Rida Desyani

COMPARISON OF PARADIGMS IN NAUTICAL TRAFFIC MODELS

MSc Thesis

Delft University of Technology

Comparison of Paradigms in Nautical Traffic Models

By

Rida Desyani

in partial fulfilment of the requirements for the degree of

Master of Science

in Hydraulic Engineering, Civil Engineering and Geoscience

at the Delft University of Technology,

to be defended publicly on Wednesday, October 23, 2019

<u>**Thesis Committee:**</u>

Chairman	:	Prof. Mark van Koningsveld	TU Delft
Supervisors	:	Dr. Winnie Daamen	TU Delft
		Yang Zhou	TU Delft
		Dr. Poonam Taneja	TU Delft

TU Delft

Preface

This MSc thesis presents the work performed during my graduation project as part of the Master Programme of Hydraulic Engineering from the Faculty of Civil Engineering and Geosciences of Delft University of Technology. This final report represents the closure of a two-year full of new experiences, challenges, gratitude, and chaotic feeling. It is an honor to have the opportunity to learn in TU Delft in such a lovely country as the Netherlands.

I would like to thank my thesis committee Mark van Koningsveld, Winnie Daamen, Yang Zhou, and Poonam Taneja for their guidance, constructive remarks for the thesis, as well as emotional support to go through this thesis journey. You all have admirable qualities that I look up to for my professional career life. My grateful thanks for my family to always pray for my success. Special thanks for Fathur for always be patient and supportive towards me. Many thanks for Amanda, Adam, Rani, Mustika, Kevin, Astri, Sinta, Hafiza, and Dwini for cheering me up during my study. Last but not least, big thanks to Joey for the distraction, and faith in me. My thesis would not be finished without these people, and I am blessed to have such amazing people around me.

Rida Desyani

Delft, October 2019

Executive Summary

The increase of ship traffic flow, densities, ship size, and the uncertainty from technological advancement raise issues in traffic safety and efficiency. In order to tackle the issue, currently a simulation model is widely used by various users as the port authority and bridge team, and for research and development team. Since the issues are varied for each modeling user, the modeling purposes are also different among the users. Therefore, this research aimed to find the insight into modeling paradigms in simulating the vessel dynamic kinetic information (position, speed, course, and heading) and the encountering (overtaking, head-on, and crossing). The insight is gained through comparison of models of the two aspects in six paradigms. The paradigms are Cellular Automata (CA), Generic Rule-Based (GRB), Specific Rule-Based Model (SRB), Artificial Potential Field (APF), Optimal Control (OC), and System Dynamics (SD). This research also aimed to improve a model given a specific modeling application purpose.

The comparison of paradigms will be made based on the modeling application purpose requirement. Each requirement is unique based on the modeling user's needs. After the models are compared, the insight into each paradigm is obtained. The dynamic kinetic information in CA paradigm are discretizes in the space state, so all information will be lack of simulation precision. Besides, the heading cannot be presented due to the discretization. The SRB and GRB paradigms have a higher potential in describing the information accurately due to continuous space-state. The mathematical-based paradigm has the potential to describe all aspects of the dynamic kinetic information with the flexibility (the highest level of detail set up in this research modeling criteria). For every time and space step a ship is continuously exposed by mathematical functions that controlled the vessel movement. By this approach, a ship can maneuver flexibly through the journey.

In simulating an encounter, the models often assign a ship to alter its course and speed. The value of alteration in the encounter maneuvering behavior is controlled by generic rules in the rule-based paradigm and mathematical functions in the mathematical-based paradigm. So, the details of the maneuver will rely on how the modeler constructs the rules / the mathematical function. In the rule-based paradigm, the rules are generic for every vessels and circumstances, except for SRB paradigm. Due to an inclusion of the CPA method, the SRB paradigm can quantify the behavior difference between vessels during an encounter. For the mathematical-based paradigm, the controlling mathematical functions are varied. It can be by the sum of artificial forces (APF), objective function and constraints (OC), and the calculation of external impact in the whole sailing process (SD). The rules and mathematical functions control the encountering sequence before until after the maneuvering is performed. This includes the detection of an encounter, the possibility of maneuvering check, the time to maneuver, the maneuvering action, assigning the vessel role and choosing the maneuvering side.

Based on the discussion, it is found that the CA and SRB are suitable for traffic flow analysis for the port authority. Both paradigms are simple and not excessive vessel maneuvering behavior for traffic flow analysis purposes. For the collision probability and risk, the SRB and GRB are recommended paradigms since they can quantify the interaction by the CPA method without going too detail on simulating the encounter maneuvering behavior. The OC paradigm is the most promising paradigm to serve the collision analysis for the port authority since it could exhibit the vessel heterogeneity and the bridge team behavior. The bridge team needs to consider all aspects of individual vessel behavior on the sailing progress, such as ship modularity and hydrodynamic forces. Therefore, the SD paradigm is recommended. For the research and development, the rule-based paradigm suits the traffic flow analysis model while the mathematical-based paradigm is better for the safety analysis model. Based on the discussion result, the model by Shu et al. (2015a, 2015b, 2018) with OC paradigm is selected to serve as a collision avoidance analysis model for the port authority. The model is extended further by adding the traffic rule for overtaking so the trajectory generated from the simulation output will resemble the bridge team behavior. In extending a model, it is important that existing feature in the model is compatible with the approach to extend a new addition.

In conclusion, the mathematical-based paradigms have a higher potential in simulating the vessel dynamic kinetic information and encounters behavior in more detail. Often, the dynamic kinetic information is retrieved from historical data. The vessel behavior is studied from this data to construct the rules / mathematical function for a model. The behavior includes evasive maneuvering behavior during an encounter. The insight of paradigms and its compatibility with the model application purpose becomes valuable information to extend a model based on its purpose.

List of Symbol

a_t = azimuth of the target vessel

a = longitudinal acceleration

a_θ = angular acceleration

B_{Wp} = safe distance of the port side of waterway bank

B_{Ws} = safe distance of the starboard side of waterway bank

B_B = target vessel width

B_{Wp} = course of the own vessel

D_s = safety distance of vessel

D_{ln} = distance between the lane of an own ship and a target ship

d = actual gap between both vessels.

d_1 = distance between the midpoint of a ship to the port side of waterway bank.

d_2 = distance between the midpoint of a ship to the starboard side of waterway bank.

$\vec{F}$ = total force

$\vec{F}_{att}$ = attractive force

$\vec{F}_{rep}$ = repulsive force

$F_{overtaking}$ = overtaking vessel force

$F_{overtaken}$ = overtaken vessel force

$F_{head-on}$ = head-on vessel force

F_{bank} = bank force

H = pitch of the adjustable propeller

LOA = length overall of a vessel

n = rotational speed of screw propeller

R = radius of the ship domain

t_{op}	= time in operational level
t_{ta}	= time in tactical level
$\vec{U}$	= total potential energy
$\vec{U}_{att}$	= attractive potential energy
$\vec{U}_{rep}$	= repulsive potential energy
u	= surge velocities
v	= sway velocities
v_{dist}	= speed from a distribution
v_x	= ship speed in x-direction
v_y	= ship speed in y-direction
v_o	= own ship speed
v_t	= target ship speed
v_R	= relative ship speed
v_{max}	= maximum ship speed
v_{min}	= minimum ship speed
w	= heave velocities
x	= position in x-direction
y	= position in y-direction
α_o	= own ship relative bearing with respect to the target ship
α_T	= target ship relative bearing with respect to the own ship
β	= drift angle
Γ	= roll displacement
Δt	= time step
Δt_{op}	= time step in operational level
Δt_{ta}	= time step in tactical level

Δx = space step

δ = rudder angle

ε_x = environmental factor in x-direction

ε_y = environmental factor in y-direction

θ_o = course of the own vessel

θ_t = course of the target vessel

θ_c = relative course of the vessels

θ_{max} = maximum course alteration

θ_{min} = minimum course alteration

θ_{dist} = course from a distribution

ρ = pitch displacement

Υ = yaw displacement

ϕ = turning angle

ψ = heading of a ship

ω = rate of turn/angular turning speed

Figures

Tables

1

INTRODUCTION

Globalization has been leading to rapid growth in world seaborne trade in the past two decades (Unctad, 2013). This growing demand is coupled with increased vessel traffic flows, higher traffic densities, and increment of ship size. This growth can raise issues with traffic safety and efficiencies, such as high collision events and traffic jam (Mou et al., 2010). Besides the growing demand, a safety issue due to uncertainty comes with an upcoming technology (ex: autonomous vessel) needs to be researched further. Therefore, the maritime industries need to tackle those possible issues in the future. For instance, the port authority needs a tool to assess the original design or the operation management of the port. The bridge team requires a tool to predict the vessel trajectory to ensure safe sailing. Currently, simulation models are widely used as a useful tool to represent, predict, and support the vessel traffic study for various model application purpose and users. Since each model is specifically dedicated for a purpose, the modeler needs to select a correct type of simulation. In nautical traffic models, the insight of model capabilities in simulating nautical traffic lies in its modeling paradigm.

A broad range of nautical traffic models has been developed according to the different requirements of application purposes at different levels of vessel behavioral description. These vessel behaviors are analyzed with various paradigms. Zhou et al. (2019) categorize nautical traffic models into six paradigms; being Cellular Automata, Generic Rule-Based Model, Specific Rule-Based Model, Artificial Potential Field Model, Optimal Control Model, and System Dynamics Model. Since the purpose of all models are specific, and they have different paradigms, the models have a varying degree of detail in describing vessel behavior. This could be due to the requirements in the modeling application or due to the incapability of the paradigm.

There are two important aspects that directly linked in navigation safety study; the vessel behavior representation and the vessel encountering behavior. The former serves as the basis of nautical traffic models. The dynamic kinematic information from AIS (Automatic Identification System) data is a chosen vessel behavior representation due to its capability in capturing vessel movement behaviors. Moreover, it is used to calibrate and validate the vessel evasive behavior (partially or entirely). The information includes position, speed over ground (SOG), course over ground (COG), and heading. Vessel encounter is chosen to be further studied in this research due to its crucial impact on navigation safety. A safety profile in a water area (for instance: risk of a collision occurring) is correlated with the number of vessel encounters that may be expected. For navigation safety, vessels encounter is a topic of interest to traffic modelers. These encounters should comply with the rules in International Regulations for Preventing Collisions at Sea (COLREGs) (International Maritime Organization, 1972) or regulations by local port authority. According to (COLREGs, 2009), there are three types of vessel encounter situation elements: head-on, crossing, and overtaking.

In this research, the capabilities of models to capture the vessel behavior during the encounters (head-on, crossing, and overtaking) and how the behavior is represented by the dynamic kinematic information (position, SOG, COG, and heading) are investigated by comparison study. By analyzing how vessel behavior is embedded in the model's algorithm for each paradigm in addition to a comparison study of each model, it is expected that the potential of each paradigm in representing vessel behavior can be revealed. This approach provides an insight into what different paradigms can/cannot simulate in the nautical traffic model. With the insight of what different paradigms have to offer, the nautical traffic modelers can be better informed in selecting which paradigms they should use for a specific application purpose. In summary, this research presents the underlying modeling paradigms and the extent to which nautical traffic models can be accurately represented to serve a modeling application purpose.

After this background, in the next section, the problem statement, research objectives, and research questions will be further highlighted. Following that, the research framework containing the phasing in the work plan and the main deliverables are elaborated. Lastly, the methodology is structured to answer the research questions.

1.1 Research Description

This section consists of the problem statement and research objective of this research. In the problem statement, elaboration of how the researcher comes to the problem is provided. In the research objective, two objectives are formulated to address the problem.

1.1.1. Problem Statement

Each nautical traffic modeling users such as the port authority, bridge team, and the research and development team need a different kind of nautical traffic simulation to help them achieve their purpose. The users' purposes include ports and waterway optimization and design, traffic management, scenario research for the future traffic state, safety analysis, or investigating the effects of current ship development, such as an autonomous vessel. Each purpose has a different modeling application requirement. Some of them need a more detail description of vessel behavior, and the other can use the simplified one. Currently, a broad range of models describing maritime traffic at different levels of vessel behavioral details has been developed. In a collective traffic flow analysis, usually, the vessel behavior is simplified. The analysis can be further improved by adding evasive behavior of a vessel to consider a safe passage of vessels during encounters (Qu and Meng, 2012; Watanabe et al., 2008). In a collision-related model, usually the individual vessel behavior is described in more detail. For instance, in the study of vessel evasive maneuvering behavior, the detailed behavior of every single vessel is simulated by describing the time-space state (Cheng et al., 2017; Miyake et al., 2015; Hasegawa et al., 2001).

As mentioned in the introduction section, vessel behaviors are analyzed with a different paradigm. From the model examples, each purpose requires a different level of vessel behavior detail. Therefore, the traffic modelers need to be aware of the different potential of modeling paradigms and of the advantages and disadvantages that each paradigm brings to represent a given practical situation. They have to realize what kind of simulation they want to develop, a feature required in the model, and which type of paradigms that suit the most for their purpose.

Currently, the study of what is the advantages and disadvantages of traffic paradigms in simulating vessel behavior is still scarce. Only the paper by Zhou et al. (2019) analyze the modeling paradigms and assess the capabilities of nautical traffic models in representing the vessel behavioral details. The results of the paper show that each model has a varying simulation approach and different level of vessel behavior description. The reason for the different description is unknown, whether it is due to the modeling requirement or incapability of the paradigm. The models in the paper are studied solely by looking into the output of the models. It does not discuss the reason behind the elements that are not presented in the paradigm or how each paradigm embeds the behaviors.

The issue in the previous paragraph brings to a need to conduct in-depth research in the nautical traffic model paradigms through its basic algorithm. This research will reveal the potential (strength and weakness) behind each of the paradigms in describing vessel behavior representation and encounters in serving modeling application purpose requirements. The gaps lead to a problem statement:

" The insight into the extent to which different nautical traffic modeling paradigms and the level to which these paradigms are able to represent the vessel behavior and the vessel encountering impacts in serving the modeling application purpose is still scarce."

1.1.2. Research Objective

Following the problem statement, the primary objective of this proposed research is to investigate how nautical traffic modeling paradigms simulate vessel behaviors representation and encounters in their approach. Objective two is meant to identify to improve the quality of the model regarding the description of vessel encounter to meet a specific modeling application purpose. This objective is proposed to answer the research gap about the capability of different modeling paradigms in serving the modeling application purpose required by users. A model can be enhanced based on the potential that its underlying paradigm has. In this objective, the level of vessel encountering detail will be enhanced. Adding the detail gives more added value compared to add another type of encounter. The type of encounters involved relies on the modeling application purpose. So, adding the details gives more reflection to what extent a paradigm can simulate an encounter. The objectives are formulated as follow:

1. Investigate how the paradigms represent vessel behavior representation and incorporate the impact of encounters.
2. Identify if the level of detail of vessel encounter in the nautical traffic model that developed in a traffic paradigm can be improved given a specific modeling application purpose and users requirements

1.2 Research Question

A primary research question is formulated to achieve the objectives listed in the previous subsection. Afterward, the sub-questions are generated to help the research to accomplish the objectives. The main research question is intended to answer the objective one about investigating how aspects of vessel dynamic kinetic information (position, speed, course, and heading) and encounter situations are incorporated in the paradigms' mathematical modeling. The first research question is formulated as follows:

" What are the specific aspects of vessel behavior representation and vessel encountering that different nautical traffic modeling paradigms possess?"

After the potential of the modeling paradigms is revealed, the research will have clear information of which paradigms suits a specific application purpose. So, the next step is to address the second objective about identifying how a nautical traffic model in a paradigm can better serve a specific modeling application purpose. The second research question is proposed as follow:

"How may the nautical traffic model in a paradigm be improved given a specific model application purpose?"

To answer the main research questions, first of all, the underlying algorithm and elaboration of how each nautical traffic modeling paradigm works should be investigated to understand the main idea of the paradigms. Next, nautical traffic models will be compared to gain an insight into how vessel behavior representation and encounter are simulated in each paradigm. Next, the paradigms will be compared to assess its suitability in describing the modeling application purpose. Lastly, a model in a paradigm will be selected, and the detail will further extend to serve a model application purpose better. In order to help the main research question, the subquestions are formulated as follows:

Subquestions:

- What are the basic algorithms of the paradigms?

- How are vessel dynamic kinetic information such as position, speed, course, and heading embedded in the paradigms?
- How are vessel encounters such as head-on, overtaking, and crossing embedded in the paradigms?
- How is the level of detail in (an) encounter(s) be improved based on the potential of the model(s) given a modeling application purpose?

1.3 Research Framework

Firstly, the definition of vessel dynamic kinetic information and encounters need to be elaborated. This general description will give a general idea and clear definition throughout this research. Also, in this phase, the elaboration of what kind of nautical traffic modeling needed by the users is given. This information becomes an input to construct the modeling requirement and criteria. This set of requirements will be the benchmark that the models in all paradigms need to attain given its application purpose.

The insight of each paradigm is investigated by comparing the underlying algorithm on nautical traffic models and other related papers. In this step, the potential of each paradigm in simulating vessel dynamic kinetic information and encounters are revealed. After this, the potential of paradigms and the set of modeling requirement based on users modeling purpose is discussed to see which paradigm suits each modeling application purpose.

Based on the literature study and discussion done in the previous steps, one model will be selected to have an improvement in its encountering simulation. This model is selected from the best paradigm to serve a specific modeling application purpose. The feature to be improved will be chosen by analyzing the model and see which encountering requirement detail is not present in the model. The research framework is structured as depicted in Figure 1-1

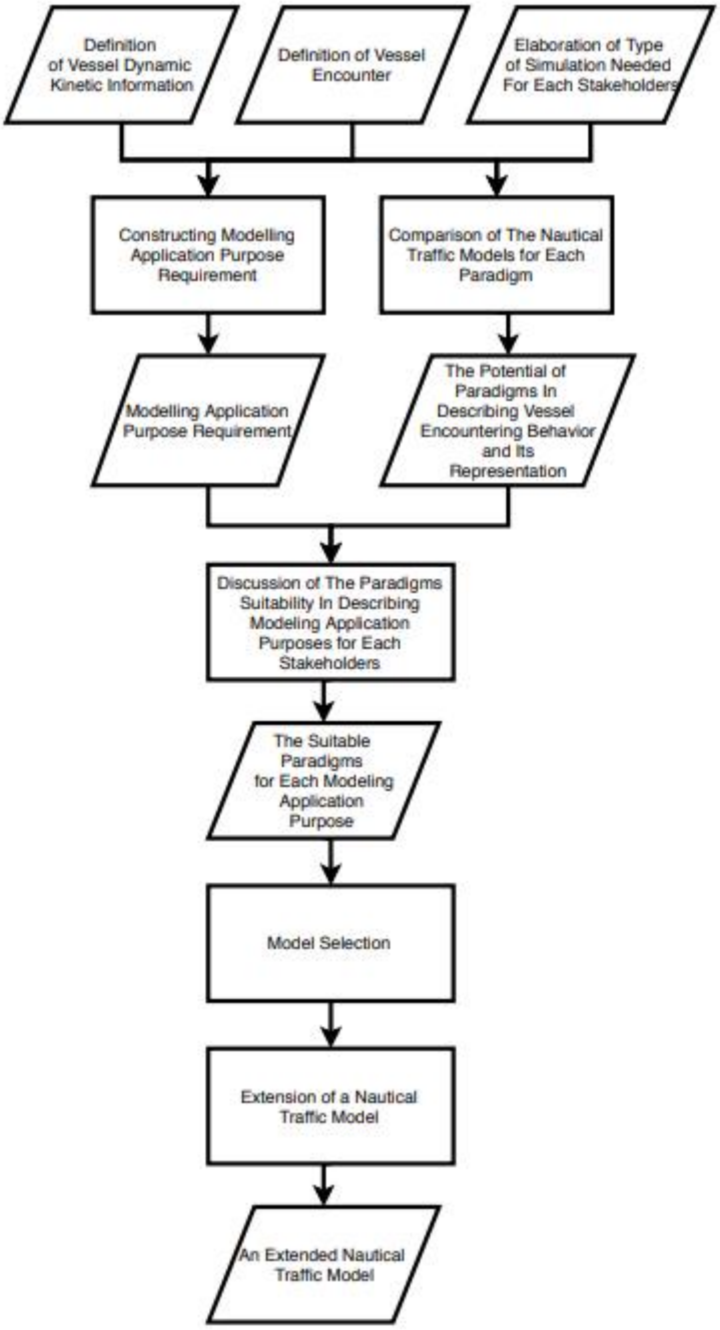

Figure 1-1. Research framework

1.4 Methodology

In this subsection, systematic methodologies are proposed to answer each sub-question mentioned in the previous section. The method to answer Sub-question 1 to 3 is by selecting the nautical traffic model, literature review, comparison study, and model assessment. The method to answer Sub-question 4 is by paradigms assessment and mathematical modeling. The research methodologies are summarized in Table 1-1.

