frac{1}{2}\left(c_2^v (v^0(\vec{x}) - v)^2 + c_2^\psi (\psi^0(\vec{x}) - \psi)^2\right) \tag{6.6}$$

- The propulsion and steering costs, indicated by

$$L^{effort} = \frac{1}{2}\left(c_3^v u_1^2 + c_3^\psi u_2^2\right) \tag{6.7}$$

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 location $\vec{x}$.

To minimize the objective function, it is assumed that the longitudinal acceleration and angular speed the bridge team selects satisfy

$$\vec{u}^*_{[t,t+H)} = \arg\min J(\vec{u}_{[t,t+H)}) \tag{6.8}$$

subject to Equation (6.1) through (6.4).

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 (Fleming et al., 2006):

$$H = L + \vec{\lambda} \cdot \frac{d\vec{\xi}}{dt} \tag{6.9}$$

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

$$-\frac{d\vec{\lambda}}{dt} = \frac{\partial H}{\partial \vec{\xi}} \tag{6.10}$$

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, it is assumed 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:

$$H(t, \vec{\xi}, \vec{u}^*, \vec{\lambda}) \leq H(t, \vec{\xi}, \vec{u}, \vec{\lambda}) \quad \forall \vec{u} \tag{6.11}$$

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

$$u_1^* = -\lambda_v / c_3^v \tag{6.12}$$

$$u_2^* = -\lambda_\psi / c_3^\psi \tag{6.13}$$

By substituting Equations (6.6), (6.7) and (6.9) in Equation (6.10), the following equations, which express the shadow costs dynamics, are obtained:

$$-\dot{\lambda_v} = c_2^v(v - v^0) + \lambda_x \cos(\frac{\pi}{2} - \psi) + \lambda_y \sin(\frac{\pi}{2} - \psi) \tag{6.14}$$

$$-\dot{\lambda_x} = c_2^v(v^0 - v)\frac{\partial v^0}{\partial x} + c_2^\psi(\psi^0 - \psi)\frac{\partial \psi^0}{\partial x} \tag{6.15}$$

$$-\dot{\lambda_y} = c_2^v(v^0 - v)\frac{\partial v^0}{\partial y} + c_2^\psi(\psi^0 - \psi)\frac{\partial \psi^0}{\partial y} \tag{6.16}$$

$$-\dot{\lambda_\psi} = c_2^\psi(\psi - \psi^0) + \lambda_x v \sin\left(\frac{\pi}{2} - \psi\right) - \lambda_y \cos(\frac{\pi}{2} - \psi) \tag{6.17}$$

Then, Pontryagin's method is used to solve the system of these equations (Hoogendoorn et al., 2012).

6.4 Case study

In previous work, the route choice was calibrated and presented (Shu et al., 2014; Shu et al., 2015b). The operational model has been calibrated as well (Shu et al., 2015a). Both models were calibrated according to AIS data, which was used in this research as well. To verify the route choice model and the operational model, a case study was carried out that applied the models in a situation other than what it had been calibrated for. The simulation results were compared with AIS data to assess the quality of the model. This section contains two parts: the case study setup and comparison and discussion of results.

6.4.1 Setup

In this section, the case study setup is presented. The scenario, consisting of the infrastructure geometry, the demand profile, and the fleet composition, is introduced. Then 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 Maasvlakte I in the Port of Rotterdam, which is shown in Figure 6.3a. The research area was chosen because an AIS data analysis had been carried out for this area in a previous study (De Boer, 2010). The AIS data from 2009 were available for this case study.

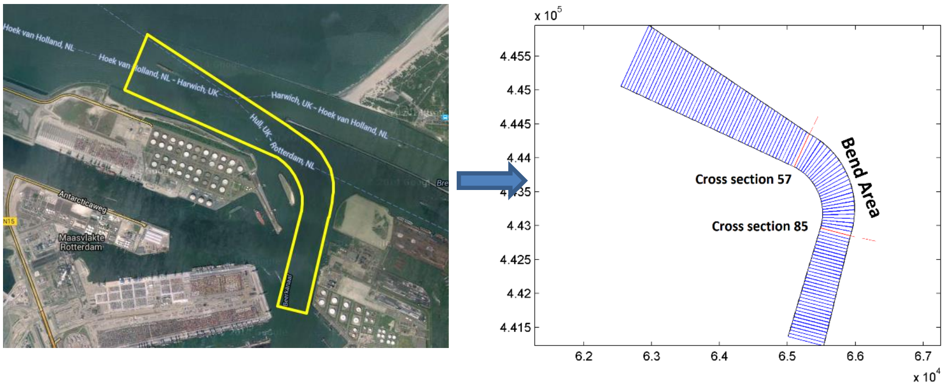


Figure 6.3. Converting the research area geometry to RD coordinates and cross sections.

In Figure 6.3, the research area geometry is defined by the yellow lines according to the buoys, the bank, and the curves in the turning area. The geographical coordinates of this geometry were transferred to coordinates on the Rijksdriehoeksgrid (RD), the national grid of the Netherlands (Figure 6.3b). This national grid in meters can be used to calculate vessel movement. In addition, 119 cross sections with intervals of around 50 *m* were defined in the research area for calculating and comparing the vessel behavior in the lateral direction. These cross sections are approximately perpendicular to the waterway longitudinal direction and can be used to extract AIS data on each cross section.

This study investigated vessels sailing from the North Sea to the berth, which is the direction from the upper left to the bottom in Figure 6.3. For this direction, 307 vessel paths from AIS data from the North Sea to Maasvlakte I were available for the case study. These paths are shown in Figure 6.4a. The vessel paths spread much wider at 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 in Figure 6.3a. 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 shown in Figure 6.4a. This study did not consider these inconsistencies, because the moves are preparation for mooring (entering the basin).

Optimized parameters

In this section, an overview of the optimized parameters for the route choice model and the operational model is given in Table 6.1.

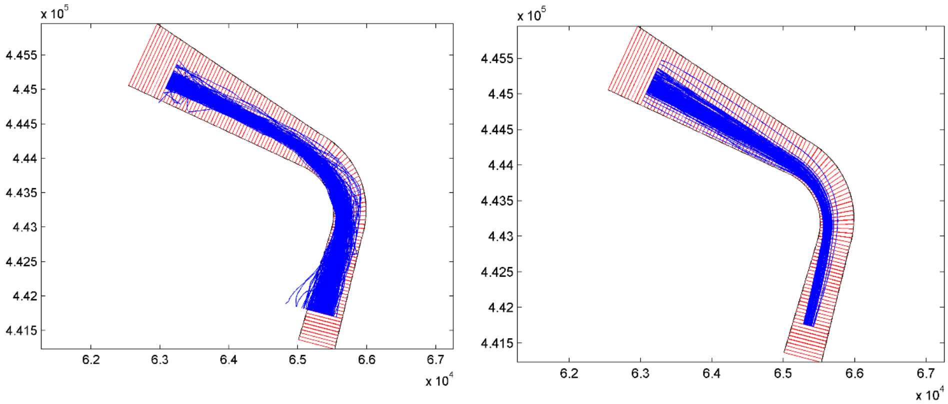


Figure 6.4: Real paths from (a) AIS data and (b) simulated vessel paths in RD coordinates.

Table 6.1: Optimized parameters for the route choice model and the operational model

Parameters	
Route choice model	
c_4	0.0354
c_5	0.0067
r_1	0.465
r_2	0.287
Operational model	
c_2^{ψ}	7.99
c_3^{v}	33.6
c_3^{ψ}	393.41

The route choice model was calibrated for four AIS data sets in another area in the port of Rotterdam, covering four sailing directions (Shu et al., 2014). In this section, the results (optimized parameters) of this calibration are used, as shown in the first and second rows of Table 6.1. The parameters c_4 and c_5 denote the strength of the influence of the portside and starboard banks, respectively, on the vessel, and the parameters r_1 and r_2 reflect the influence range of both banks in the lateral direction. The influence of the portside bank is larger than that of the starboard bank both in strength and in range. Table 6.1 shows 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 were used when the model was applied in the case study, described in the next sections.