Table 1-1. Research questions and methodologies

No	Research Question	Methodology
1	What is the basic algorithm of the paradigms?	Model Selection, Literature Review, Models Assessment and Comparisson
2	How are vessel dynamic kinetic information such as position, speed, course, and heading modeled in the paradigms?	
3	How are vessel encounters such as head-on, overtaking, and crossing modeled in the paradigm?	
4	How can the level of detail in (an) encounter (s) be improved based on the potential of the model(s) given a modeling application purpose ?	Paradigms Assessment and Comparison, Mathematical Modeling

The models in this research are obtained from the literature search through Google Scholar. The keywords that are used are "nautical traffic model," "vessel traffic model," and "nautical traffic simulation." In this research, it is assumed that the model description presented in the papers agree with their implementation. Since this research do not focus on implementing all models and comparing their performance. The model selection is based on the focus of this research; which are vessel behavior description and its underlying paradigm. The model should present the vessel behavior representation, in this case, is the dynamic kinetic information (position, speed, course, and heading) and the encounters (overtaking, head-on, crossing). The model is not expected to capture all details of vessel behavior representation and encounters. Moreover, in order to have a clearer picture of the paradigm, each paradigm should be represented by at least two models. In this step, 24 models are selected. After the model is selected, a literature review of models is conducted. A general overview of each paradigm, definition of vessel dynamic kinetic information and encounters, and the information of requirements in serving the users's modeling purpose will be searched through books, COLREGs code, scientific papers, internet articles, and other literature studies.

An assessment of models is done to see how the vessel behavior representative and encounter are embedded in those models. The models from each paradigm will be compared by studying its similarities and differences in order to gain an insight into the paradigms capabilities in simulating the nautical traffic. After the comparison of models is made, the comparison of paradigms is conducted to assess the suitability of paradigms in serving the modeling application purpose. The selection of the model will be decided based on its suitability in serving a specific modeling application purpose. Lastly, one model will be selected to be improved further. The extension includes mathematical modeling learned from the approach that the other models used in the comparison study.

1.5 Document Structure

This thesis research structure is shown in Figure 1-2. Chapter 1 is the introduction of this research. Chapter 2 contains information about the modeling criteria and application purpose requirement. Chapter 3 is the comparisons of nautical traffic models. This chapter is meant to answer subquestion one to three. In Chapter 4, the paradigms will be compared and discussed based on each application purpose requirement. Chapter 5 provides an extension of a nautical traffic model. So, Chapter 4 and 5 are dedicated to answer the last subquestion. Lastly, Chapter 6 is given to conclude and give recommendation for future works.

DOCUMENT STRUCTURE			
1	INTRODUCTION	1.1	Research Description
		1.2	Research Question
		1.3	Research Framework
		1.4	Methodology
		1.5	Document Structure
2	NAUTICAL TRAFFIC MODELING REQUIREMENTS BASED ON APPLICATION PURPOSES	2.1	Introduction
		2.2	Modeling Criteria for Vessel Behavior Representation
		2.3	Modeling Criteria for Vessel Encounters
		2.4	Modeling Application Purpose Requirement for Maritime Stakeholders
3	COMPARISON OF NAUTICAL TRAFFIC MODELS IN MODELLING PARADIGMS	3.1	Cellular Automata Models
		3.2	Generic Rule-Based Models
		3.3	Specific Rule-Based Models
		3.4	Artificial Potential Field Models
		3.5	Optimal Control Models
		3.6	System Dynamics Models
		3.7	Conclusion of The Paradigms in Serving Model Application Purpose
4	DISCUSSION OF THE PARADIGMS	4.1	Comparison of Paradigms for Port Authority
		4.2	Comparison of Paradigms for Bridge Team
		4.3	Comparison of Paradigms for Research and Development
		4.4	Conclusion of The Discussion of The Paradigms
5	EXTENSION OF A NAUTICAL TRAFFIC MODEL	5.1	Selection of a Model in Optimal Control Paradigm
		5.2	Selection of Features to be Extended
		5.3	Study of The Nautical Traffic Model by Shu et al
		5.4	Theoretical Approach at Aggregate Level
		5.5	The Overtaking Encounter Maneuver Sequence Details
		5.6	Analysis of The Existing Feature in The Model by Shu et al
		5.7	Theoretical Approach Details Elaboration
		5.8	Conclusion of Extension of a Nautical Traffic Model
6	CONCLUSION	6.1	Conclusion
		6.2	Recommendation and Future Work

Figure 1-2 Document Structure

In the next chapter, the nautical traffic modeling requirements will be set based on the nautical traffic modeling users point of view This chapter also provides a brief definition of vessel dynamic kinetic information and encounters.

2

NAUTICAL TRAFFIC MODELING REQUIREMENTS BASED ON APPLICATION PURPOSES

In this chapter, traffic modeling requirements are composed based on how a model should be developed from the users of traffic modeling point of view. The users are the port authority/consultant, the bridge team, the research and development team. The scope of modeling requirements in this research is only for the vessel dynamic kinetic information and encounters. In Subchapter 2.1, a brief overview of the type of models used by users are elaborated. In Subchapter 2.2, the terms in vessel behavior representation such as position, speed over ground (SOG), course over ground (COG), and heading are elaborated to generalize the use of those terms through this paper. This chapter also gives information about the different approach used by a model in describing the dynamic kinetic information. By that information, the vessel behavior representation modeling criteria is constructed. In Subchapter 2.3, the vessel encounters types specified by COLREGs (2009): head-on, overtaking, and crossing, are described and illustrated. The encountering sequences and the terms related to the vessel encounters are elaborated in detail. This information becomes an input for constructing the vessel encounter modeling criteria. Lastly, Subchapter 2.4 provides a modeling application purpose requirement for each modeling users.

2.1 Introduction

Traffic simulation models are used to determine the effectiveness of infrastructural, design, mobility, and traffic management measures. The traffic simulation models are usually developed with a specific approach and for a particular application purpose. There is a vast domain in which a wide range of modeling types exist. Since the models are developed with a specific purpose, their performance is only optimal for that purposes. The nautical traffic models are used by several users; there are the port authority, bridge team, and researcher. Each user has a different requirement to achieve its simulation purposes.

The port authority with the help from consultant needs to analyze the traffic flows and vessels collision for various purposes; there are capacity assessment, traffic forecasting, performance assessment, traffic management and regulation, safety assessment and, etc. In the traffic analysis, the capacity of the waterway is often traded with safety. Therefore, a balance between both aspects should be achieved

(Bellsolà Olba et al., 2018; Xu et al., 2015; Piccoli, 2014). In a simple traffic flow analysis, the vessels encountering is not considered at all, and sometimes the vessel behavior is simplified. When the authority needs more thorough analysis, the vessel behavior is given in more detail. Moreover, the collision risk and avoidance are involved (Hasegawa et al., 2000, 2001; Hasegawa, 1990). The acceptable traffic flow is now limited by the safety of vessels. Another type of safety assessment modeling by the port authority is the maneuvering safety of a specific kind of vessel / only several vessels involved in a waterway by simulating a more detailed behavior of those vessels (Shu et al., 2015b, 2015a, 2018; Xiao, 2014). In the maneuvering safety analysis, the vessel evasive behavior and its behavior representation need to be given in more detail.

The bridge team utilizes the traffic simulator mainly for collision avoidance purpose. The type of simulation used is ship handling simulator. The simulator requires to be stable and connected with the real-time databases. Furthermore, the models should adapt to change in traffic in time, and therefore, only dynamic models will be found in use by the bridge team. This type of simulation should be able to detect the collision risk and avoid the collision itself by providing a safe trajectory of a vessel. Moreover, the models should pose the ability to include the hydrodynamical factors in a vessel maneuver (Fang et al., 2018; Beschnidt and Gilles, 2005; Sariöz and Narli, 2003). For this purpose, a high-level description of vessel behaviors and encounters descriptions are required.

For the researcher and model developer (R&D) point of view, the nautical traffic models should be able to give more accurate details and capabilities. This R&D department is meant to develop a model for safety assessment and traffic flow analysis by the port authority. The model should be easy to be extended and have the potential to embed more functionality in order to support the extension. Since every area and modeling application purpose is unique, it is assumed that the model should be able to simulate a necessary but also a high level of modeling.

2.2 Modeling Criteria for Vessel Behavior Representation

From the viewpoint of other vessels or the traffic manager, the most basic information of vessel behavior can be observed by position, speed over ground (SOG), course over ground (COG), and heading. This dynamic kinetic information is also mandatorily transmitted by the Automatic Identification System (AIS), according to the requirement of the International Maritime Organization. These unique identifications are put in in the nautical traffic models for various purposes, such as trajectory prediction, vessels behavior during a collision, validation of traffic models, etc. These aspects can be used partially or entirely in the nautical traffic models; it depends on the purpose and requirements of the models. In some models COG is often deemed as heading and speed used in the models can vary and be different from SOG. Therefore, an elaboration of these aspects needs to be defined in this chapter.

The position of vessels is given in maximum a two-dimensional space, which describes the longitudinal and lateral position in the water area. SOG is the distance traveled in one hour relative to the ground, and it considers external factors such as wind, tide, and current. For instance, when a vessel travels through the water 5 knots, if there are tides present that are directly against the boat, the vessel will have a speed of only 3 knots over the ground. The course of a vessel is the direction in which the craft is to be steered. It is the actual direction of progress of a vessel, between two points, concerning the surface of the earth. The course should be distinguished from the heading, which is the compass direction in which the craft's bow or nose is pointed. So, the vessel's heading may differ from the course over the ground due to environmental factors. Both COG and heading are referenced to true north. The illustration of the vessel's course and heading is given in Figure 2-1.

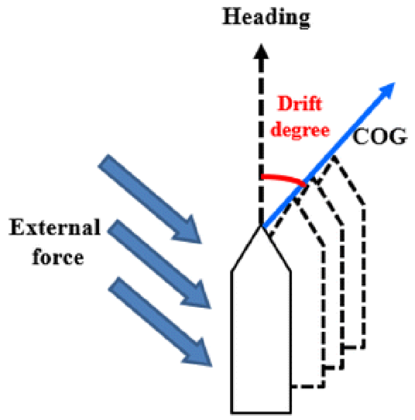

Figure 2-1 Vessel's COG and Heading

(Source: https://link.springer.com/article/10.1007/s13437-016-0115-7)

In constructing the dynamic kinetic information criteria, the research analyses the models briefly and set up the possible criteria. It is found that the nautical traffic models describe the dynamic kinetic information in various ways, and it depends on their application purpose. The position can be described in one or two-dimensional space state. For the speed aspects, some models assign a fixed speed value through the journey, some apply a speed change without acceleration, and the others assign the speed change with acceleration and deceleration feature (flexible). In most of the traffic flow analysis model, the vessel course is fixed to follow the designed route. However, in most of the safety assessment model, the model gives more flexibility for the course change. Lastly, the heading can be deemed as or separated from the course. The modeling criteria of the vessel dynamic kinetic information is given in Table 2-1.

Table 2-1 Vessel dynamic kinetic information model criteria

Dynamic Kinetic Information	Criteria	Mark
Position	1D	*
	2D	!
Speed over ground	Fixed speed through the voyage	*
	Several fixed speed choices	!
	Able to accelerate/decelerate	#
Course over ground	Fixed course to follow the designed routes	*
	Able to deviate flexibly along the route	!
Heading	Heading is deemed as course	*
	Heading is distinguished from course	!

2.3 Modeling Criteria for Vessel Encounters

In Section 2.3.1, the type of encounters and the detail of the encountering maneuvering sequence are elaborated. Section 2.3.2 explains a modeling criterion for the vessel encounters.

2.3.1. Type of Encounters

According to COLREGs, there are three types of vessel encounters: head-on, overtaking, and crossing. When ship interactions happen, one (or both) vessel should perform maneuvering. In a straight one-way channel, the only allowed encounter is overtaking, while in the two-way waterways, head-on can also be possible. If there is an intersection, then crossing interactions may occur. Generally, the models will determine a certain distance between vessels to detect the existence of other ship(s). The models also specify the time when the vessel should (or should not) be taking any evasive action; the vessel tries to avoid collision with one another based on regulations and standard practices. The avoidance behavior is reflected by changing speed or altering the course.

The overtaking situation happens when there is a vessel approaches another vessel with a higher speed from a direction more than 22.5 degrees abaft her beam (COLREGs, 2009). The overtaking vessel with higher speed is a give-way vessel, and the other one is an overtaken or stand-on vessel. In COLREGs, (2009), it is said that the give-way vessel should alter its course to its starboard and accelerate, and the stand on the vessel should maintain her speed and course. However, in a real sailing situation, usually, the stand-on vessel will decelerate to speed up the encountering process. Also, the give-way vessel can overtake either to starboard or to port. However, in a narrow waterway, alteration to the port side is preferred. This alternative direction of course alteration can be chosen if overtaking to the port is potentially dangerous.

Next, there is head-on interaction; this happens if two vessels are meeting on reciprocal or nearly reciprocal courses for each of the vessels. In this situation, both vessels are a give-way vessel, and they should alter their course to their starboard or, in other words, the vessels shall pass on the port side of the other (COLREGs, 2009). According to Goerlandt and Kujala (2011), the reciprocal angle is about 10 degrees. In a typical situation, the vessel will alter her course to starboard (port-to-port situation), however in some cases, if the port-to-port situation is not possible, the vessels will alter their course to port or starboard-to-starboard (which can be dangerous).

Lastly, in the crossing situation, a vessel meets another vessel that comes in the perpendicular direction ahead of it. The vessel which meets another vessel on its starboard side is deemed as a give-way vessel, and it must alter course, slow down, or stop. The stand-on vessel should maintain its speed and course. The behavior of vessels during an encounter and their incoming direction are given in Figure 2-2 and 2-3.

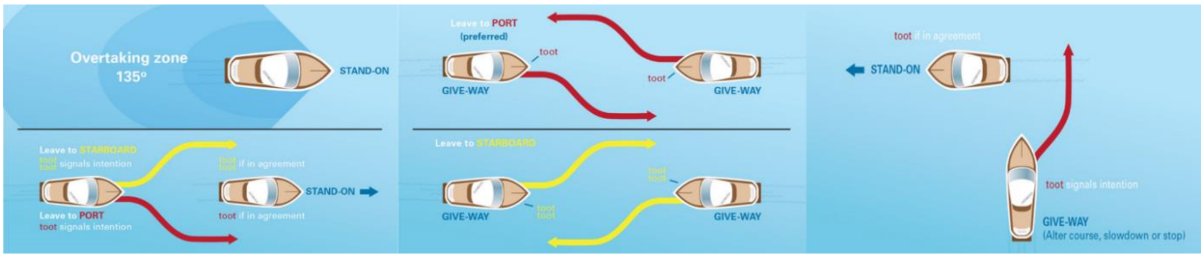

Figure 2-2 Vessels encounters (left to right: overtaking, head-on, crossing)

(SOURCE: http://watercraft.ohiodnr.gov/laws/ohio-boat-operators-guide/ch-5-navigation-rules)

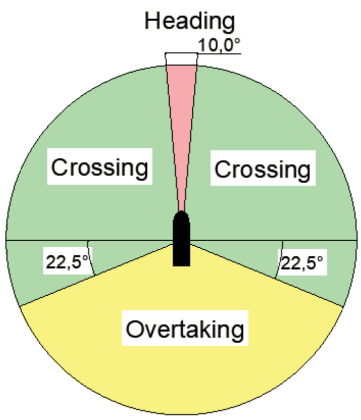

Figure 2-3 Encountering types according to COLREGs (based on Goerlandt et al., 2011)

2.3.2. Encountering Sequences

The encounter-maneuver can be split into the following stages. In this research, the steps of vessels encounter modeling algorithms are divided into before, during, and after the encounter. Before performing conflict resolution, the model needs to define how it detects the possible encounter, checks the possibility to maneuver and decides the time to maneuver. During the maneuver, the action can be taken by a vessel only or by both vessels based on the determination of the status of both ships in the model. In a restricted waterway, it is essential for a ship to go back to the initial course and speed after the maneuver. (Colley et al., 1984).

There are several methods to detect an encounter and measure the collision risk. The simplest one is by assigning a safety distance. A complete check of lateral and longitudinal distances can be done as well as the simplified longitudinal safety distance check only. Another method is by using the criterion of Closest Point of Approach (CPA). CPA refers to "the positions at which two dynamically moving objects reach their closest possible distance." There are two critical parameters of CPA, named Time to Closest Point of Approach (TCPA) and Distance to Closest Point of Approach (DCPA). TCPA is often used to estimate the degree of collision risk, and DCPA is used to investigate whether a collision will occur between vessels. The calculation of CPA assumes that vessels are simplified to a geometrical point. The last standard method is by applying the concept of ship domains. Ship domain is an area that can be used to evaluate and visualize the collision risk with target ships in the current scenario (Wang et al., 2019). The ship domain is determined based on considerations such as vessel geometry, maneuvering ability, speed, etc. So, the formulation of ship domains can vary among models. Besides for detecting an encounter, safety distance, CPA, and ship domain are also used to quantify the ship-ship interaction. So, the maneuvering action such as how much the vessel should deviate or how fast the vessel should accelerate to avoid a collision situation is determined by these methods. An example of a ship domain by Jingsong et al. (1993) are given in Figure 2-4, and an illustration and mathematical equations for CPA is given in Figure 2-5 and Equation 2-1.