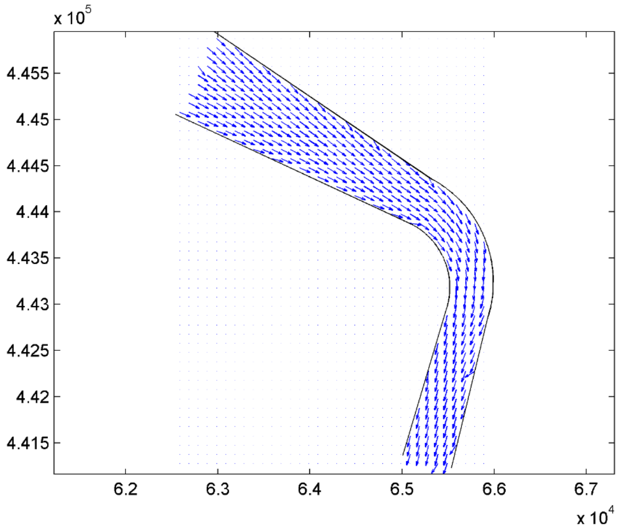


Figure 6.5: Desired course in continuous space by the route choice model.

Desired course by route choice model

To apply the dynamic programming approach and the numerical solution approach, the research area was discretized into a 5- × 5-m grid. On the basis of the optimized parameters in Table 6.1, the desired course in continuous space was generated by the route choice model in each cell formulated by the grid. The desired course is shown in Figure 6.5, where the arrow in each cell indicates the desired course and forms the so-called desired course field for a vessel sailing from the upper left to the bottom of the figure. In this course field, when the vessel is close to the bank, it will be repelled from the bank. The vessel also will smoothly follow the bend. This desired course is plausible and corresponds to the AIS data analysis.

From this course field, the desired course for any location in this area can be derived by interpolation. This desired course field can be used as input in the operational 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 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 so were not included in the model. As an approximation, the average vessel speed (from AIS data) on each downstream cross section was used 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 the desired speed. The vessel speed mostly decreased considerably in this research area when the vessels sailed from the open sea to their final destination (berth).

Application of operational model

The route choice model and the operational model were calibrated according to AIS data for small general dry cargo vessels (Shu et al., 2013b). In the available AIS data for this case study, the vessels are classified by the vessel deadweight tonnage. This study modeled only the vessels in the category of smaller than 10,000 deadweight tonnage, which corresponds best to the vessel category for which the model was calibrated.

With the desired course and the desired speed as input, the operational model was applied to predict vessel speed, course, and path. (This simulation cannot cover the whole area, because the operational model is based on prediction, which makes a vessel exceed the boundary when it is too close to the boundary.) Then Cross Section 10 was chosen as the origin and Cross Section 110 as the destination. For generating the vessels in the simulation, the real vessel state (position, speed, and course) at Cross Section 10 was used as the initial state, since it is input to the operational model.

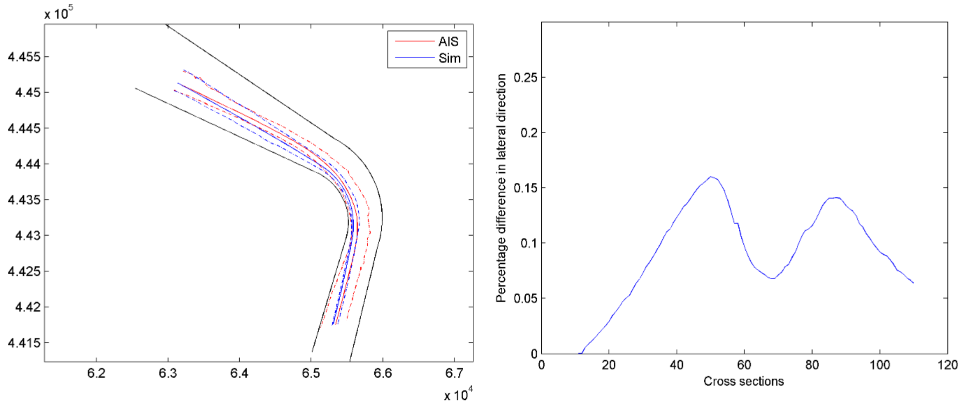
6.4.2 Results comparison and discussion

Vessel path

Figure 6.4 shows the real paths from AIS data and predicted vessel paths in the research area. Some real paths are shown outside the boundary. These ships turn around in the waterway because they enter the basin stern first for logistic reasons. Compared with the AIS data paths in Figure 6.4a, predicted paths have less variation because the interactions of other vessels, human factors, and external conditions are not included in the operational model.

For the predicted paths, vessels concentrate on the right-hand side of the waterway, which corresponds to the AIS data analysis (Shu et al., 2013b). In the bend area, the vessel tracks also follow the turning curve well. Compared with the lateral position of these tracks before the bend area, the vessels after the bend area are farther from the starboard bank. In general, the simulated vessels are more concentrated in the center of the waterway than are the vessels in the AIS data.

Figure 6.6 shows the average vessel path (solid blue line) of the predicted vessel paths and 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. The distribution of the AIS paths in the bottom is wider than in the upper part, because of the mooring behavior explained above. In addition, the simulation paths are more concentrated than the AIS paths, probably because the factors that may increase the variability of the paths were not considered in this case study. Comparison of the average path of simulation paths in the lateral direction shows that vessels are closer to the starboard bank in the bend area, which corresponds 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.



(a) (b)

Figure 6.6: Average vessel paths (solid lines) and their 95% confidence interval (dotted lines): (a) comparison between AIS data and simulation results and (b) relative error in lateral direction.

Figure 6.6b gives the relative error in the lateral direction for each cross section. The x-axis is the distance in the average path of AIS data from origin (Cross Section 10) to destination. The largest relative error is about 13%.

The difference between the average paths of predicted paths and the AIS paths are compared with the root-mean-square deviation (RMSD) measure. Let *n* denote the number of the data (cross-section number), and let (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

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{n}((x_t^{sim} - x_t^{AIS})^2 + (y_t^{sim} - y_t^{AIS})^2)}{n * (D_t)^2}} \tag{6.18}$$

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. With Equation (6.18), the value of RMSD is 6%, which means the average relative error in the lateral direction is 6%. This difference may be introduced by both the route choice model and the operational model. Most of the error could be attributed to the optimized parameters applied to generate the desired course in the route choice model, as these optimized parameters were achieved in a situation different from the case study situation. The rest of the error may have been introduced by the operational model, as the factors influencing the vessel path, such as interaction with other vessels and the influence of external conditions, had not been considered in the model at this stage.

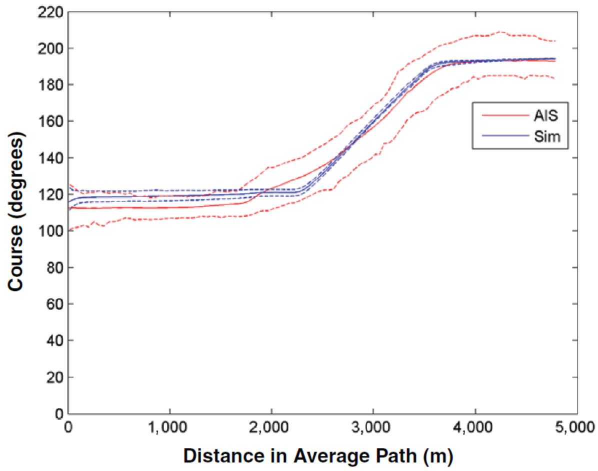


Figure 6.7: Average vessel course (solid lines) and their 95% confidence interval (dotted lines): comparison between AIS data and simulation results.

Vessel course

In Figure 6.7, the vessel course of the AIS data and the simulation results are compared. The figure shows that the simulated vessel course is well in accordance with the AIS data. However, the deviation of the simulation course is much less than that of the real course from AIS data, because the factors influencing vessel behavior were not considered in this case study.

The RMSD for vessel course is defined by

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{n}(C_t^{sim} - C_t^{AIS})^2}{n}} \tag{6.19}$$

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. From Equation (6.19), the calculated *RMSD* is 3.68°, which means the prediction error for the vessel course is about 3.68°.