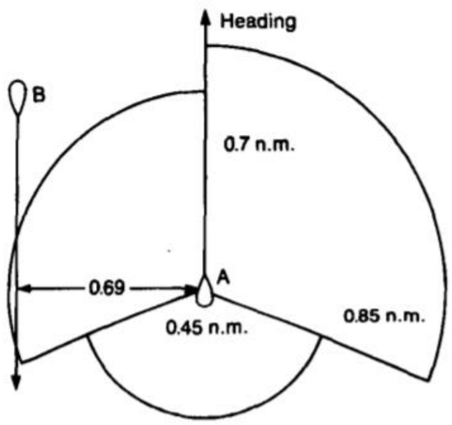

Figure 2-4 An example of a ship domain

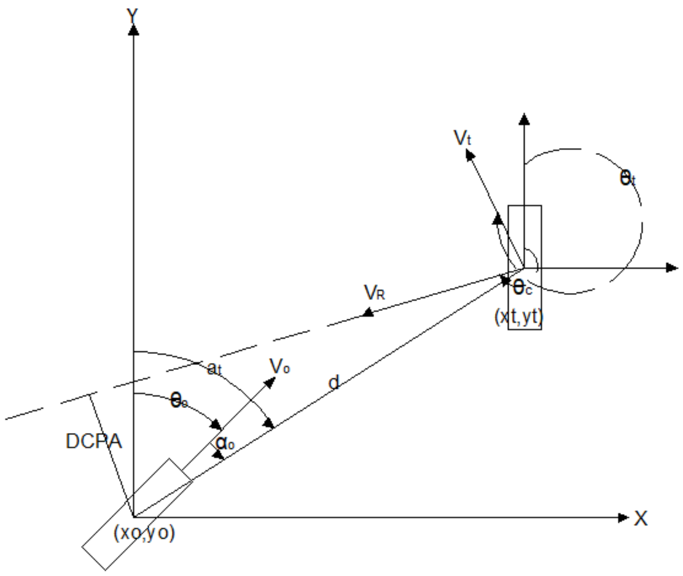

Figure 2-5 Illustration of CPA method

$$d = \sqrt{(x_t - x_o)^2 + (y_t - y_o)^2} \tag{2-1}$$

$$v_R = v_o \sqrt{1 + \left(\frac{v_t}{v_o}\right)^2 - 2\frac{v_t}{v_o} cos(\theta_o - \theta_t)^2}$$

$$\theta_c = \cos^{-1}\left(\frac{v_o - v_t \cos(\theta_o - \theta_t)}{v_R}\right)$$

$$DCPA = d \sin(\theta_c - a_t - \pi)$$

$$TCPA = \frac{d \cos(\theta_c - a_t - \pi)}{v_R}$$

In Equation 2-1, (x_o, y_o) and (x_t, y_t) are the coordinate of own and target vessel respectively. d is the distance between vessels, v_o, v_t and v_R are the speed of own vessel, target vessel, and relative speed respectively. θ_o, θ_t, and θ_c are the course of own vessel, target vessel, and relative speed respectively. a_t denotes the azimuth of the target ship.

After the risk is detected, the two vessels will check what kind of encounter situation they are in. This is done by checking the location of the target vessel relative to the own vessel, as shown in Figure 2-3. When the encounter is detected the forward traffic need to be checked whether there is a risk of collision or not. In the overtaking situation, there will be a risk of collision if the own vessel speed is higher than its succeeding vessel. The collision due to head-on will occur if the lateral distance between two vessels approaches each other from the opposite sailing direction is too small. Lastly, collision due to crossing will happen if there is a vessel sailing towards the port or starboard side of another vessel, and there is a probability of collision in a short time.

If the model detects the possibility of an encounter, and there is a risk of collision in the future time, the model should assign the vessels to avoid the collision by maneuvering. The first step before conducting a maneuver is to check the possibility to perform it. The own vessel needs to make sure that the distance gap is sufficient for maneuvering (lateral and longitudinal / longitudinal only). The model also checks the forward and backward traffic to make sure if there is no vessel in another lane or the own vessel is not being overtaken in the overtaking process. In the most advanced checking, the vessel can predict the safest trajectory to maneuver. A safe trajectory is generated in the multi-vessels encounter where a vessel has to avoid several vessels by creating a safe path to sail. If maneuvering is possible, then the vessel will immediately take action to maneuver, or the model will specify an optimal time to make a maneuver. Otherwise, the vessel will decelerate.

The maneuvering action is done by either change their course only, speed only, or both. The action is taken either by one vessel only or both vessels; it depends on the modeler judgment. Also, the maneuvering side is decided by the traffic rule, the status of the vessels, and bridge team judgment depends on the traffic situation at the moment. As mentioned in the previous section, in the overtaking and crossing, only the overtaking and the give-way vessel will change their sailing behavior. In the head-on encounter, both vessels have to deviate preferably to their starboard side. The simulation can apply this COLREG rule or simulate a more realistic maneuvering situation by allowing both vessels to decide which maneuvering side is the safest based on the traffic condition at that time to resemble the bridge team behavior. After the encounter, the vessel(s) needs to go back to its initial course and speed. Returning to the initial course can be done as soon as there is no detected collision risk or the optimal time to maneuver is specified.

2.3.3. Modeling Criteria

The encounters will be compared based on the maneuvering sequences on a real sailing behavior as described in previous paragraphs about the encountering sequences. The way of nautical traffic models describing the encountering sequences reflects the model's potential to serve other modeling application purposes. The list of elements to be compared are: detection of the possibility of an encounter, checking the possibility of maneuver, time to start a maneuver, speed and course change during the encounter, traffic rule scheme applied, and vessel ability to go back to its initial speed and course. The details of modeling requirements are given in Table 2-2

Table 2-2 Vessel encountering model criteria

Criteria				Mark
Before/After	Detection of The Encounter		Safety distance	*
			Ship domain	!
			CPA	#
	Possibility To Manoeuvre		Gap sufficiency (lateral and longitudinal)	*
			Gap sufficiency, vessel maneuverability and forward/backward traffic check	!
			Safe trajectory prediction	#
	Time To Start a Manoeuvre		Immediately after detection/no risk of collision	*
			Determined by a specific parameter	!
During	Overtaking	Speed	Instant speed change	*
			Acceleration/Deceleration	!
		Course	Vessel(s) manoeuvre to one specific side	*
			Flexibility of choosing maneuvering courses	!
		Traffic Rule	Specified with rules for overtaking vessel	*
			Specified with rules for both vessels	!
	Head-on	Speed	Instant speed change	*
			Acceleration/Deceleration	!
		Course	Vessel(s) manoeuvre to one specific side	*
			Flexibility of choosing maneuvering courses	!
		Traffic Rule	Specified with same rules for both vessels	*
			Both vessels cooperate to take actions	!
	Crossing	Speed	Instant speed change	*
			Acceleration/Deceleration	!
		Course	Vessel(s) manoeuvre to one specific side	*
			Flexibility of choosing maneuvering courses	!
		Traffic Rule	Specified with rules for only give-way vessel	*
			Specified with rules for both vessels	!
After	Action		Adjust the initial course and speed to initial or a new traffic condition	*

2.4 Modeling Application Purpose Requirement

After the modeling criteria of vessel dynamic kinetic information and encounters are set. Model application purpose is set using the rating criteria and the requirement for each users (port authority, bridge team, researcher, and developer).

2.4.1. Port Authority

- **Traffic Flow Analysis**

As mentioned in the previous subchapter, the port authority utilizes the traffic flow analysis for various kind of purposes such as capacity assessment, traffic forecasting, performance assessment, and traffic management and regulation. For that purposes, the results output of the traffic can be the traffic speed, a number of vehicles, traffic density, traffic flow, waiting time, and, etc. Looking at the output, defining the vessel in one-dimension (longitudinal position) is sufficient to be set as the lowest requirement. Including the position in the lateral direction is a higher level of simulation since the effectivity of including such a feature will depend on various factors such as the complexity of the waterway layout (the impact of bottlenecks and junctions).

Usually, the nautical traffic rules regulate the speed limit for all kind of ships. The impact of the speed change to the simulation output result depends on various factors such as the regulation in a specific section of a waterway or encountering. The difference in output result is also linked to how often the speed change will occur and the stretch of the waterway. Therefore, the vessel speed will be set to be fixed as the minimum requirement for traffic flow analysis purpose. The same argument also holds for the course; the impact of the course change depends on how often the vessel turns during the voyage. In a simple assumption, the vessel needs to follow a predetermined route, and a small course change does not make a significant impact on the results. Heading can be deemed as a course because separating those two aspects would be insignificant when analyzing the traffic flow. The configuration of the ships would not make a significant difference for the output when accounting the traffic flow.

The vessels interaction can be discarded in the traffic flow analysis for the port authority. As mentioned before, when the focus of modeling is to get an analysis of the traffic flow, sometimes the safety of waterway is neglected. The vessels can be assumed to overlap with each other. The impact of lane and speed change to the traffic flow can be varied among models. It depends on the number of encountering events, the stretch of the waterway, and the traffic flow of the studied area. Therefore, the impact of the interactions on the output analysis highly depends on a waterway itself.

- **Safety Assessment – Collision Probability and Risk**

The port authority has two several kinds of safety analysis; there are collision probability and risk and collision avoidance. In general, the model that specifically aimed to assess the safety of a waterway needs more details in both aspects (vessel dynamic kinetic information and encounters) than the other type of modeling purposes. However, the requirements are set to be varied for each safety analysis. The main idea of this kind of simulation is to find the probability of overlapping event between two vessels and to quantify the degree of risk involved. Therefore, the details of the maneuver are unnecessary. The encountering process does not need to be simulated since the output is only the collision probability or risk.

The maneuverability limit and environmental condition are factors that can increase the collision accident. In a real-sailing behavior, a ship constantly changes its dynamics to cope with the environmental and encountering impact and ensure safe navigation. However, in a simple assumption, the maneuverability and environmental factors can be neglected if the analysis of comparison results between the accident statistics and close encounters is reasonable (Goerlandt and Kujala, 2011). By this assumption, the minimum requirement of collision probability and risk is constructed. The position should be defined in two dimensions because the movement of the vessel needs to be flexible. Since the vessel often sails with a fixed speed and course, it is assumed to sail in fixed and full speed, and the course is set to be fixed to follow the designed routes. Lastly, the heading can be defined as the same as the course. The difference between the course and heading depends on the environmental condition in the area. Therefore, if the difference between the heading and course is small, the results output will not give a huge difference.

In this safety assessment, the detection of a probability of an encounter and the risk of collision should be defined. The detection of an encounter can be defined with safety distance. The degree of risk will depend on the distance between the encountered vessels. The closer the vessel to another object, the higher a chance for collision. Quantifying the degree of risk can be defined by giving a layer of risk in a safe distance.

- **Safety Assessment – Collision Avoidance Analysis**

The purpose of this kind of simulation is to assess the maneuvering safety of the vessel. Therefore, the detail process of the evasive maneuver needs to be presented in the output of this simulation. The maneuverability is defined as a performance ability of ships related to shipping motion due to steering. Maneuverability is essential to be included for the operation of the ship in averting the danger of collisions and stranding, which is directly related to the safety of the ship. It is composed of turning, course change, course keeping, speed change, stopping ability, and, etc. A varied kind of vessels will dock at the port, and each of its maneuverability is unique. Therefore, it is important to consider the vessels heterogeneity in the encounter.

Based on the explanation above, the necessary input is that the position needs to be defined in two dimensions, the speed change has to be included with acceleration feature, and the course has to change flexibly through the voyage. Differently, the deviation between heading and course highly depends on the environmental factors and the course keeping ability of the ship. If the deviation is relatively small, it can be neglected, and the heading can be deemed as course.

The detection of an encounter and collision can be done by two methods; there are ship domain and CPA. Both methods can quantify the risk involved and decide the evasive maneuvering action. Both methods are different, and they are chosen based on the modeler judgment. Usually, for the confined or restricted waterway, the ship domain is used, and the CPA is more common in the open water. Therefore, both methods can be flexibly chosen by the modeler. After an encounter is detected, the vessel should seek the possibility to maneuver. In the simulation, the vessel will check the backward and forward traffic if there is another vessel that will hinder the maneuvering process. The own vessel needs to check if there is a risk of colliding with another vessel and check if the vessel is in the process of being overtaken. Ship maneuverability is paramount to be considered in the collision avoidance model. Every kind of ship have inherent maneuverability limitations, so the vessel should check the feasibility of a ship to maneuver with the available gap. After the vessel is allowed to maneuver, in a real sailing behavior, it needs time to take a maneuver, and it highly depends on the navigator's behavior/experience. The time to maneuver will be either assumed with a rule of thumb, observation or simply assumes that a vessel will evade immediately after the detection. Since the time is varied and it cannot be generalized for all vessel, the easiest way is to define the time directly after the collision is detected.

During the encountering process, the avoidance behavior will be different for the two vessels. Since the maneuvering actions are different, the traffic rules need to be assigned for both vessels. In the real evasive process, the vessel(s) will constantly change course and accelerate. The behavior of the target vessel relies on the assumption of the developer. After the encountering process is done, the vessel will go back to its initial course, and the new position is parallel to the initial one. For the speed after the encounter, it can either go back to the vessel's initial speed or follow the traffic speed in the vessel's new position. In modeling purpose, the detail of the evading process is the most crucial process to assess maneuvering safety. Therefore, after the encounter, the speed is assumed to be equal to its initial.

2.4.2. Bridge Team – Safety Analysis - Collision Avoidance

The bridge team needs to analyze the maneuvering safety of a single vessel with a ship handling simulator. A ship handling simulator is a computer-aided machine system which enables performing in-house ship navigation with simulated hydrodynamic ship movements, simulated visual environment, and real ship bridge man-machine interfaces. The ship handling simulator presents a very realistic bridge system which can mimic real navigation experience at sea (or on the waterway). When the vessel encounters other vessels, the bridge team needs to predict a safe trajectory to go through the traffic. Since the model can simulate complex hydrodynamic interactions, it is a challenge when the model has to simulate the ship-ship interaction that includes a large number of vessels. The vessel interaction simulation is only possible if it involves several vessels only.

Based on the description above, in the collision avoidance and risk simulator for the bridge team, all the vessel dynamic behavior and encounters should be set to the highest level of details. The speed and course should be allowed to be flexibly changed through sailing. The heading needs to be distinguished from course. An encounter can be detected with two methods, either ship domain or CPA. Since the bridge team sails in both open and restricted water area, it is best if the model can be versatile in applying both methods. Although it is more common for the industry to use the CPA method. The bridge team needs to predict a safe trajectory in every situation. All encounters need to be defined with flexibility in speed and course. Also, the traffic rules need to be specified for both vessels.

2.4.3. Research and Development

- **General Model - Traffic Flow Analysis**

For further research and development of the traffic flow, the model should be easy to be extended but also possess more functionality in describing vessel behavior representation and encounters. For instance, in the case of a port extension or adapt new traffic management in a new area, the model should be easy to be extended. The R&D department tries to compose a model to analyze the traffic flow output in an area that needs more in-depth and detailed output result analysis. For example, in a complex water area such as in a junction, in a continually changing waterway, and in a bottleneck. Another possible case is when a ship sails in a restricted waterway with a substantial environmental impact or in a complex waterway geometry. A ship might wander significantly through the voyage due to this dynamic environmental factor. A more functionality such as adding the flexibility to change speed is needed in a water area where the speed and lane change often occur, for instance, in a waterway where encounters are common. Those factors can make a huge difference to the traffic flow analysis output (waiting time, speed, density, flow). Therefore, the minimum modeling requirements are set to be higher than the traffic flow models used by the port authority.

To serve the purpose, the model needs to possess several modeling requirements: the vessel position is defined in two-dimensions. For the speed change feature, several fixed speeds need to be defined. In the traffic flow analysis, the output does not depend on the configuration of the vessels. Also, in a real sailing situation, the ships often sail back and forth in the same sailing route; therefore, the course can be set to follow a predetermined route, and heading can be deemed as course for a general traffic flow analysis model for research and development application purpose.

As mentioned in the first paragraph, a frequent speed and course change may impact the output results. Therefore, the encounter needs to be added in the model. However, a detailed movement and traffic rules of the vessels are unnecessary for the output. The detection of an encounter and the possibility to maneuver is added by checking the distance in the lateral and longitudinal direction. The flexibility to choose maneuvering side is irrelevant in this application purpose. Only the own vessel will take action to maneuver immediately after the detection in overtaking and crossing encounter. In the head-on encounter, both vessels will take the same maneuvering manner to one specific side.

- **General Model – Safety Assessment**

Since this research focus is on the vessel encounter, for general safety assessment purpose, a model should be able to be extended and describe more functionality to support the extension in describing vessel encounters. The model should have the potential to integrate the aspects that impacting evasive vessel maneuvering. For instance, embedding human behavior or integrating environment and hydrodynamical impact.

In order to achieve the purpose, a model should have the potential to accommodate future development. Therefore, the model should have the potential to describe the highest details of the vessel behavior representation and encounters defined in this research modeling requirement. In defining the dynamic kinetic information, besides allow the flexibility of the position, speed, and course change, heading needs to be separated from the course. This separation is needed in order to reflect the vessel behavior changes during an encounter. For instance, if the model needs to assess the safety in an extreme bend or in a water area with a significant environmental impact. A high detail also needs to be defined in the maneuvering sequence. In detecting an encounter, the ship domain or CPA concept can be applied depending on the modeler judgment and the traffic condition. In a real-sailing situation a model should be able to predict a safe trajectory when encounters other vessel(s) and provide some time for the bridge team to negotiate and assess the encounter situation before taking a maneuvering decision. During the encounter, both vessels should be given the highest flexibility to maneuver to any side. The traffic rules are now applied for both vessels since they need to cooperate to decide the best actions need to be taken in order to avoid a collision. After the maneuvering, both vessels should go back to its initial speed and course. The summary of the modeling requirements is given in Table 2-3.

2.5 Conclusion of Nautical Traffic Modelling Requirements

Since the application purpose is different for each user, a requirement of vessel behavior representation for each purpose must be constructed. It is found that there are several users with their specific purposes, named: port authority (traffic flow analysis, collision probability and risk analysis, collision avoidance analysis), bridge team (safety assessment analysis), and research and development (traffic flow and safety assessment analysis). The requirements of model are set up based on the criteria of vessel behavior representation and encounters. To construct this requirement, the study of what kind of output analysis used by each purpose and what input criteria needed to achieve the purpose are researched. The criteria are constructed based on the explanation and literature study of how both aspects are simulated in the models. The literatures are obtained from the existing nautical traffic models and other relevant papers. The study includes an explanation of what is the vessel behavior representation (in this case: dynamic kinetic information), type of encounters, and sequences of encounters and a brief study of how the model usually simulate the vessel behavior representation and encounters.

Based on the criteria and the output that the users need, the requirements are constructed. The requirement becomes a minimum benchmark that the model needs to attain to serve each modeling purpose. Together with Chapter 3, this chapter becomes an input to the discussion of the paradigms in Chapter 4 to see which paradigms suits the modeling application purpose the best.