6.5 Conclusions and recommendations

This paper presented an operational vessel sailing model in detail. A case study applied the route choice model and the operational model to verify the applicability of both models as a whole by using the AIS data in the Port of Rotterdam (the entrance channel to Maasvlakte I). The proposed model was formulated with optimal control theory and a numerical solution approach.

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

The vessel path and the vessel course were compared for AIS data and simulation results with RMSD. The results showed a good prediction for vessel path (6% relative difference in lateral direction) and vessel course (3.68°). These errors may be attributed to the optimized parameters, which were achieved in a situation different from the case study situation. In addition, the factors (such as external conditions and vessel encounters) may have contributed to the error, since they have not yet been included in the model. Because no other model has been built specifically to predict vessel behavior in a port area, the current methods provide a fundamental basis for investigating vessel behavior in restricted waterways.

This research showed the potential of the model to simulate vessel traffic in a selected area of a port. Future research will simulate larger and more complex parts of the port. The goal is a model that can be used by port authorities and port and waterway designers 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 for investigating the safety and capacity of ports and inland waterways. For the port authority or administrative departments, such as vessel traffic service, the model could be used to improve the management of maritime traffic, for example, by testing the potential of time slot management.

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 could 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, calibration will be performed for more vessel classes and other waterway layouts.

Acknowledgments

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Chapter 7

Findings, conclusions, implications and recommendations

In this chapter, we introduce the main research findings in Section 7.1, followed by the conclusions in Section 7.2. Then, Section 7.3 presents implications for practice. Finally, recommendations for future research are proposed in Section 7.4.

7.1 Main findings

In this section, the main findings of this research are structured in three parts corresponding to research questions 1-4 in Section 1.1.4.

7.1.1 AIS data analyses

AIS data of the Botlek area in the Port of Rotterdam are used to investigate the unhindered vessel behavior and to identify potential factors that can affect vessel behavior (Chapter 2 and 3).

In Chapter 2, the unhindered vessel behavior of different vessel categories and for different navigation directions was investigated. It was found that vessel speed is influenced by vessel size, vessel type, waterway geometry and navigation direction. Smaller vessels have larger speeds in the research area, where outgoing vessels navigate at greater speed than incoming vessels, and vessels in wide waterways sail faster than vessels in a narrow waterway. Furthermore, vessel course hardly depends on vessel size and vessel type, but it does depend on waterway geometry and navigation direction. Finally, vessel path is influenced by vessel type, vessel size, geometry and navigation direction. It was found that smaller vessels keep a larger distance from the waterway centerline.

In Chapter 3, the influences of external conditions (i.e. wind, visibility and current) and vessel encounters (head-on and overtaking) on vessel speed, course and relative distance to starboard bank (the distance divided by the waterway width) are analyzed by comparing uninfluenced and influenced vessel behavior using AIS data and historical data of wind, visibility and current. The findings are as follows:

- **Wind**: stern wind and bow wind (> 8 m/s) mainly influence vessel speed, while starboard wind and portside wind (> 8 m/s) can affect the relative distance to the starboard bank. Results showed that vessel speed is on average increased by 2.3% for container vessels and by 3.4% for GDC vessels under stern wind, but it is decreased by 2.5% and 9.6%, respectively by bow wind. Vessel course is barely influenced by wind, except for starboard wind. The relative distance to starboard is increased by 4.2% and 7.3% and is decreased by 4.9% and 9.4% respectively for the two vessel types. It also can be seen that GDC vessels are easier to be influenced by wind than container vessels.

- **Visibility**: bad visibility has a negative influence on vessel speed for container vessels (4.9%), but it does not influence GDC vessels. Vessel course is not influenced by visibility. The relative distance to starboard bank is decreased by bad visibility by 3.6% and 5.1% for container vessels and GDC vessels, respectively.

- **Current**: current has a significant influence on vessel speed compared to the uninfluenced vessel speed. GDC vessel speed is decreased by 11.6% from the Sea to the Oude Maas and by 5.3% from the Oude Maas to the Sea for the category of "Against current", and is increased by 6.1% from the Sea to the Oude Maas and by 12.9% from the Oude Maas to the Sea for the category of "With current". In addition, the influences of current on vessel course and relative distance to starboard are observed to be significant. However, further research on the influence of current is required. For example, it can be questioned whether it would make more sense to consider the actual speed through water instead of the speed over ground.

- **Head-on encounters**: vessel speed in two directions is decreased by 5.3% and 1.2%, and relative distance to starboard bank is decreased by 13.3% and 9.7% at the relative cross section 0, which is the cross section nearest to the Closest Point of Approach (CPA). Although vessel course at the relative cross section 0 is observed to be uninfluenced, it changes before and after CPA (relative cross section 0). It was also found that the research area is sufficient to cover the head-on encounters, which are approximately completed between relative cross sections −20 and 20. In addition, the two vessels show cooperative behavior during the encounters: both will deviate from the desired path to give more space when they are approaching.

- **Overtaking encounters**: vessel speed and relative distance to starboard bank are influenced during overtaking encounters. Vessel speed is decreased around 20% for overtaken vessels and is increased around 10% for overtaking vessels. Vessels overtake each other either on the portside or on starboard side, according to the experience of the bridge team, traffic situation, etc. The relative distance is decreased by around 25% for overtaken vessels and is increased by 50% for overtaking vessels in portside overtaking, while these figures are 37% and 33% in starboard overtaking. In addition, it turns out that the behavior of the bridge teams are cooperative: both vessels will deviate from their desired path, and vessel speed for overtaking vessel is increased and speed of overtaken vessels is decreased.

7.1.2 Model development and calibration

Based on the empirical findings presented above, this thesis presents the development of a new maritime traffic model, including two sub-models: the route choice model and the operational model. The calibrated results of the route choice model in Chapter 4 show that vessels keep a certain distance from both portside and starboard banks, which corresponds to the observations in AIS data. It is found that ships keep a distance of 54% of the waterway width from the portside bank and keep a distance of 23% of the waterway width from the starboard bank. This will lead to that vessels concentrate in the right part of the waterway. The results also showed plausible example preferred routes in the research area, which aid understanding of the desired vessel behavior (route). The optimized parameters from VMP model in Chapter 5 are all positive values, which correspond to our expectation. The relationships between each parameter and the error by varying each parameter while keeping the other parameters constant at their optimal value show the robustness of the calibration and the reliability of the optimal parameters. In the validation for three scenarios, it was found that different deviations in longitudinal direction are less than 5% of the waterway stretch. The example paths also show plausible vessel paths during encounters.

7.1.3 Case study

In chapter 6, a case study is performed by using the route choice model and the operational model. The aim is to verify the applicability of both models as a whole by using the AIS data of unhindered vessel behavior in the entrance channel to Maasvlakte I in the Port of Rotterdam (which is different from the area where the model was calibrated). In the case study, the desired course generated by the calibrated route choice model is used. Together with the desired course, the desired speed based on historical data serves as the input to the operational model. The simulated vessel path and the vessel course were compared with AIS data using Route-Mean-Square Deviation (RMSD). The results showed a good prediction of the vessel path (6% relative difference in lateral direction) and vessel course (the root mean square error is 3.68°).

7.2 Conclusions

Based on the findings listed in Section 7.1, the following conclusions can be drawn. Firstly, this thesis provides many evidences showing that the vessel behavior including vessel speed, course and path is influenced by vessel size, vessel type, waterway geometry, navigation direction, external conditions and vessel encounters, it can thus be concluded that the AIS data is a useful source for insight into vessel behaviour and these influencing factors should be included in the model. Secondly, optimal control theory could be used to formulate the route choice model and the operational model, which can be applied to predict vessel behavior including vessel speed and course, and with that to investigate the safety and capacity of maritime traffic. Thirdly, the desired vessel course could be used to calibrate and validate the route choice model, while vessel encounters serve as the input into the calibration and validation of the operational model. Furthermore, the AIS data could be used as a functional resource for the calibration and validation of a maritime traffic model. Lastly, the new maritime traffic model integrated by the route choice model and the operational model can be used to simulate vessel traffic in ports and waterways, as shown in Chapter 6.