Table 2-3 Modeling application purpose requirement

Application Purposes		Vessel Dynamic Behavior				Vessels Encounters													
						Before / After			During										After
									Overtaking			Head-on			Crossing				
		Position	Speed	Course	Heading	Detection of The Encounter	Possibility to Maneuver	Time to Start Manuever	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic
Port Authority	Traffic Flow Analysis (capacity assessment, forecasting, performance assessment, traffic management)	*	*	*	*													
	Safety Assessment - Collision Probability and Risk	!	*	*	*	*												
	Safety Assessment - Collision Analysis	!	#	!	*	!/#	!	*	!	!	!	!	!	!	!	!	!	*
Bridge Team	Safety Analysis - Collision Avoidance (Real-Time)	!	#	!	!	!/#	#	!	!	!	!	!	!	!	!	!	!	*
Research and Development	General Model Development for Traffic Flow Analysis	!	!	*	*	*	*	*	*	*	*	*	*	*	*	*	*	
	General Model Development for Safety Assessment	!	#	!	!	!/#	!	!	!	!	!	!	!	!	!	!	!	*

3

COMPARISON OF NAUTICAL TRAFFIC MODELS IN MODELLING PARADIGMS

This chapter compares several nautical traffic models based on its paradigm to get an insight into how vessel behavior is represented, and encounters are embedded in the models. According to Zhou et al., (2019), there are two general types of modeling paradigm; there are rule-based type (Cellular Automata, Generic Rule-Based, Specific Rule-Based), and the mathematical-based type (Artificial Potential Field, Optimal Control, System Dynamics). For each paradigm from Subchapter 3.1 to 3.6 the comparison between models is conducted to see the similarities between models and reveal the modeling potential in describing vessel behavior representation and encounters. For each subchapter, the following steps are conducted: First, the general definition and brief introduction of each paradigm is elaborated. Next, the comparison of vessel behavior representation (position, speed over ground, course over ground, and heading) among the models is given. After that, the comparison of how vessel evasive behavior is varied among models for each encounter (overtaking, head-on, crossing) are given. Lastly, Subchapter 3.7 provides a conclusion of the comparison of models.

3.1. Cellular Automata Models

Cellular automata (CA) are discrete dynamical systems that can simulate complex behaviors by animating cells on the lattice of cells. A waterway is defined as an array of uniform cells, and the vessel can occupy either one cell or several cells. The vessel evolves in discrete space and time by following a simple rule for updating its state. The value $x_i$of the site (state) at each position, i is updated in discrete time steps according to deterministic rules and depending on a neighborhood of states around it.

In CA, a vessel is described in only one state. The vessels might have moved around with advanced behaviors and physics; however, they remained the same type of object throughout their digital lifetime. The behavior of a cell is influenced by the neighborhoods cells around it. Different types of neighborhoods can be defined. In a von Neumann neighborhood, cells to the north, south, east and west of the center cell are defined as neighbors. A Moore neighborhood includes diagonal cells to the northeast, northwest, southeast, and southwest. By this information, it can be concluded that vessel position can be described in maximum two dimensions. The motions of the ship, such as sway, surge, and yaw, cannot be modeled.

3.1.1. Vessel Behavior Representation in Cellular Automata

This section explains the movement of the vessel in CA paradigm and how the dynamic kinetic information is changing through the lattice of cells.

- **Position**

As mentioned before, a vessel can be described in one or more cells with a constant length of cells. Due to the space discretization, the representation of vessel behavior is lack of accuracy. For instance, when the width of the vessel is 16 m, and a cell length is 7.5 m, then the model will approximate the width by defining it into two cells. With this discretization, a detailed length and width of a vessel cannot be presented. In the CA model for traffic flow analysis, the position of a vessel is often described in one-dimensional although some models are identified defining the position in two-dimensions due to several reasons. According to Qu and Meng (2012), ship behavior is distinct; it may wander significantly due to the wind, tide, and current. Therefore, their model considers two-dimensional position instead of one. Another modeling reason to enhance the position into two-dimensions is the complex situation of a waterway such as in intersection, unstable (constantly changing width) natural waterway (strait or river), or the modeling purpose such as collision avoidance and risk. (Qi et al., 2017a; Blokus-Roszkowska and Smolarek, 2014). The position change is formulated in Equation 3-1 as follow:

$$\boldsymbol{x(t_{i+1}) = x(t_i) + v_x(t_i)\Delta t} \qquad (3\text{-}1)$$

$$\boldsymbol{y(t_{i+1}) = y(t_i) + v_y(t_i)\Delta t}$$

Where $x(t_i)$ and $y(t_i)$ are the positions of *i* th vessel at time t, t ≥ 0, $v_x(t_i)$ and $v_y(t_i)$ are the velocities of *i* th vessel and Δt is a time step.

In summary, CA paradigm consists of a regular grid of cells, and each cell can be in any finite number of dimensions. In CA models the vessels and waterway are often defined in squared discretize cells. The vessel and waterway can be discretized in two dimensions. However, due to the discontinuity in space, the exact positions and dimensions of a vessel are approximated. Also, the waterway and vessel dimensions cannot be defined accurately unless the cell is defined in a smaller size.

- **Speed Over Ground**

In the CA paradigm, the velocity change is usually taken from a normal distribution and a random sampling method. This method is used to represent the speed change behavior of a vessel. The speed is often described as cells/Δt. The speed is discretized and only attain discrete value as shown in the Equation 3-2, with this equation for $v(t_i) = 1$, a vessel moves one cell ahead in a one-time step.

$$\boldsymbol{v_{actual} = v(t_i)\frac{\triangle x}{\triangle t}\ with\ v = 0, 1, \ldots v_{max}} \qquad (3\text{-}2)$$

The model by Qu and Meng (2012) and Qi et al. (2017b, 2017a) use a velocity distribution based on the vessel type. The model takes an optimum speed value from the distribution. Differently, in a model by Blokus-Roszkowska and Smolarek (2014), instead of taking the speed value from the distribution, the model calculates an exact value of speed by the mathematical equation, as shown in Equation 3-3.

As mentioned in the paragraph above, Qu and Meng, (2012) stated that the ship might wander due to the environmental factors; therefore they specify this velocity change in parallel (v_x) and perpendicular (v_y) to the course direction. The model has detail rules of the velocity change in two directions. The rules depend on the vessel type, water area characteristic, type of encounter, and visibility. To a certain degree, Qi et al. (2017b) specified the velocity in more detailed. Besides of divided the velocity in two directions, the velocity impact due to weather is also divided into two types: randomization probability of velocity fluctuation and the regular change of velocity due to the weather and sea. Using the randomization probability, the natural velocity fluctuations caused by human behavior or due to varying external conditions were taken into account. In this model, the vessel continuously adjusts its speed through the voyage.

The speed change is described to a different degree. In the model by Qu and Meng, (2012) the acceleration/deceleration is defined in an exact fixed value. In the model by Blokus-Roszkowska and Smolarek (2014), during encountering, a vessel can either change speed with a predetermined acceleration (2 m/s) or calculated based on Equation 3-3. $D_{i,E}$ denotes a distance on scheduled course line during a collision, $t_{i,E}$ is a time to perform a collision avoidance maneuver in minutes and CS denotes a cell size in m.

$$\boldsymbol{v_{i,E}} = \frac{\boldsymbol{D_{i,E}\ .\ \triangle t}}{\boldsymbol{t_{i,E} \cdot CS \cdot 60}} \tag{3-3}$$

In the model by Qi et al. (2017b, 2017a) the acceleration and deceleration during encountering are taken from the possible optimum velocity distribution as shown in Equation 3-4 and 3-5 respectively as follow:

$$\boldsymbol{v(t_{i+1}) = min(v(t_i) + 1, v_{max})} \tag{3-4}$$

$$\boldsymbol{v(t_{i+1}) = min\big(v(t_i), d - D_s(t)\big)} \tag{3-5}$$

Where $v(t_i)$ denotes the velocity of a ship of i, $D_s(t)$ denotes the minimum distance from the i th ship to its preceeding ship, and d represents the actual gap between both vessels.

The CA paradigm gives a coarse representation for speed. The inaccuracy is rooting from the discretization. Firstly, the speed value highly depends on cell size. With Equation 3-2, we could expect that for each time step, there is a maximum speed value. Secondly, if the speed is given in a distribution, the non-integer value obtained from the randomization should be converted to the closest integer value.

In the CA paradigm, the speed should be an integer value. Therefore, the model will take the smallest integer that not less than the actual speed. The non-integer value will result in inaccuracy, although the inaccuracy can be lowered if the waterway is divided into smaller cells. Thirdly, either the speed value is obtained by equation or picked from the speed distribution, the vessel speed needs to be rounded up to the closest speed value per time step.

The command for a speed change is given by rules so the details can be increased by simply adding more rules. Most of the models assume that a vessel only changes speed during the encounter. Otherwise, it will sail with a constant speed. The level of details needed of speed rule is based on the purpose of the models, so if a model wants to assess the behavior of a ship in a roundabout, the rules can be defined simpler than in a busy strait. The speed change rule can be given in parallel and perpendicular to the course direction.

- **Course Over Ground**

The COG can be defined to follow a predetermined route or flexible to change. The latter one is not necessarily better than the former. It depends on the model application purpose. In special conditions such as in a strait, the width of the waterway may become smaller due to morphodynamic change. Qi et al. (2017a) suggest an SLM (Spatial Logical Mapping) method to create a more logical ship trajectory in a bottleneck. In a bottleneck, as shown in Figure 3-1, there is a pseudo lane change movement done by a vessel, and this will affect the accuracy of lateral and longitudinal speed. Therefore, the model adds a null cell to resemble the actual trajectory of the ship. The null cell has no influence on the voyage of any lanes, but it can increase the cells number of each lane, this is correct since the distance traveled at the edge is longer than at the center of the bottleneck.

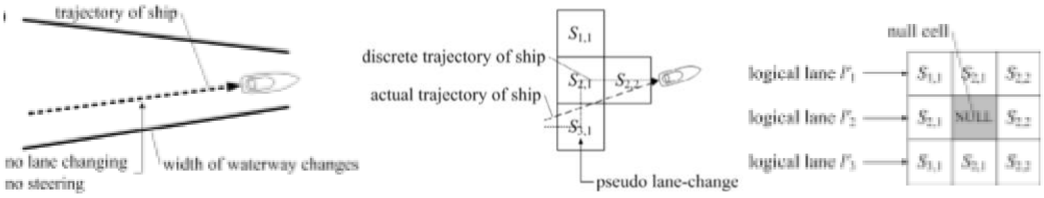

Figure 3-1 Bottleneck of a waterway, waterway discretization, additional null cell in discretization (left to right)

(Source: Qi et al. (2017a). A cellular automaton model for ship traffic flow in waterways)

In Qu and Meng (2012) model, ships course can be more flexible because of the AIS data inclusion. However, in a real sailing situation, the ship will follow a predetermined route. Therefore, in this model, if the ship deviates from the route, the model will adjust the velocity (in a lateral and longitudinal direction) to make the ship go back to their right of way by defining a set of rules. This velocity adjustment to control the course takes into account the deviation by the environmental factor such as tide, wave, current, and wind. Without AIS data, Blokus-Roszkowska and Smolarek (2014) enable the vessels to choose an appropriate course by mathematical equations. A ship will start with an initial rudder angle δ_0 and when a ship decides to perform an evasive action, an appropriate turning angle will be predicted based on the safety distance, the distance between vessels and the length of the target vessel. If the predicted rudder angle does not suffice, a new optimum rudder angle will be chosen from the distribution.

The inclusion of the SLM method would increase the accuracy of course (and speed of the vessel), in a bottleneck. The method is better applied if the aim of the model, for instance, to study the future capacity in a river with a continuous width change. This method can be a good model for the safety and traffic flow analysis in a bottleneck for future traffic. The flexibility of course, by including the AIS data distribution, and adjusting the speed to follow a preferred route can reflect a real sailing behavior in the CA model. However, if a waterway configuration is complex, these methods would require a massive amount of repetitive speed rules. A different method to add the flexibility to change course is applied differently in the model by Blokus-Roszkowska and Smolarek (2014), instead of a course data from AIS, the model uses a rudder angle distribution. In summary, the course itself can be obtained from various source. The course change is still defined by repetitive rules which is very subjective to model developer, the traffic condition, and the rules are generic for all kind of vessels.

In summary, the course change in CA paradigm can change flexibly to give a more realistic sailing behavior. The course change is done by adding the sailing rules to move the vessel in lateral and longitudinal position. However, even though the course flexibility can be presented, the paradigm has some inherited drawbacks in defining the vessel movement in a complex waterway geometry. For instance, the details of a course change in a bend or intersection during encountering can only be presented by discretizing cells with an angle as shown in Figure 3-2 by Blokus-Roszkowska and Smolarek, (2014). In the bottleneck, a vessel will continuously change lanes or so-called pseudo lane change as depicted in Figure 3-1. This movement is unrealistic if a model aims to get greater detail in course. Moreover, the course of a vessel cannot be distinguished from heading due to the discretization.

3.1.2. Vessels Encounter in Cellular Automata

In order to avoid a collision, a vessel needs to maintain a gap from another vehicle and the waterway bank along the journey. In a simple scenario, when the safety distance or ship domain are infringed, the vessels will detect a possible encounter. CA model usually uses several empty cells as a safe distance. Qu and Meng (2012) adopt a safety distance value from van Dorp and Merrick (2011) by defining the critical time headway between two consecutive ships, in term of distance and time were half a nautical mile and 5 min respectively. Besides the time headway, the distance headway can also be applied as shown by the model by Blokus-Roszkowska and Smolarek (2014) that choose a specific safety distance between the vessel (3704 m). In a more detailed model, Qi et al. (2017a, 2017b) define the ship domain as the minimum distance between a ship and its preceding and a braking distance of an own ship. These minimum distances are distinguished into the distance between the front side of own ship to the rear side (D_s), to the left side (D_l), and the right side (D_r) of another ship. This safe distance is updated for each time step because it is different among ships. The parameters like size, speed, and type of ship influence this ship domain.

When the safety distance/domain is smaller than the actual distance between ships, the models by Qi et al. (2017a, 2017b) and Qu and Meng (2012) accelerates their vessels speed otherwise the vessel will decelerate if the environmental condition does not allow overtaking (Qi et al., 2017b, 2017a). In a more sophisticated model by Blokus-Roszkowska and Smolarek (2014), a probability of a vessel to not performing maneuver is taking into account. This probability is based on the risk area of vessels, the smaller the distance between vessels, the higher the probability of taking evasive behavior. This probability is generated by randomization.

In summary, the models studied in CA paradigm defines some steps before performing an evasive maneuver. In defining a safety distance, the model often defines a longitudinal distance due to simplification. The paradigm has the potential to check the lateral gap sufficiency before the maneuver if a model is defined in two-dimensions. Qi et al. (2017a, 2017b) give safety distance in the lateral and longitudinal direction that is similar to ship domain concept. To some degree, the model gives a more realistic maneuvering decision since the domain considers the maneuverability of vessels. Another possibility to maneuver such as visibility, environmental allowance, and waterway section allowance can also be specified by adding the rules. The CA paradigm is also able to consider maneuverability by providing speed and course distributions. The allowance from forward and backward traffic can be checked by specifying an assumption of time/distance headway needed during the maneuvering process.

The time to start a maneuver in the CA paradigm is executed when the safety distance is violated but defining a specific method to include the time is also possible. The time value is often obtained from a traffic observation or an interview with the bridge team. The time also can be added in distribution, so a random time value will be taken when a vessel should take an evasive behavior. This method resembles human behavior (bridge team) to take immediate or late action in maneuvering. In addition, the probability of a vessel for not taking action during an encounter is shown in the model by Blokus-Roszkowska and Smolarek (2014). This can be beneficial for a safety assessment model.

- **Overtaking**

The first requirement to do overtaking encounter for all models is to check if there is a vessel that sails faster than another vessel ahead of it. A straightforward rule for overtaking maneuver is presented by Qu and Meng (2012). The model controls vessels speed change magnitudes in parallel (v_x) and perpendicular direction (v_y). By this way, an own vessel changes their speed as well as course to avoid a collision. It will increase its gap from either the starboard or port side of the overtaken vessel by increasing the speed as can be seen from the Equation 3-6 where ε_x and ε_y are the environmental factors. In this model, when the vessels drift off from the route, another speed change rules will apply to maintain the vessel course. By this information, it can be concluded that the traffic rule only applies for the own vessel.

$$\boldsymbol{v_y(t_{i+1}) = v_y(t_i) - 1 + \varepsilon_y \,;\; v_x(t_{i+1}) = v_x(t_i) + \varepsilon_x} \qquad (3\text{-}6)$$

In another model, as presented by Qi et al. (2017a, 2017b), the model describes the velocity change in the overtaking for the own ship only as follow:

$$\boldsymbol{v(t_{i+1}) = \frac{\left(v(t_i)\right)^2}{\sqrt{\left(v(t_i)\right)^2 + \left(D_{ln}(t_i)\right)^2}}} \qquad (3\text{-}7)$$

Where $v(t_i)$ *de*notes the velocity of the ship i at t and $D_{ln}(t_i)$ is the distance between the lane of an own ship and a target ship.

In summary, both models give generic rules for all kind of vessels. However, looking at the Equation 3-6 and 3-7, the model by Qi et al. (2017a, 2017b) gives a better interaction ship-ship interaction during overtaking. The model considers the relative distance between two encountering vessels. Therefore, to a certain degree, the behavior of the target vessel behavior is taken into account. The model by Qu and Meng (2012) gives simple movement rules based on expert judgment. The model does not take into account the target vessel behavior.

- **Crossing**

In order to avoid crossing, the models in CA uses several local traffic rules to regulate the traffic flow instead of applying COLREGs. The rules can be varied depending on the waterway geometry, type of vessels, and priority of vessels. In a T-junction of the Singaporean Strait studied by Qu and Meng (2012) as shown in Figure 3-2, the rules are relatively simple. The vessel will check several cells to see if there is another vessel ahead. If there is a vessel ahead, the vessel will reduce its speed and not performing the encounter. In a roundabout as presented in a model by Blokus-Roszkowska and Smolarek (2014). The first rule is that a vessel having another vessel on her starboard side shall keep out of the way. The second rule is a vessel being on a roundabout-lane has priority, and a vessel is entering a roundabout crossing is directed to keep out of the way. The third rule is that the lane W1 and W2 are the main lanes, so the vessels in this area are the stand-on vessels, and the other two lanes are dedicated for the give-way vessels that should keep out the way of stand-on vessel. Lastly, there is an exception for the first rule, when a large vessel with low maneuverability enter the roundabout other vessels are directed to keep out of the way of the vessel being on the roundabout-lane.

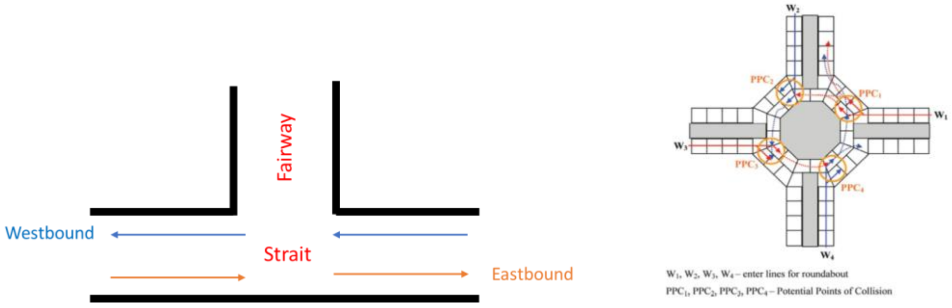

Figure 3-2 T-junction in Singapore Strait (left) and a roundabout (right)

(Source: Blokus-Roszkowska and Smolarek (2014). Maritime traffic flow in intelligent transportation)

In a crossing situation, the rules can be very flexible, depends on the situation of the waterway itself. Both models apply the local traffic rule, but it does not mean that the COLREGs rule cannot apply in CA. The role to be the give-way or stand-on vessel depends on their sailing location, type, and priority of vessel. In the crossing encounter, the interaction between vessels is hardly found. The vessel only checks several cells to see if there is a vessel ahead and start to change its speed and course without considering the target vessel state.

In summary, the CA paradigm can simulate all the encountering type studied in this research (overtaking, head-on, and crossing). If a model does not show a specific type of encounter, it must be due to the application purpose. The traffic rules can be assigned for both vessels, and both are able to maneuver differently according to their roles. In the overtaking and crossing encounter, the own vessel can either maneuver to port or starboard by adding the vessel movement rule. The model will check the gap sufficiency in the lateral direction to decide which side it needs to maneuver. The head-on encounter is not present in any models studied in this research. However, the CA paradigm has the potential to include a head-on encounter by checking the lateral distance. If there is a vessel approaching an own vessel from different lane, and the lateral distance is small enough, then the own vessel will detect the possibility of the head-on encounter. The traffic rule can be determined for both port-to-port situations as well as the starboard-to-starboard situation by adding the rules. When encounter maneuvering is done, the paradigm can adjust its speed and course to go back to its main path by adding rules. This paradigm hardly includes ship-ship interaction. However, the sailing behavior can be more realistic by providing more rules and data of the vessel maneuverability during an encounter.

3.2. Generic Rule-Based Models

Rule-based model is a paradigm that uses a set of rules to specify a mathematical model. The rules can be translated into the differential equation, Markov-chains, or be treated using tools that directly work on the rule-set in place of a translated model. It is effective for a model that has a simply repeated manifestation of a limited number of patterns.

3.2.1. Vessel Behavior Representation in Generic Rule-Based

Like the CA paradigm, in the GRB paradigm, the vessel movement behavior is represented by rules. However, now, the space domain is described continuously.

- **Position**

Most of the models are dedicated for traffic flow model simplify the vessel position into one-dimensional space (Gucma et al., 2018; Piccoli, 2014; Camci et al., 2009; Almaz et al., 2006; Thiers and Janssens, 1998). In a complicated situation such as in a multi-bridge river (Xu et al., 2015) or to model a collision risk (Goerlandt and Kujala, 2011), a two-dimensional position can be applied by adding the lateral position of the vessels. The lateral position of vessels is obtained from the historical data.

Most of the models adopt the concept of waypoints connectivity. So, the position of vessels is determined by several nodes. The location of the nodes and the initial position of each ship is given in distribution for each starting node. The distribution is obtained from AIS data. The position is updated for every time step, and it depends on the steering regulation in the network line. Since the space domain is continuous, this paradigm gives a higher accuracy of a vessel movement compared to the CA paradigm. Also, the geometry of vessels and waterway can be simulated in an exact dimension.

In defining the position dimension, if a model defines vessel position in one dimension, it is due to the modeling simplification to analyze the traffic flow. In a complicated modeling situation such as in a waterway with many obstacles or for the collision avoidance/risk purpose, the lateral position distribution data can be added in a node to get a more realistic vessel movement.

- **Speed Over Ground**

The vessel speed is usually given in a distribution function, except for Xu et al. (2015) that uses a deterministic value in the model. The speed change of a vessel can be assumed as constant along the journey (Goerlandt and Kujala, 2011), without acceleration and deceleration (Xu et al., 2015; Piccoli, 2014), or with acceleration and deceleration (Camci et al., 2009; Almaz et al., 2006). The model by Almaz et al. (2006) and Camci et al. (2009) use software (a tool) that enable them to embed speed, acceleration, and deceleration. The latter model uses path mover models to include speed, acceleration, and deceleration.

Generally, the speed change rules are described in a very detailed way in all models in this paradigm, except for Goerlandt and Kujala (2011) that consider the speed is route-indifferent. The speed change rules are influenced by the waterway segment (depth or width restriction); environmental factors encounter impacts, the ability of the ship to maneuver or many more. In other models, the speed of the vessel is the minimum value of the maximum possible speed from the combinations of different speed influencers mentioned above. For instance, the maximum sailing speed of a container vessel is 25 knots, however, in a waterway section with limited depth, the maximum speed limit is 20 knots, then the vessel will sail at 20 knots. The speed limit is often specify based on a real traffic condition. The speed limit can be fixed for every vessel and circumstances. The limit can also be specified due to the specific water area condition (Piccoli, 2014; Thiers and Janssens, 1998) or the sailing direction of vessels (Xu et al., 2015; Almaz et al., 2006). The speed rules applied in this paradigm is easy and relatively simple to apply. However, the rules defined in this paradigm generalize the speed change for all kind of vessels. All models only apply the speed rules based on the factor that gives a significant influence on the vessel speed.

In summary, most of the models use a waypoints connectivity concept, and due to this, the speed change can only be done in a node. Otherwise, the vessel will maintain its speed. So, if the model needs to simulate the speed detail in maneuvering, it needs to make the gap between nodes shorter or provide more nodes with a speed distribution in it. The ability to change speed is also determined by the acceleration or deceleration feature. A simplification of taking a fixed ship speed can only be acceptable for traffic flow analysis purpose. In the collision-related detail, the acceleration and deceleration features need to be embedded to reflect the maneuvering detail of a vessel. The acceleration per time step can be calculated with the Equation 3-8.

$$\boldsymbol{a}(\boldsymbol{t_{i+1}}) = \frac{\boldsymbol{v}(\boldsymbol{t_{i+1}}) - \boldsymbol{v}(\boldsymbol{t_i})}{\triangle\, \boldsymbol{t}} \qquad \textit{(3-8)}$$

- **Course over Ground**

Most of the models define the waterway as a set of the straight links, nodes, waypoint, and connectivity information, (Xu et al., 2015; Piccoli, 2014; Goerlandt and Kujala, 2011; Camci et al., 2009; Almaz et al., 2006; Thiers and Janssens, 1998), as shown in Figure 3-3. The waterway is a combination of links, and each link is split up by nodes, or so-called a segment. Each segment during a discrete-time slot is occupied by only one sailing vessel. The vessel sails with a straight course in a link and makes a turn when reaching the waypoint. The waypoints positions are generated from a Gaussian distribution.

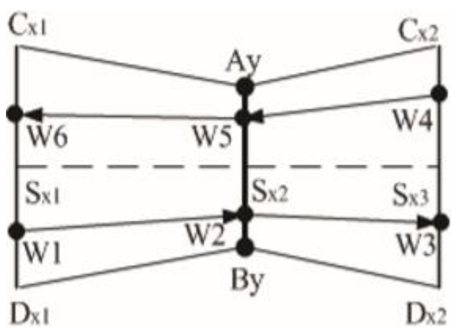

Figure 3-3 Waypoint nodes connectivity concept

(Source: Xu et al., 2015. Simulation models of vessel traffic flow in an inland multi-bridge waterway)

There are several ways to define the vessel course change by the rules imposed in the models. First, all vessels course should follow the same route along the journey (Thiers and Janssens, 1998). Secondly, the models can assign several vessels only to follow a fixed route, while the other vessels can follow another route. Thirdly, the rules are imposed in each segment of the waterway, so the vessel itself will decide which route it has to follow (Piccoli, 2014; Camci et al., 2009; Almaz et al., 2006). The flexibility in choosing route is done by the model by filtering the vessels based on the vessel type and size, waterway dimensions restriction, one- or two-way operation, or priority of vessels to determine which vessel can sail through a specific route. In conclusion, the course change details can be improved by adding more rules in the model.

Based on the description above, in the waypoint's connectivity concept, it can be predicted that the course change cannot be represented in detail. Most of the generic rule-based model utilizes node and link concept, so the vessel's course will follow the predetermined links and change its speed and course at the node. So, the detail of maneuver, especially during an evasive maneuver, will depend on how wide the gap between nodes. If the gap is wide, then the maneuvering accuracy will be less. However, such detail would not be necessary for a particular purpose of traffic modeling, for instance, in the model for traffic flow and capacity assessment. For the collision-related model, the course change accuracy can be improved by adding more node points.

- **Heading**

The heading of a vessel only presents in the model by Hasegawa et al. (2000, 2001) to analyze the behavior of vessels during an evasive maneuver. Heading can be separated from a course by constructing a time-space series of the vessel behavior as shown in Figure 3-4 by Hasegawa et al. (2000, 2001). So, in the figure, the vessel maneuvering history in space (a) and time (b) are plotted. However, this method is not applicable to every application purpose. The model can only plot and analyses the collision maneuvering behavior of vessels based on the vessel maneuvering data.

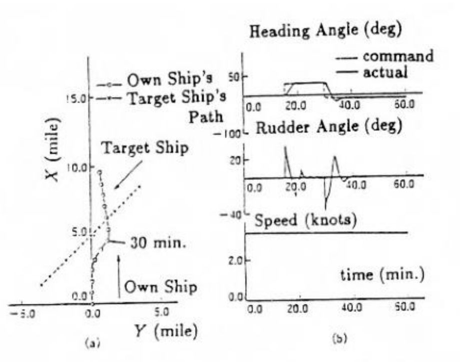

Figure 3-4 Waypoint nodes connectivity concept

(Source: Hasegawa et al. (2000,2001). An Intelligent Marine Traffic Evaluation System for Harbour and Waterways System)

3.2.2. Vessel Encounters in Generic Rule-Based

In the GRB models studied in this research, most of the models detect an encounter if the safety distance is violated, except for the model by Goerlandt and Kujala (2011) and Hasegawa et al. (2000, 2001). Goerlandt and Kujala (2011) detect the probability of encounter by checking if two vessels courses are crossed with each other. In another risk assessment model, Hasegawa et al. (2000, 2001) embed the CPA method to detect an encounter and quantify the collision risk by the fuzzy logic reasoning. The safety distance can be given in an exact value for all kind of vessels and situations (Camci et al., 2009; Almaz et al., 2006), or it can also vary depending on the location of a ship (Thiers and Janssens, 1998) or the type of ship (Piccoli, 2014). Even more detail, Piccoli (2014) also considers the time headway. In the model, the typical values are equal to 5 times the vessel length. So, for instance, if the maximum vessel length is 346 m and when considering a sailing speed of 10 knots, the corresponding distance in time is 5-6 minutes.

Some models always allow maneuvering during encountering for all type of vessels and in any circumstances when the safety distance is violated. There are also some models that assign several rules before allowing a vessel to maneuver. Some models check the forward and backward direction if the target vessel is not being overtaken by another vessel and the future traffic allows the maneuver (Camci et al., 2009; Almaz et al., 2006; Thiers and Janssens, 1998). Moreover, the model by Almaz et al. (2006), determines that there will be no encountering maneuver nearby until the expected maneuver is completed.

In summary, most of the models in this paradigm use a safety distance to detect the possibility of an encounter. Although it is rather a simple detection method, it can be enhanced to detect an encounter better, for instance, by adding a safe distance around a vessel. In order to include the maneuverability, the distance can be a function of the vessel speed, size, type, and many more. Defining the safety distance with this approach can resemble the ship domain concept in a simple manner. Besides of that, the CPA concept can be embedded as shown in the model by Goerlandt and Kujala (2011) and Hasegawa et al. (2000, 2001) to quantify the collision probability and risk. Therefore, the detection of an encounter by safety distance, ship domain, and CPA method is possible. The paradigm is also able to add the possibility to maneuver by checking the vessel maneuverability and the allowance from forward and backward traffic. The vessel maneuverability is included by giving the speed and course distribution limit of the vessel. The time to start a maneuver can be done directly after the detection, or the model can also give a deterministic time value based on the expert judgment or analysis of the traffic condition.

- **Overtaking**

The obligation of which vessel and how they maneuver in overtaking is varied among models. The rules of when and where the vessel can maneuver are also different among models. Even though the overtaking mechanism can be applied differently, the first check for overtaking is the same, that there is a vessel that sails slower than its preceding. The following mechanism during overtaking is different. In a simple mechanism, vessels do not necessarily have to change their speed or course during overtaking; vessels will overlap each other (Piccoli, 2014). In the model by Xu et al. (2015), the traffic rules are applied for both vessels. An own vessel alters the course and accelerates, while a target vessel keeps its course and speed. A different rule is applied by Thiers and Janssens (1998), instead of accelerating the overtaking vessel, the overtaken vessel will reduce speed, and after the encounter, it will restore its speed.

Besides the mechanism of how the vessel performs an evasive maneuver, the rules of when and where a vessel can maneuver is often specified in the model. Some models only allow overtaking in a specific segment of a waterway. It can be due to the dimension of the waterway, such as a narrow width or limited depth of the waterway.

The overtaking maneuver in this paradigm is relatively simple; it is either changing speed or course, or a combination of both. The maneuvering action is often assigned to the overtaking vessel only, while the target vessel will maintain its sailing behavior. The model determines the value of speed and course change by simple rules. The specific traffic rules such as when and where to overtake are also can be easily embedded in this paradigm. Even though the evasive maneuver behavior is not described well and lack of ship interactions, the rules of when, where and how to maneuver is practical and simple. This simplicity is beneficial for traffic flow analysis purpose which does not require a very detailed overtaking maneuver behavior.

- **Crossing**

In the model by Thiers and Janssens (1998), for a crossing encounter, if an evasive maneuver lacks safety, the speed of one or both vessels is reduced. There is no clear information regarding how the model checks the forward direction and the opposite sailing direction or the details of how the maneuver will conduct.

In summary, the maneuvering rules in the GRB paradigm can be varied and flexible. The rules highly depend on the expert judgment and the traffic pattern in the simulated area. The paradigm can only use the CPA for calculating the collision probability and risk, or to study the behavior of a ship during a collision maneuver. The ship-ship interaction is described in the paradigm with a direct and simple movement rule or by a simple kinematic equation. For the type of encounter, overtaking is the most common encounter simulated in the models. Head-on and crossing encounter in the models. This can be due to the geometric complexity or the traffic regulation of the water area. The paradigm has the potential to integrate the head-on and crossing encounter if it defines the position in two-dimensions. Head-on can be included by checking the gap distance between vessels, in the opposite direction. If the gap is small, then there is a possibility of head-on encounter. The model can assign both vessels to move to one specific side. However, to add the flexibility to maneuver, a more specific checking, interaction, and movement rules should be further elaborated. The crossing encounter can be added by checking the forward traffic if there is a possible encounter in the intersection. The vessel can be assigned to move to another link that is perpendicular to the current link (for instance: in the intersection) to avoid the vessel ahead.

3.3. Specific Rule-Based Models

Specific SRB paradigm describes the difference and the interaction between vessels better than the GRB paradigm. In this paradigm, the ship-ship interaction is often quantified by calculating DCPA and TCPA (Zhou et al., 2019).

3.3.1. Vessel Behavior Representation in Specific Rule-Based

The vessel behavior is simulated in a similar way as the GRB paradigm. Most of the models apply the waypoints connectivity concept, although the models often add some enhancement.

- **Position**

In the SRB paradigm, most of the models define the vessel position in two-dimensions, except for Rayo (2013) that describes the position in one-dimension. The position of vessels in the model is mostly obtained from historical distributions and generated from Monte Carlo random sampling.

The model by Huang et al. (2016) uses a navigation network concept, which is different from the waypoints connectivity concept. The model defines the fairway by a sequence of segments, as shown in Figure 3-5. Each segment is a node with a convex polygon shape with three or four corner points. Each corner of a segment is defined by latitude and longitude coordinates. A mode to allow or forbid a vessel to pass through is assigned in each segment. The segments can represent the anchorage, terminal/shipyard, and entry/exit points. The edge of a segment that enables both entry and exit will split traffic into halves to separate the incoming and outgoing vessels. Depending on the width, in each segment, two or more vessels may move in parallel in the same direction and overtake each other.

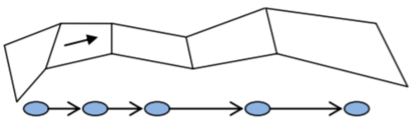

Figure 3-5 Navigation network fairway

(Source: Huang et al. (2016). A Marine Traffic Simulation System and Scenario Studies for a Major Hub Port)

Differently, Li (2013) and Xu et al. (2013) defines the nodes as waypoints and straight links as the fairway segments. The position information is given in the node, and every time the vessels pass the node, the position of vessels will be updated. The movement of a vessel is defined as Equation 3-9. Specifically, in the two-dimensional model, the movement with angle is described in a more detailed way. The example of movement in angle is given in the model by Xu et al. (2013) as follow:

$$\boldsymbol{\theta} = \boldsymbol{arctan}\frac{|\mathbf{y}\,(\boldsymbol{t_{i+1}}) - \mathbf{y}(\boldsymbol{t_i})|}{|\boldsymbol{x}(\boldsymbol{t_{i+1}}) - \mathbf{x}(\boldsymbol{t_i})| \times \boldsymbol{cos}\,\mathbf{y}(\boldsymbol{t_i})} \tag{3-9}$$

$$\boldsymbol{x}(\boldsymbol{t_{i+1}}) = \mathbf{x}(\boldsymbol{t_i}) + \boldsymbol{v_x}(\boldsymbol{t_i}) \times \triangle\, \boldsymbol{t} \times \mathbf{cos}\boldsymbol{\theta}$$

$$\mathbf{y}\,(\boldsymbol{t_{i+1}}) = \mathbf{y}(\boldsymbol{t_i}) + \boldsymbol{v_y}(\boldsymbol{t_i}) \times \triangle\, \boldsymbol{t} \times \mathbf{sin}\boldsymbol{\theta}$$

Unlike the previous models, Miyake et al. (2015) make a time-space state of a ship’s state that constructed from AIS data. For each time interval, the state of a ship is generated. Therefore, the position of a ship is a kind of mapping from the historical data.

Generally, all models give the vessel position information in the node and retrieve the information from AIS data. Defining the vessel position distribution in the special segments, as shown by Huang et al. (2016) gives a general overview of the vessel movement. The exact position change of the vessels cannot be shown. This type of approach will only suit for a model with a bigger network scale, such as a hub port. The waypoint connectivity concept represents the vessel behavior better than the navigational network since now the route consists of several nodes containing the vessel position information.

- **Speed Over Ground**

The vessel speed can be retrieved from various sources. It can be depending solely on vessel classification (Watanabe et al., 2008), distribution from historical data such as AIS data or field collecting (Huang et al., 2016; Miyake et al., 2015; Li, 2013; Xu et al., 2013) or defining the dynamics of a ship as first-order model between the current and the desired speed (Aarsæther, 2011).

In this paradigm, the speed change is determined by both rules and CPA calculation. The rule of speed depends on the waterway segment and type of vessel speed. This rule is often based on real traffic regulation. The models can perform the speed change with or without acceleration/deceleration. In the model by Huang et al. (2016), the speed change is done without acceleration/deceleration. The speed change range is the minimum value of the maximum vessels’ speeds based on their type and the allowable speed in the vessel location. In the model with acceleration and deceleration features, most of the models consider the relative velocity between own vessel and a target vessel. Li (2013) uses a rate of acceleration and deceleration as a parameter for the speed change; the parameter value is between 0 and 1. For instance, a vessel will calculate the maximum relative movement between two vessels (gap distance before reaching a new node considering the safety distance of the vessel) and compared it to the distance if the vessels will decelerate at a maximum rate. If the distance of the vessels at the highest deceleration rate is lower than the maximum relative movement, the model will find the rate as such that those distances are equal or keep the current speed for some time and then decelerate at a maximum rate.