To summarize, this thesis provides insights into vessel behavior and factors influencing vessel behavior, and a new maritime traffic model including two sub models has been developed, calibrated, validated and verified.

7.3 Implications for practice

The findings and conclusions in this thesis provide important implications for practice, since they provide insights into vessel behaviour, including speed, course and path, and also a new methodology to predict (simulate) vessel behavior in ports and waterways in detail.

Firstly, the model could be used by the port authority in assessment of the safety and capacity of existing harbor channels based on the simulation of multiple vessels in the research area. For the safety, the simulation results could be used to identify potentially dangerous situations for vessels. Therefore, it could be used to improve the maritime traffic management by port authorities, such as the Vessel Traffic Service (VTS). Furthermore, improvement of dangerous areas in ports and waterways could be evaluated. Regarding capacity, it is possible to investigate the maximum capacity of existing harbor channels for a predefined risk level.

Secondly, the simulation results of the model could be used to improve the maneuvering of the bridge team. The results provide insights into vessel behavior and influence of external conditions on vessel behavior. These insights could benefit the maneuvering decisions of the bridge team, especially in extreme conditions, such as strong wind and bad visibility.

Thirdly, the model could be applied in the design of new channels/improvement existing channels and in the design and evaluation of new port lay-outs with respect to capacity and safety. By comparing alternative designs using the model, the best option could be determined by the port authority.

7.4 Recommendations for future research

In this section, several directions for future research are indicated.

Firstly, a limited number of factors that could influence vessel behavior was investigated in this thesis. However, more factors, such as berths and bridge piers, could affect vessel behavior as well. Further analysis for these factors could provide more insight into vessel behavior, so future research should consider these factors. In addition, while influence of individual factors is investigated in this thesis, the relationships between these factors and vessel behavior need to be further investigated. This future research requires more data, which contains various situations that could investigate the correlation between different influencing factors. For example, it would be meaningful to investigate if there is a synergy between the impact of strong wind and bad visibility on vessel behavior.

Secondly, the route choice model is only applied for one vessel category. However, it was found that larger vessels keep a larger distance from the starboard bank, which means that the desired route choice is different for different vessel sizes. To further develop the model, it is recommended to develop the route choice for different vessel categories. In addition, the route choice model is only derived for a rather simple waterway stretch. The real sailing environment can be much more complicated than a simple waterway, because more infrastructures can influence vessel behavior, such as berths and jetties. To apply the model for different ports and waterways, it is important to integrate these infrastructures in the model and calibrate the route choice model for these ports and waterways. To this aim, a new cost term that is likely influenced by different infrastructures should be developed and added in the cost functions in the route choice model in future research.

Thirdly, the decision making process to determine the portside or starboard overtaking for overtaking encounters is not included yet in the operational model. This is very important for overtaking behavior. It is decided by the bridge team according to their experience or communications. To this aim, the future research should focus on adding extra cost in the cost function to determine on which side the vessels overtake each other.

Fourthly, the route choice model is based on vessel course. Furhter research should show whether the desired speed and course should be included in the models. As we found in Chapter 2 and Chapter 6, the desired speed is influenced by lot of factors, such as waterway geometry, vessel size and navigation direction. It is suggested to develop the desired speed based on these different factors mentioned above by analyzing more vessel behavior in different areas, and then integrate this derivation into the route choice model in future research.

Last but not the least, the model has been developed and applied only for one ship, but should be able to run for all vessels in the given water area and time duration. This may be a considerable challenge in terms of computer capacity and time.

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Yaqing Shu was born in Jiangsu, China in 1985. He studied in Shanghai Jiao Tong University and obtained his Bachelor degree on Traffic and Transportation (International Shipping) in 2008. After the bachelor, he was selected for Direct Doctoral (from Bachelor to PhD) Academic Program in the department of Design and Construction of Naval Architecture and Ocean Structure at Shanghai Jiao Tong University.

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Publications

Journal articles:

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