Differently, in Aarsæther (2011) model, the acceleration is proportional to the deviation between the current speed and the desired speed. The current speed is the actual speed of the ship from data, while the desired speed is the speed based on the predetermined speed. This acceleration is used by the model vessel to resemble the actual vessel speed in the data.

$$\dot{v_x} = (v_x - v_{xd}).T_u \quad (3\text{-}10)$$

$$\dot{v_y} = \mathbf{r}\,.T_{vr}$$

$$\dot{r} = (r - r_d).T_r$$

Where v_{xd} is the desired speed, r is a cross-track offset computed in the autopilot and dependent on the maneuvering mode, T_{vr} and T_r are maneuvering parameters. The parameter with a subscript d such as v_{xd} and r_d are the desired parameters.

Most of the models only specify the speed change at special circumstances, such as during an encountering maneuver. Also, in the waypoint connectivity and the navigational network method, the speed change can only be done at the node or when entering a new segment. Even though the model by Li (2013) gives the flexibility to choose the acceleration/deceleration rate, the speed change cannot be done immediately. It could be expected that for a higher-level modeling purpose such as a collision avoidance analysis model, the models will give a rough estimation. However, with proportional-integral feedback, as shown by Aarsæther (2011), the model will constantly observe the need to change speed along the journey. The method reflects real sailing behavior.

During an encounter, not all model defines the feature with acceleration. In the model by Huang *et al.* (2016), the speed change is simplified without acceleration due to its application purpose to study a complex area such as a hub port. Such simplification could be due to the insignificant impact of adding the acceleration feature to the output result. In another model that focuses on collision analysis as shown by Li (2013), the speed rule is quite extensively elaborated by allowing a vessel to take early action if the rate deceleration is not sufficient to make a vessel stop on time. Therefore, it can be concluded that the addition of acceleration and deceleration features depend on the modeling application purpose.

- **Course Over Ground**

Most of the models describe the vessel course to follow the preferred route and change the course at a waypoint except for Aarsæther (2011) that describes the course as proportional feedback of the rate of turn when the course of a route is changing. Most of the vessel course in the models is predetermined (Huang et al., 2016; Li, 2013). For collision avoidance purpose, the model by Li (2013) define the route in a straight section, turning point, and during maneuver/change lane by a set of mathematical equations. This course change is extensively modeled with mathematical equations by considering the angle at which the vessel needs to turn, vessel speed, the position of the vessel at the turning point, and many more as shown in Figure 3-6. In the other model, with traffic flow analysis purposes, the route is chosen by vessels based on different parameters.

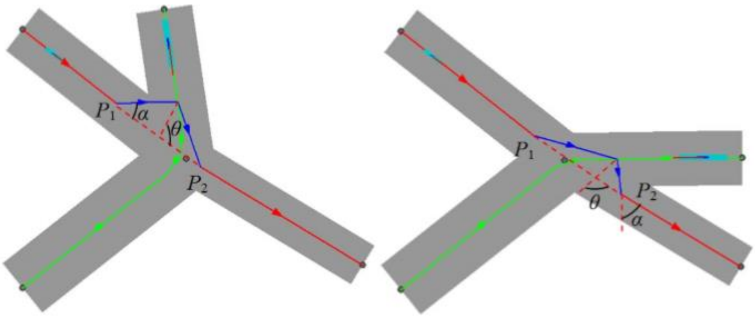

Figure 3-6 Vessel trajectory at a node

In the model by Aarsæther (2011), the course change is flexible. The ship may wander significantly through the voyage although the traffic lanes are predefined. Both in a straight track or in a turning point, the vessels can deviate from the original route. The model uses AIS data to create the traffic lanes; each lane consists of track lines of a single ship. The track line has some control points, and if the vessels deviate from the perpendicular lines at the control points, the speed and cross-track offset are calculated. The first line in the Equation 3-11 is applied at the straight section and the other equation at the turning section. This equation becomes an input for the Equation 3-10. θ_d is the desired course, and R_{turn} denotes the turning radius. The representation of this approach is shown in the Figure 3-7.

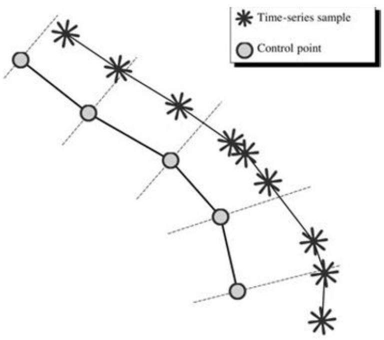

Figure 3-7 Time series sample and control point

$$r_d = -r.K_p + (\theta_d - \theta).K_i \qquad (3\text{-}11)$$

$$r_d = \frac{v_x}{R_{turn}}$$

R_{turn} is the radius of the maneuver circle, K_i and K_p are the maneuvering parameters. All models described above simulate the vessels to follow a predetermined route with some route change choices at a waypoint. The model by Li (2013) gives a sophisticated level of details to model the course change. The model presents that the waypoint connectivity concept can predict an exact trajectory of vessel turning motion by providing mathematical equations in a node. However, this feature can only be presented in a node. In another approach, as presented by Aarsæther (2011), the vessels can wander significantly but keeps trying to adjust the dynamics to follow the route. This approach resembles real sailing behavior. With this model, the course change can be done immediately without reaching a node first.

- **Heading**

Most of the models deemed the heading as a course. The only model in this paradigm that separates heading from the course is a model by Miyake et al. (2015) to study the collision avoidance behavior of vessels. Separating the heading can be done by mapping the state of vessels from historical maneuvering data into a time-space state series. The heading in this model is shown in Figure 3-8.

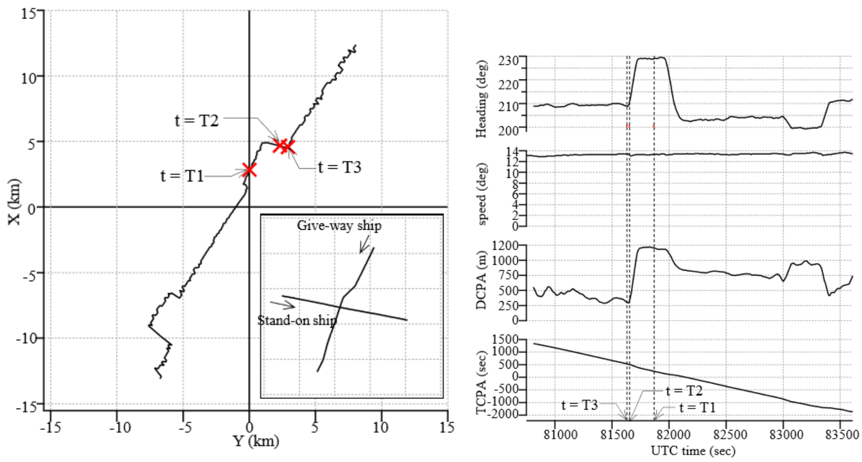

Figure 3-8 Time series of the vessel state

However, the applicability of this approach is limited to a specific purpose to study the vessel collision maneuvering behavior. So, the existing maneuvering details need to be known beforehand. For another modeling purpose, none of the models distinguish the heading and course.

3.3.2. Vessel Encounters in Specific Rule-Based

In order to quantify the ship-ship interaction, the models in this paradigm adopt different criteria to judge an encounter situation and calculate DCPA and TCPA to trigger an evasive maneuver. In general, the TCPA is used to estimate the degree of collision risk, and DCPA is the criterion used to examine whether a collision will occur between two vessels. Some models adopt DCPA and TCPA only (Miyake et al., 2015; Li, 2013; Aarsæther, 2011), but the other models use an additional approach to better check a possible encounter. Aarsæther (2011) uses a safety distance of 2 km for all vessels before calculating the DCPA and TCPA. If the safety distance less than a specific value, DCPA and TCPA are computed for the current state. In case DCPA is smaller than the safety distance or TCPA is positive, the model will start an evasive action. Huang et al. (2016) uses DCPA for the first check and adds separating axis theorem for the second check. DCPA test is aimed to filter out vessels that will not be getting close to each other within a time horizon. The second check is done by creating a rectangular domain around a vessel and add the two normal vectors to every axis. This method will checks if the two stationary convex polygons of the vessels will intersect or not. The illustration of separating axis theorem method is displayed in Figure 3-9. In the figure, the arrows represent the possible direction of a vessel to collide with each other.

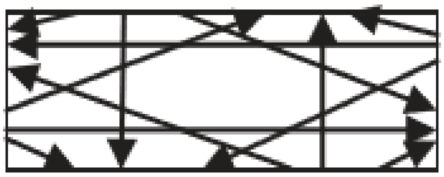

Figure 3-9 Separating axis theorem domain

(Source: Huang et al. (2016). A Marine Traffic Simulation System and Scenario Studies for a Major Hub Port)

The CPA calculation is an easy method to detect an encounter, obtain the degree of collision risk, and to quantify how the vessels should behave to avoid a collision. Calculation of CPA assumes that vessels are simplified to geometrical points. This assumption is reasonable for radar tracking in the open sea environment, considering two approaching vessels are far away so that their actual size is ignored. However, in a restricted water area, the size of vessels is matters. Therefore, combining two or more encounter detection approach as shown by some models above can be a good solution for the restricted water area.

In quantifying the collision avoidance maneuver, the CPA method has an inherent limitation for a restricted water area. The CPA applies to an open sea where vessels can freely take actions while the ship domain has been proposed as a more comprehensive and accurate criterion to measure collision risks in restricted waters such as narrow fairways (Jingsong et al., 1993). The CPA criterion is difficult to use in narrow fairways where a vessel cannot choose routes freely, and its maneuvering is restricted. However, on the other hand, since a ship domain depends on many factors (speed, visibility, maneuverability, traffic condition), it is difficult to construct a correct domain shape as well as quantifying the ship-ship interaction.

For the possibility to maneuver, the paradigm is able to compute the safe path in a lateral and longitudinal direction. The paradigm also shows its capability of checking the forward and backward traffic by means of equations. The vessel maneuverability is given in the speed and course distribution.

Also, in this paradigm, the time and responsibility to start the evasive behavior can be specified when the CPA value is violated. Another way to define the time is by computing a fixed value by a simple kinematic equation. The parameter to trigger an encounter maneuvering is still subjectively determined by the user for a specific area only. Therefore, the time to maneuver in one model might not be applicable in another model.

- **Overtaking**

In performing the overtaking maneuver, the behavior of a vessel is determined by the role of a vessel. The role is given by the traffic rule written in COLREG. The traffic rule is only applied to the own vessel except in the model by Aarsæther (2011). An own vessel needs to alter its course to starboard. While the target vessel has to maintain its speed and course. None of the models include the evasive maneuver by both the own vessel and the target vessel.

When there is a vessel that travels faster than its succeeding, the model will check if overtaking maneuver is possible. The models check if the lateral width is sufficient to conduct an overtaking, of the waterway is enough to conduct an overtaking (Li, 2013; Aarsæther, 2011; Watanabe et al., 2008) or the rules are predefined in some segments if overtaking is allowed or forbidden (Huang et al., 2016). In this paradigm, all models specify the lateral gap sufficiency.

If the overtaking maneuver is possible, then the own vessel will overtake the target vessel. Otherwise, the own vessel will reduce the speed. During overtaking, the vessel will change its speed through acceleration (Li, 2013; Watanabe et al., 2008) without acceleration (Huang et al., 2016) or no speed change at all (Aarsæther, 2011). The model that does not include the speed change argues that it is hard to notice from the other vessel point of view. However, in a real sailing, the own vessel will accelerate, and the target will decelerate to execute a maneuver as fast and as efficient as possible. In the model by Aarsæther (2011), the vessel will test several course angles and cross-track offset to avoid the target vessel. If the course change is not possible, then the own vessel will use the combination between changing the course angle and increasing the speed. If all combinations fail, the vessel will decelerate.

In summary, the overtaking maneuver in this paradigm is mostly performed by the own vessel by changing its speed and course, while the target vessel keeps its sailing behavior. The assumption of not taking acceleration is not applied in real practice. In most of the case, the own vessel needs to accelerate as recommended by COLREG.

- **Crossing**

The most desirable action to avoid a collision is to change the course behind and on the port side of a target vessel at the point of conflict. The models often set the rule to alter the course without speed change as a priority during the crossing maneuver (Li, 2013; Aarsæther, 2011). The model by Li (2013) set a predetermined turning trajectory in each waypoint. In the model, a vessel is assumed to maneuver at a current rudder angle; however, it can be increased if the turning angle is not sufficient to evade another ship. When maneuvering with this angle causes a conflict with other vessels at the turning, the own vessel will decelerate. Looking at the algorithm applied, the model has the potential to continuously change course during the maneuver but also to add the speed change feature. Differently, the model by Huang et al. (2016) allows the give way ship to choose a combination of altering course and changing speed by acceleration or deceleration. If all combinations fail, an own vessel will decelerate.

- **Head-on**

In the head-on encounter, the models apply a COLREGs rule by altering the course of both vessels to their starboard (Huang et al., 2016; Aarsæther, 2011). Both models specify the vessels behavior during a head-on situation is similar to the overtaking encounter. There is no further detail information regarding how the head-on encounter works on the papers. However, based on the overall description of both models, the algorithm in the head-on encounter is similar to the previous two encounters. Both models define that altering course is their priority.

In conclusion, all types of encounter and the detail of maneuvering listed in this research requirement is possible to be embedded in the SRB paradigm. The behavior of evasive maneuvering is often taken by changing the vessel speed and course as such to decrease TCPA and DCPA. The traffic rule also can be assigned for both vessels. The choice either one or both vessels to perform maneuvering depends on the model developer definition and necessities. The rule of taking which maneuvering direction the vessels should take can also be specified in this paradigm by adding more rules. Also, the paradigm is capable to assign the vessel back to initial course and speed or adjust to a traffic condition, again, by adding more rules. The paradigm can simulate the traffic in a wide area and involving many vessels with a decent detail of vessel behavior. However, the difference in vessel behavior details in encounter maneuvering cannot be presented.

3.4. Artificial Potential Field Models

The artificial potential field is a modeling paradigm that assumes an entity (vessel) moving in an abstract, artificial force field. This artificial field consists of an attractive and repulsive potential field. The derivation of these potential fields is an attractive and repulsive force. A vessel destination sets an attractive force that makes a vessel move towards it. The obstacles generate a repulsive force, which is inversely proportional to the distance from an object to obstacles.

To control the vessels movement, APF paradigm moves vessels from a high potential to a low potential region (its destination) or so-called gradient-descent. APF also controls the course of vessels by summing the attractive and the repulsive potential. These forces terminate as soon as the gradient vanishes or equal to zero. This potential function is constructed as:

$$\vec{U}(\vec{p}) = \vec{U}_{att}(\vec{p}) + \vec{U}_{rep}(\vec{p}) \qquad (3\text{-}12)$$

Where $\vec{p}$ represents a point on the water surface, $\vec{U}(\vec{p})$ is the total potential energy, $\vec{U}_{att}(\vec{p})$ and $\vec{U}_{rep}(\vec{p})$ denotes the attractive and repulsive potential energy.

The ship is subjected to a force which is derived from the potential field as follow:

$$\vec{F} = \vec{F}_{att} + \vec{F}_{rep} \qquad (3\text{-}13)$$

Where $\vec{F}_{att} = -grad\,(\vec{U}_{att}(\vec{p}))$ and $\vec{F}_{rep} = -grad\,(\vec{U}_{rep}(\vec{p}))$

Although the concept of attractive and repulsive forces is similar, they are defined differently in the APF models. Rong et al. (2015) represent the impact of banks by a series of obstacles for every 500 m, while Xiao (2014) generates the repulsive force along the bank. Differently, in the model by Cheng et al. (2017) the repulsive potential field is given around the obstacles with several layers to avoid collision with vessels. The inner layer possesses the largest repulsive potential. The example of attractive and repulsive general equations are given below:

a. The Attractive Potential and Force

The attractive potential should be increasing with the current distance of the vehicle to the goal. The attractive potential field is given in the equations follow:

$$U_{att(x)} = \frac{1}{2} k_p (x - x_d)^2 \qquad (3\text{-}14)$$

The attractive force is the derivation of the attractive potential function.

$$F_{att(x)} = -k_p(x - x_d) - k_v \ddot{x} \qquad (3\text{-}15)$$

x is the current position of a vessel, x_d denotes the desired position, k_p and k_v are constant parameters.

b. The Repulsive Potential and Force

The obstacle avoidance potential field is formulated as follow:

$$U_{rep(x)} = \begin{cases} \frac{1}{2}\eta\,(\frac{1}{p} - \frac{1}{\rho_o})^2, & \rho \le \rho_o \\ 0, & \rho > \rho_o \end{cases} \qquad (3\text{-}16)$$

The derivative of the repulsive potential function is the repulsive force which is,

$$F_{rep(x)} = \begin{cases} \eta(\frac{1}{\rho} - \frac{1}{\rho_o})\frac{1}{\rho^2}\frac{\partial\rho}{\partial x}, & \rho \leq \rho_o \\ 0, & \rho > \rho_o \end{cases} \tag{3-17}$$

Where ρ_0 represents the limit distance of the potential field influence and ρ the shortest distance to the obstacle. The sum of the repulsive potential field can be formulated as follow:

$$U_{rep(q)} = \sum_{k=1}^{N} U_{rep,}(q) \tag{3-18}$$

3.4.1. Vessel Behavior Representation in Artificial Potential Field

The dynamics of a vessel is given in the set of mathematical equations. All models in APF paradigm present the vessel position in two-dimensions. The movement is realized by following the negative gradient of the sum of attractive/repulsive potentials or merely the following vectorial sum. The vessel state is defined differently in the models. Xiao (2014) adopts the vessel state equations from Nomoto model as given in the Equation 3-19. The vessel speed and course are obtained from historical data. The distributions are distinguished based on the size of a vessel, and the sailing direction of a vessel (incoming and outcoming). Differently, Rong et al. (2015) differentiate the speed distributions based on the type of vessel (cargo and container).

$$\begin{aligned} x(t_{i+1}) &= x(t_i) + v_x * \cos\theta_i \,.\, \Delta t \\ y(t_{i+1}) &= y(t_i) + v_y * \sin\theta_i \,.\, \Delta t \\ \theta(t_{i+1}) &= \theta(t_i) + R_i \,.\, \Delta t \\ R_{i+1} &= R_i + (K.\delta - R_i) \,.\, \frac{\Delta t}{T} \end{aligned} \tag{3-19}$$

K is an ability of the ship to change course while T indicates the ability of the ship to keep its course. Both parameters depend on several ship's parameters such as LOA (length over all), B (beam), d (draught), C_b (block coefficient) and L_d/A_R (rudder area ratio)

The speed is defined differently in the model by Cheng et al. (2017). The speed change is shown in the Equation 3-20. In this model, the forces are explicitly included in the speed equation.

$$\begin{aligned} v_x &= v\sin\theta_i + \left(\frac{F_x}{m}\right)\Delta t \\ v_y &= v\cos\theta_i + \left(\frac{F_y}{m}\right)\Delta t \end{aligned} \tag{3-20}$$

In this paradigm, a vessel should follow a predetermined trajectory or so-called path following behavior. However, the repulsive force steers the vessel course, so it can deviate from the ideal path. Once the deviation is too large, the model should be able to steer the ship position to the main trajectory. So, during the journey to reach its destination, a vessel will be exposed to attractive and repulsive forces. The attractive force is defined by the distance between a vessel position and its destination point, and this force is getting smaller when a vessel approaches the destination point. The repulsive force is given in the obstacles such as the waterway bank and other vessels.

In the model by Rong et al. (2015), ship route-finding concerns the representation of obstacles. A series of obstacle points are placed on the boundaries of the main trajectories. These obstacle points are placed discretely for every certain distance, so the ship must follow the route corridor and change its course at the goal point as displayed in Figure 3-10. Similarly, Xiao (2014) apply the repulsive force along if a vessel is too close to the bank. In addition, this model includes the current field to influence a vessel steering behavior. By the simulated current filed, the current impact can be integrated into the vessel movement.

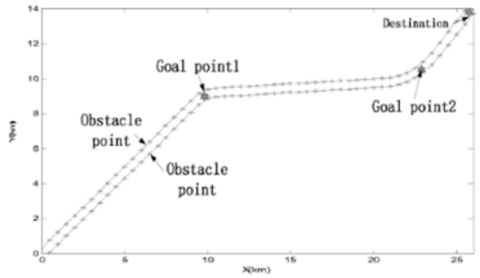

Figure 3-10 Separating axis theorem domain

(Source: Rong et al. (2015). Simulation and analysis of maritime traffic in the Tagus River Estuary)

The heading can be distinguished from the course by defining it in the mathematical equation. Some models cannot separate heading and course due to several reasons. For instance, the application area is in a straight waterway, strong path following behavior, or environmental impact is not included in the simulation. In the model by Xiao (2014), the heading is exclusive from the course. However, the model shows that the deviation between heading and course is very small due to a rigid course following behavior in the simulation which tries to make the ship headings the same as the curve of the channel. Also, due to the assumed straight waterway in the model. So, it is not because of the incapability of the paradigm. The heading is also simulated in the model by Cheng et al. (2017).

In summary, all vessel behavior can be represented in the highest detail described in this research requirement. The summation of all influencing external factors is accounted for by the vessel to control their movement. All vessel dynamic behavior aspects are controlled by attractive and repulsive forces. Therefore, it can be concluded that in this paradigm, the model will work well in the hindered situation. In unhindered situation, the movement is hard to simulate, unless the model creates another sub-model that generates the current force field as shown by Xiao (2014)

3.4.2. Vessel Encounters in Artificial Potential Field

The APF models can use several methods to detect the possibility of an encounter. The most common one is by generating the repulsive force field around an object such as a ship, fixed objects, or channel bank. Once a vessel is in the field, it will react to the force and change its dynamic behavior. The sum of forces obtained by the vessel will decide how much it will change its dynamic behaviors. In some models, the force field is given in layers, and this concept is similar to the ship domain concept with a fuzzy characteristic. In a fuzzy ship domain, the probability and risk for collision depend on which area the vessel sails. The closer the vessel to an obstacle, the higher the probability and risk for collision. Rong et al. (2015) The example of this fuzzy ship domain is given in the Equation 3-21 by Rong et al. (2015) as follows:

$$\vec{F}_{rep}(\vec{D}) = \begin{cases} \infty, & if \ \| \vec{D}_{tar_j}(t) - \vec{D}(t) \| - A \leq \rho_0 \\ -\dfrac{\partial \vec{U}_{rep}(\vec{D})}{\partial \vec{D}}, & if \ 0 < \| \vec{D}_{tar_j}(t) - \vec{D}(t) \| - A \leq \rho_0 \\ 0, & if \ \| \vec{D}_{tar_j}(t) - \vec{D}(t) \| - A > \rho_0 \end{cases} \tag{3-21}$$

Where $\| \vec{D}_{tar_j}(t) - \vec{D}(t) \|$ is an absolute distance between the target ship and own ship, $\frac{\partial \vec{U}_{rep}(\vec{D})}{\partial \vec{D}}$ is the repulsive force generated by the obstacle, A and ρ_0 are the parameters of the model.

With a similar concept but a different description, Xiao (2014) gives a distance limit to start the repulsive force. The model does a statistical analysis of AIS ship tracks with encounter to study the time when a vessel needs to maneuver. This time value is given in a normal distribution, and a number is picked from a randomization method. Once the distance limit is infringed, a vessel will start to maneuver. The repulsive force and the influence range for head-on and overtaking encounter are given in Equation 3-22 and 3-23 below:

$$F = \begin{cases} \dfrac{k_{obst}}{D^n}, & if \ \mathrm{D} < \mathrm{D}_s \\ 0, & otherwise \end{cases} \tag{3-22}$$

$$D_{s\,-\,head-on} \sim N(1548, 706^2) \tag{3-23}$$

$$D_{s\,-\,overtaking} \sim N(384, 358^2)$$

F denotes the force exerted by the obstacles, k_{obst} is a constant and a function of ship type, size and speed, and n indicates the steepness of the repulsive potential. D is the shortest distance between the ship and the obstacles, and the D_s represents the threshold value for the forces, so if D is larger than D_s, the exerted force is zero.

In detecting an encounter and quantifying the ship-ship interaction, it is also possible to embed the CPA method in the paradigm. In the model by Xiao et al. (2013), once a vessel is in the force field, the model will generate a link between two vessels to determine the distance between both vessels. This distance is the main parameter for the vessel behavioral change. This concept indicates that it is possible to apply the CPA method.

The other checking to ensure a safe maneuver is presented in the repulsive force field generated by another vessel or waterway bank. This force field around a vessel makes sure that the lateral and longitudinal distance is clear to maneuver. The repulsive force exerted from the banks ensure there will be no collision at the bank. The time to start the maneuver can be taken immediately after the vessel sense the force field or determined by a fuzzy domain concept. The fuzzy domain concept simulates a real navigator behavior of taking a fast and optimal time maneuvering execution, and it portrays uncertainty of the navigator for taking a maneuver accordingly. Besides the fuzzy domain, a randomization method, as shown in the model by Xiao et al. (2013), is also possible to be embedded in this paradigm. So, a set of possible time to maneuver is given in the distribution. For each maneuver, the model will pick one random value when it needs to maneuver. The value in the distribution is obtained from observation of the traffic condition in the application area.

- **Overtaking**

The overtaking maneuver degree is determined by a repulsive and attractive force. Rong et al. (2015) specify the repulsive force from the target ship with the Equation 3-11. A detailed behavior during vessel overtaking maneuver is shown by Xiao (2014). The model generates different forces in the beginning, during, and after maneuvering. The side where the vessel should maneuver is determined by repulsive at the waterway bank. So, the traffic rule to which direction a vessel should maneuver is implicitly embedded in these forces. Only in this model, the evasive maneuver is done by both vessels. The overtaking ship deviates to port, while the overtaken ship slightly deviates to starboard to avoid a collision. During the maneuver, $F_{overtaken}$ from port and ΔF_{bank} should be balanced. From the study done in this model, besides the distance between a vessel to the waterway bank, the length of a vessel also has a strong correlation to the bank forces. A longer vessel needs to deviate more than the short one. These two factors (distance to waterway bank and vessel length) become inputs to Equation 3-24 and Equation 3-25. The overtaking encounter process is shown in Figure 3-11 and 3-12:

$$\Delta F_{bank} = F_{bank,p}(L_2) - 0 = 168260 \,.\, \frac{LOA}{L_2^3} \qquad (3\text{-}24)$$

$$F_{overtaking} = \Delta F_{bank} \sim N(6.87, 6.3^2) \qquad (3\text{-}25)$$

$$F_{overtaken} = \Delta F_{bank} \sim N(2.27, 6.8^2)$$

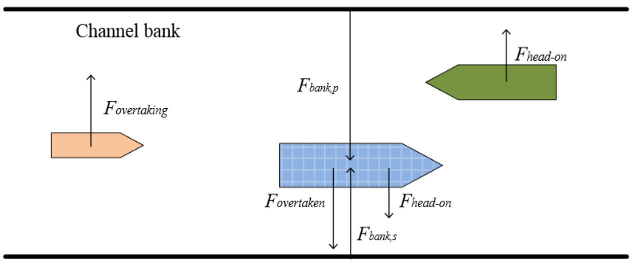

Figure 3-11 Artificial potential forces in encounters

(Source: Xiao (2014). Ships in an Artificial Force Field: A Multi-agent System for Nautical Traffic and Safety)

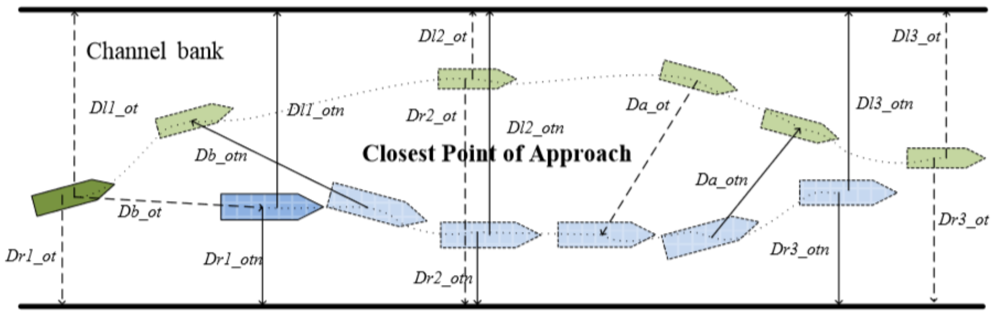

Figure 3-12 Overtaking sequences in an artificial potential field

(Source: Xiao (2014). Ships in an Artificial Force Field: A Multi-agent System for Nautical Traffic and Safety)

So far, only the model by Xiao (2014) simulates the movement of both ships during the overtaking encounter. This model can show a real sailing behavior during overtaking where the own ship moves to one side and the target vessel slightly deviate to the other side. This kind of details can be beneficial to assess the safety of a waterway area with restricted width. However, all models have the potential to specify which vessel(s) and to which direction it should maneuver by assigning the role of vessels and controlling the magnitude of forces.

- **Head-on**

Both models, Rong et al. (2015) and Xiao (2014) describe head-on in the same behavior as the overtaken ship in the overtaking encounter. In the head-on encounter, the ship will slightly deviate from its original position. The head-on force in the model by Xiao (2014) is given in Equation 3-26, and the head-on encounter process is displayed in Figure 3-13

$$\boldsymbol{F_{head-on}} = \Delta \boldsymbol{F_{bank}} \sim \boldsymbol{N}(\mathbf{2.27, 6.8^2}) \qquad (3\text{-}26)$$

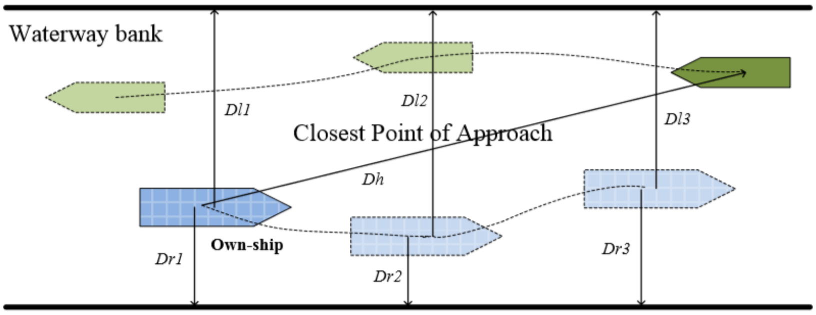

Figure 3-13 Head-on sequences in an artificial potential field

All models assume that in the head-on encounter, both vessels will behave like the overtaken vessel. From the Equation 4-26, the force exerted by the model is small compared to the force for an overtaking vessel. Both vessels are assigned to deviate slightly and behave similarly. For safety analysis purpose, the model by Xiao (2014) has a potential to improve a more detail movement by adding force distributions for different kind of vessels. By this approach, the maneuvering behavior between two vessels will not be similar.

In summary, the APF paradigm shows good potential in simulating the nautical traffic model, especially in the restricted waterway and in a hindered situation. The traffic rule can be assigned to both vessels, and the maneuvering action can be done by both vessels with help from the repulsive and attractive forces exerted by the waterway bank and vessels. During the maneuvering process, the speed and course are often given with flexibility to change. Both vessels can be assigned to take specific maneuvering actions. Despite only overtaking and head-on encounters are found in the models, the crossing encounter is also possible to be simulated. In the nautical traffic models, vessel trajectory is often predetermined, and the vessel will keep following the route unless there are obstacles detected. In embedding the crossing encounter, the vessel will follow the route, and if maneuvering is needed, then the maneuvering degree will be controlled by the banks and the encountered vessel. Therefore, the absence of crossing encounter is due to the modeling application purpose.

3.5. Optimal Control Models

OC paradigm deals with the problem of finding a control law for a given system such that a specific optimality criterion is achieved. In this paradigm, a vessel is described in a state equation, and vessel behaviors are driven by control functions based on the output given by the minimization task and the constraints the model possesses. These control functions and minimization task is managed by so-called “navigator” or “bridge team.” So, a vessel should achieve its goal with the constraints that it possesses by finding a minimum disutility/cost. The general process of the OC model is given in Figure 3-14.

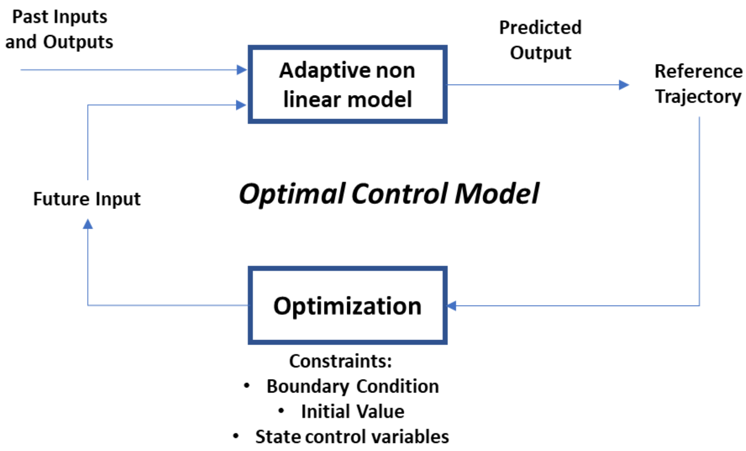

Figure 3-14 Optimal control paradigm process

3.5.1. Vessel Behavior Representation in Optimal Control

The state equation contains dynamic vessel behavior such as position, SOG, COG, heading, and control variables. In OC models, a vessel is defined as a state denoted by $\vec{\xi} = (x, y, v, \theta)$ where x and y denote the position of a vessel, v, and θ represent the vessel speed and course, respectively (Shu et al., 2015a). In the state equation by ten Hove and Wewerinke (1990) more parameters are included such as rate of turn (R) and heading (ψ), $\vec{\xi} = (x, y, v, \theta, R)$. A more detailed state is given by a model by Lisowski, (2014, 2012), $\vec{\xi} = (x, y, v, \theta, R, \beta, n, H)$, where β, n, H represent the drift angle, rotational speed of the screw propeller, and the pitch of the adjustable propeller of the own ship.

Besides the state, there are dynamic constraints and control variables equations. It is often called the first-order dynamic constraint. The state control variable in the model by Shu et al. (2017, 2015a) is given in the Equation 3-27 as follows:

$$\dot{x} = v\cos\left(\frac{\pi}{2} - \theta\right) \qquad (3\text{-}27)$$

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

$$u_1 = \dot{v}$$

$$u_2 = \dot{\theta}$$

In a model by ten Hove and Wewerinke (1990), instead of controlling the rudder angle implicitly in a longitudinal acceleration, this model controls the rudder angle in an explicit equation to optimize the speed, longitudinal and angular acceleration of a vessel. In this model, the heading is separated from the course. There are also additional random system disturbances (W_1 and W_2) and constant current components $\dot{x}_s$ and $\dot{y}_s$ resulted from a non-linear equation optimization. The set of state control variable from ten Hove and Wewerinke (1990) are given in Equation 3-28.

$$\dot{x} = v\cos(\theta) + W_1 + \dot{x}_s \qquad (3\text{-}28)$$

$$\dot{y} = v\sin(\theta) + W_2 + \dot{y}_s$$

$$\dot{v} = a\,v + b\,\Delta v$$

$$\dot{R} = -\frac{1}{T}R + \frac{K}{T}\delta$$

$$\dot{\theta} = \dot{R}$$

$$u_1 = \dot{\Delta v}$$

$$u_2 = \dot{\delta}$$

The model by Lisowski (2014, 2012) describes the control variable even more detailed than the previous models has been introduced. Besides acceleration and rudder angle, the model controls pitch (H) and the rotational speed of the propeller (n). Also, the other ship course and speed are included in order to model an optimum ships encounter. The set of state control variable by Lisowski (2014, 2012) is presented in the Equation 3-29. The subscript *j* indicates the variable of a target vessel.

$$\dot{\theta} = R \qquad (3\text{-}29)$$

$$\dot{R} = a_1 R v + a_2 v|v|\beta + a_3 v|v|\delta$$

$$\dot{v} = a_4 v|v||\beta|\beta + a_5 v|v|\beta^2 + a_6 R\beta|\beta| + a_7 R v\beta|\beta| + a_8 v|v| + a_9 n|n|H + a_{10} v|v|\beta\delta$$

$$\dot{\beta} = a_4 v\beta + a_5 v\beta|\beta| + a_6 R\beta + a_{10} v\delta + a_{11} R$$

$$\dot{n} = a_{12} n + a_{13} n_r$$

$$\dot{H} = a_{14} H + a_{15} H_r$$

$$\dot{D}_j = -v + N_j R + \theta_j \cos\theta_j$$

$$\dot{N}_j = -R D_j + \theta_j \sin\theta_j$$

$$\dot{\theta}_j = -R + a_{16}\theta_j\theta_j$$

$$\dot{v}_j = a_{17} v_j|v_j| + a_{18} v_j$$

$$u = (\delta, n, H, \theta, V)$$

All models presented in this paradigm have the potential to assess the maneuvering behavior of a ship considering the vessel characteristic, encounters, and traffic state. Ships typically control their motions by altering speed and rudder angle (Thomas and Sclavounos, 2007). The rudder needs to be kept in a certain angle and time to maintain the course angle. Because of these typical control variables, most of the models use a speed change and rudder angle as their control variables in the optimal control equation, except Shu et al. (2017, 2015a) that uses a course change instead of rudder angle.

Explicitly including a rudder angle in the equations have an up and downside. In one hand, the addition of the rudder angle represents a more detailed analysis to assess the human operator behavior during a maneuver. On the other hand, more variables can generate noise/error. The vessel dynamic behavior representation will give more information on vessel behavior compared to the other variables. It is also important to be used for validation. Therefore, predicting the optimum dynamic behavior representation is more important. For example, the course angle is often formulated as a function of the rudder angle. So, predicting the optimum rudder angle first before the course instead of directly predicting the course will create more noises/error. The argument also holds for the model by Lisowski (2014) that gives many detail variables such as drift angle, the rotational speed of the screw propeller, and the pitch of the propeller. The model with many control variables will give a deep insight of how those variables could affect the ship movement. However, it is a trade-off to the model accuracy.

In summary, OC paradigm describes the vessels dynamic information with the highest level of details set up in this research modeling criteria. Most of the modeling purpose in this paradigm is to assess the safety of vessels in traffic, and such a purpose requires a high level of vessel behavior description. So, a high level of vessel dynamic behaviors description is due to both, the application purpose requirements and the paradigm's capability. Specifically for heading, the separation of heading and course only present in a model by ten Hove and Wewerinke (1990), the other models still deemed it as a course. However, the paradigm has a potential of adding the heading feature can be separated from course by adding the heading mathematical equation.

3.5.2. Vessel Encounters in Optimal Control

The OC paradigm aims to optimize vessel behavior during sailing for any circumstances and external conditions listed in OC constraint functions. During the evasive maneuver, it can be predicted that the action taken by a vessel will be done as fast and as effective as possible.

In detecting a possible encounter, the OC models use various methods; there is CPA (ten Hove and Wewerinke, 1990), influence range (Shu et al., 2018), and combination of both (Lisowski, 2014, 2016). The influence range by Shu et al. (2018) has an elliptical shape with radius R. This range assumes that a larger vessel leads to a more significant influence distance. This ellipse radius is a function of the vessels length, width, and the angle between own ship course and the connection line between two encountering vessels (γ). The safety domain is formulated in the Equation 3-30 as follow:

$$R(\gamma) = \frac{ab}{\sqrt{a^2 \sin^2 \gamma + b^2 \cos^2 \gamma}} \quad (3\text{-}30)$$

$$a = p \frac{L_A + L_B}{2}$$

$$b = q \frac{B_A + B_B}{2}$$

Where p and q are scaling coefficient of the vessel length, L_A and L_B correspond to vessel lengths and B_A, and B_B denotes the vessel width.

Instead of defining the ship domain by distance only, the model by (Lisowski, 2014) assumes the shape of a circle, hexagon, or parabola. This ship domain is based on a safe distance in certain visibility condition at sea based on the COLREG rules and vessel behavior. Although it is not mentioned the reason behind the chosen shape of the domain, from the illustration given in the paper, it could be interpreted that the closer an encountered ship to the own ship the more distorted the shape from a circular shape as shown in Figure 3-15. This ship domain becomes a constraint for the own ship to sail towards its goal. The safety domain itself is a function of another ship state and control as expressed in the Equation 3-31 below:

$$g_j(x_j\,;\,u_j) \leq 0 \quad (3\text{-}31)$$

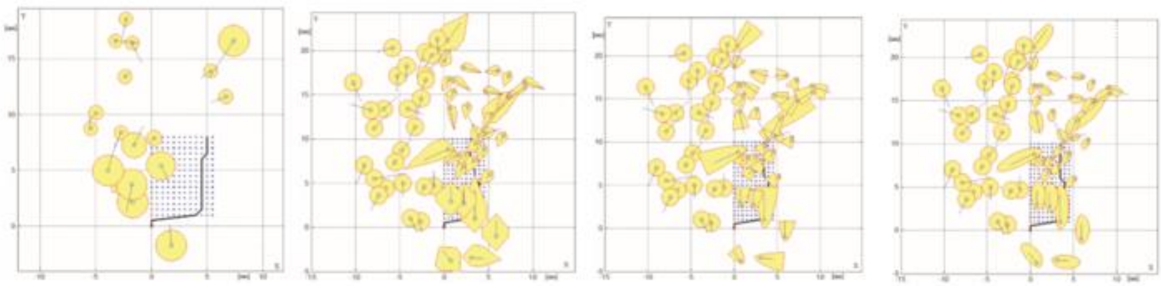

Figure 3-15 Various shapes of ship domain

As mentioned before, in the OC paradigm, an own vessel takes into account its target vessel(s) to decide when and how to maneuver. In a simple mechanism, the model by Shu et al. (2018) includes the relative position between the simulated vessel and the encountered vessel in the objective function, as shown in the Equation 3-32. In this equation, the proximity cost increase when the distance between vessels smaller, and if the distance is larger than the ellipse radius (R), the proximity cost is zero. An optimum maneuver track and speed is obtained by minimizing the proximity cost in the objective function. The interaction between ships is included in a non-linear model by predicting the target ship state and the collision interaction state between both vessels. The proximity cost for overtaking is given in the equation follow:

$$L^{prox} = \begin{cases} c_1(e^{-\frac{D}{R}} - e^{-1}), & D < R \\ 0, \; D \geq R \end{cases} \tag{3-32}$$

Where c_1 is the weight factors for the proximity cost defined based on the relative position between the simulated vessel and the encountered vessel (D). In the equation, the proximity cost increase when the distance between vessels smaller, and if the distance is larger than the ellipse radius (R), the proximity cost is zero.

In a more advanced model as shown by Lisowski (2014, 2016) and ten Hove and Wewerinke (1990), a vessel predicts the most optimum and safe trajectory by predicting another vessel(s) state and minimizing DCPA and TCPA. In the model by Lisowski (2014), the navigator decides the encounter occurrence by predicting the state of an own ship (ξ_i), a target ship (ξ_j) and a collision avoidance state (ξ_{ij}). The prediction gives acceptable control values, and the values become an input to the three states in the next time step. After that, ξ_{ij} is compared with the criterion value to take an evasive action ξ_{cij}, if ξ_{ij} is smaller than ξ_{cij}, then the evasive maneuver is done by an own vessel; otherwise, there is no action taken. After the maneuver is done, the own ship will resume its original route. The interaction between vessels is formulated in the equation 3-33

$$\dot{\xi}_{cij}, = (\mathbf{D}, \mathbf{DCPA}, \boldsymbol{TCPA}) \tag{3-33}$$

$$\dot{\xi}_{cij} = \begin{bmatrix} ((x_j - x_i)^2 + (y_j - y_i)^2)^{\frac{1}{2}} \\ \dfrac{(v_j \cos\psi_j - v_i \cos\psi_i)(v_j - v_i) - (v_j \sin\psi_j - v_i \sin\psi_i)(x_j - x_i)}{(v_j^2 + v_i^2 - 2v_j v_i \cos(\psi_j - \psi_i))^{\frac{1}{2}}} \\ \dfrac{(v_j \cos\psi_j - v_i \cos\psi_i)(x_j - x_i) - (v_j \sin\psi_j - v_i \sin\psi_i)(y_j - y_i)}{v_j^2 + v_i^2 - 2v_j v_i \cos(\psi_j - \psi_i)} \end{bmatrix}$$

With a more detailed approach, Lisowski (2014, 2012) simulates two types of optimization models. The first one is the multi-stage positional game; the essence of this game is to subordinate a strategy of the own ship to the current position of the encountered vessels. With the multi-stage game, the model takes into account any possible alterations of the course and speed of the encountered vessels while steering is in progress (multi-vessels encounter). Therefore, the steering of the own ship will be dependent on the acceptable strategies of the other ships. The multi-vessels encounter is out of the scope of this research. The second one is a multi-step matrix game; this control algorithm determines game and safe trajectory of the own ship with relation to the most dangerous ship only. In this game, DCPA and TCPA calculation are included in a risk equation, as shown in the Equation 3-34. The model sets acceptable control strategies by both vessels ($u_{i,}u_j$) by minimizing the risk of an own ship and maximizing the target ship, the minimization function is presented in the Equation 3-35. This approach is similar to the one possessed by ten Hove and Wewerinke (1990). The state of a vessel and control are simplified as seen in Equation 3-36 and 3-37.

$$r_j = \left[\alpha_1 \left[\frac{DCPA}{D_s}\right]^2 + \alpha_2 \left[\frac{TCPA}{T_s}\right]^2 + \left[\frac{D}{D_s}\right]^2\right]^{-\frac{1}{2}} \tag{3-34}$$

$$I = \min_{u_i} \max_{u_j} r_j \tag{3-35}$$

$$\dot{\xi}_{cij'} = f_{ij}\ (\mathbf{D}, \mathbf{N}) \tag{3-36}$$

$$u = (\dot{v}_i, \dot{v}_j, \dot{\theta}_i, \dot{\theta}_j) \tag{3-37}$$

Where D_s and T_s are the safe distance and time to start collision maneuver and D is the actual distance between two vessels. Both alfa coefficients in the Equation 4-34 are dependent on the sea visibility, kind of water region, and the dimensions of a ship.

The OC paradigm can embed two types of encountering detection, the ship domain, CPA, or both. The reason why the models use a different kind of detection is due to the application purpose and modeler judgment. The model by Shu et al. (2018) considers the ship domain because the model wants to assess the interaction between vessels in ports and waterways while the other model focuses on open water area where the maneuvering movement is more flexible than in confined water.

From the elaboration above, the time to maneuver can be immediately after the detection (Shu et al., 2015b, 2015a, 2018), or in a higher level, the optimum time to maneuver is calculated. In ten Hove and Wewerinke (1990) and Lisowski (2014), TCPA is inputted in the minimization function. So, the time to start a maneuver is the time when the collision risk is the lowest.

In summary, all models focus on finding the safest and most optimum sailing trajectory. The OC paradigm can show the interaction between the vessels by setting up an acceptable strategy for both vessels during encountering that includes the state of both vessels. OC paradigm will predict the other vessel state and make a strategy for the own ship to avoid a collision. Both models (Lisowski, 2014; ten Hove and Wewerinke, 1990) formulates the optimization function by adding the DCPA and TCPA calculation. By minimizing DCPA and TCPA, the models can find an optimum strategy of encountering. The strategy includes how, and when or where a vessel should maneuver. Both models embed the traffic rule specified by COLREGs. In the model by Shu et al. (2018), there is no traffic rule identified applied to both ships. The model only considers the distance between two vessels without any interaction. This OC paradigm has the potential to determine a safe trajectory for a ship in a multi-vessels encounter (Lisowski, 2014).

- **Overtaking**

All models in this paradigm assign an own ship to maneuver, while the other ship is privileged to have the right of way during the overtaking process. There is no information regarding which direction (port or starboard), the own vessel should maneuver. This maneuver is achieved by an acceptable control strategy by both own and target vessel. Looking at the equations used, all models have the potential to choose the overtaking direction to any side.

- **Head-on**

For this type of encounter, all models simulate both vessels to make an evasive maneuver to starboard. Since both models explicitly stated the maneuvering direction, both vessels would not alter their course to port.

- **Crossing**

ten Hove and Wewerinke (1990) and Lisowski (2016) apply the COLREGs rule in a crossing encounter, where the starboard ship is privileged, and the port ship needs to maneuver towards starboard. Both models also give an alternative that allows a maneuver to the port side if the starboard side is not possible. The alternative predicts a better safe trajectory by giving more flexibility and more options of the maneuvering direction.

Based on the elaboration of the encounters, the direction of which the vessel(s) should alter the course is given by rules. The alteration direction in overtaking and crossing are flexible in the models although the maneuvering action is done only by an own vessel and the other ship maintain its right of way. The models only focus on one vessel movement, so the action to maneuver can be assigned for own vessel only. In a head-on encounter, the models often assign both ships to maneuver to one specific side only (port-to-port). However, the flexibility to maneuver in this type of encounter is possible if the model meets an acceptable strategy in the encountering minimization function.

In conclusion, it can be summed up that the OC paradigm can simulate the thinking processes of a navigating officer steering of own ship and making decisions on maneuvers. This paradigm is suitable to simulate the human sailing behavior (bridge team) to predict safe and optimum navigation during sailing when encountering several vessels. All modeling application purpose can be simulated with this paradigm except the one for the bridge team since the bridge team needs a real-time simulator, and it needs more vessel maneuvering details. In addition, looking at the models, the OC paradigm has the potential to construct a model and represent the vessel behavior without relying too much on AIS data. With the calibration for optimized parameters. It is expected that the model can be used in any other area.

3.6. System Dynamics Models

System dynamics (SD) is a methodology and mathematical modeling technique to frame and understand complex issues and problems. It can represent a complex network of cause-and-effect relationship through which such effects propagate. The model can quantify the costs of indirect effect and trace back to specific conditions.

3.6.1. Vessel Behavior Representation in System Dynamics

SD model describes either the motions of a vessel or the vessel dynamic behavior. The motions of a vessel are defined in the second-order equations, while the dynamic behaviors are given in the first-order equation. All vessel behavior representation can be shown in this paradigm with a high level of description. Besides of the vessel movement, the paradigm can describe the equations of motion up to six degrees of freedom (heave, yaw, roll, pitch, sway, surge) as shown in Figure 3-16 for the model-based simulation. The left side of the equation often describes either the dynamic behaviors of a vessel such as speed, position, speed, and course or the mass balance equations for describing the motions of a ship. The right side of the equations usually contains the external forces such as the impact of hull, rudder, and propeller. The advanced description is due to the modeling application purpose that mainly focuses on a single vessel movement/motion. The paradigm can consider all parameters that might impact the vessel movement/motion, such as environmental factors, vessel sub-modules, hydrodynamics factors, etc.

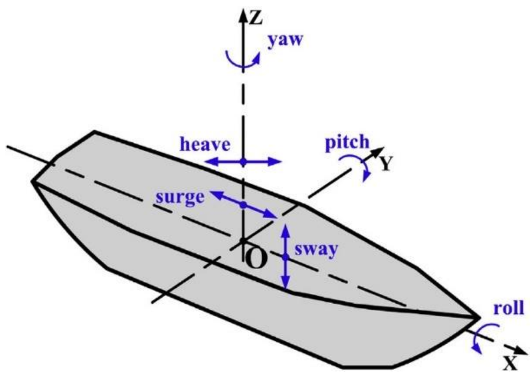

Figure 3-16 Global Coordinate System (UMS)

In the first-order system dynamic model by Beschnidt and Gilles (2005), the movement model adopts a first-order Nomoto model with some modification by Zimmermann and Gilles (2017). The model describes the longitudinal and lateral dynamics of the vessel movement as first order delay relations with nonlinear coefficients, as shown in Equation 3-38.

$$\dot{x} = v \sin\psi + L_l \omega \cos\psi + L_q \omega \sin\psi \qquad (3\text{-}38)$$

$$\dot{y} = v \cos\psi + L_l \omega \sin\psi + L_q \omega \cos\psi$$

$$\dot{v} = \frac{1}{T_l(v)}\left(-v + K_l(n_s, n_p)\right)$$

$$\dot{\omega} = \frac{1}{T_q(v)}\left(-\omega + K_q(v)\delta + K_d(v, n_s, n_p)\right)$$

$$\dot{\psi} = \omega$$

Where L_l and L_q denote the distance of the arbitrarily chosen ship reference point to the actual centroid. T_q and T_l denote the speed-dependent time constant for the lateral and longitudinal movement, respectively. K_q and K_d are the sets of nonlinear curves to take into account the properties of different vessel type. These K_q and K_d are functions of n_s and n_p, which are the machine revolutions from the starboard and port, respectively.

In the other models, a set of second-order equations to describe the ship motions is used. The equations details can be varied due to the simplification of the modeling study area and assumption. A further simplification can also be done by a close-fit method. So, instead of adding an unknown parameter, some terms can be written as a coefficient. Equation 3-39 describes ship motion in four degrees of freedom by Nomoto (Sariöz and Narli, 2003; Sarıöz et al., 2002) :

$$\textbf{Surge: } m\left[\dot{u} - rv - x_G r^2\right] = X_H + X_R + X_P + X_{EXT} \tag{3-39}$$

$$\textbf{Sway: } m\left[\dot{v} - ru - x_G \dot{r}\right] = Y_H + Y_R + Y_P + Y_{EXT}$$

$$\textbf{Yaw: } I_Z \dot{r} + m x_G(\dot{v} - ur) = N_H + N_R + N_P + N_{EXT}$$

$$\textbf{Roll: } I_X \dot{p} = K_H + K_R + K_P + K_{EXT}$$

Where m is the mass of the ship; u and v are ship velocities in x and y axes; r and p are yaw and roll rates; I_x and I_z are hull moments of inertia; X and Y are hydrodynamic and external forces in x and y axes; K and N are moments acting on the maneuvering ship; H, R, P, and EXT subscripts denote hull, rudder, propeller and external forces. The model also gives an additional equation to describe the response of the propulsion system to external forces as follows:

$$2\pi I_P \dot{n} = Q_E + Q_P \tag{3-40}$$

Where Q_E and Q_P denote the propeller torque and the main engine torque respectively; n is the propeller speed, and I_P is the propeller moment of inertia.

Even more detailed, the model by Fang et al. (2018) describes the ship motions in six degrees of freedom and more parameters involved. The model presents the highest details of ship motions among all of the models studied in this research. A set of equation motions is given in the Equation 3-41.

$$
\begin{aligned}
& m\left(\dot{u}-v\dot{\Upsilon}\right)=\left(m_y-X_{v\dot{\Upsilon}}\right)v\dot{\Upsilon}-m_x\dot{u}-m_z w\dot{\rho}+X_{FK}+X_{RF}+T\left(1-t_p\right)-R \qquad (3\text{-}41)\\
& m\left(\dot{v}-u\dot{\Upsilon}\right)=-m_x u\dot{\Upsilon}-m_y\dot{v}-Y_v v+Y_{\dot{\Upsilon}}\dot{\Upsilon}+Y_{v|v|}v|v|+Y_{v|\dot{\Upsilon}|}v\left|\dot{\Upsilon}\right|+Y_{\dot{\Upsilon}|\dot{\Upsilon}|}\dot{\Upsilon}\left|\dot{\Upsilon}\right|\\
& \qquad +Y_{FK}+Y_{DF}+Y_{RF}\\
& m\dot{w}=-m_z\dot{w}-Z_w w+Z_{\ddot{\rho}}\ddot{\rho}-Z_{\dot{\rho}}\dot{\rho}-Z_{\rho}\rho+Z_{FK}+Z_{DF}+mg\\
& I_x\ddot{\Gamma}-I_x\dot{\rho}\dot{\Upsilon}=J_x\dot{\rho}\dot{\Upsilon}-J_x\ddot{\Gamma}-K_{\dot{\Gamma}}\dot{\Gamma}+\left(Y_v v-Y_{\Upsilon}\dot{\Upsilon}\right)Z_H+K_{FK}+K_{DF}+K_{RF}\\
& I_y\ddot{\rho}+I_x\dot{\Gamma}\dot{\Upsilon}=-J_x\dot{\Gamma}\dot{\Upsilon}-J_y\ddot{\rho}-M_{\dot{\rho}}\dot{\rho}+M_{\rho}\rho-M_{\dot{w}}\dot{w}+M_w w+M_{FK}+M_{DF}\\
& I_Z\ddot{\Upsilon}+I_x\dot{\rho}\dot{\Gamma}=J_x\dot{\Gamma}\dot{\rho}-J_x\ddot{\Upsilon}-N_{\dot{v}}\dot{v}+N_v v-N_{\dot{\Upsilon}}\dot{\Upsilon}+N_{\dot{\Upsilon}|\dot{\Upsilon}|}\dot{\Upsilon}\left|\dot{\Upsilon}\right|+N_{vv\dot{\Upsilon}}v^2\dot{\psi}+N_{v\dot{\Upsilon}\dot{\Upsilon}}v\dot{\Upsilon}^2\\
& \qquad +N_{\Gamma}\Gamma+N_{v|\Gamma|}v|\Gamma|+N_{\dot{\Upsilon}|\dot{\Gamma}|}\dot{\Upsilon}|\Gamma|+(-Y_v v+Y_{\dot{\Upsilon}}\dot{\Upsilon}+Y_{v|v|}v|v|\\
& \qquad +Y_{v|\dot{\Upsilon}|}v\left|\dot{\Upsilon}\right|+Y_{\dot{\Upsilon}|\dot{\Upsilon}|}\dot{\Upsilon}\left|\dot{\Upsilon}\right|)x_H+N_{FK}+N_{DF}+N_{RF}
\end{aligned}
$$

Where m and I are ship mass and mass moment of inertia respectively. X, Y, and Z are external forces with respect to surge, sway, and heave. K, M, and N are external moments concerning roll, pitch, yaw. u, v, and w are a surge, sway, and heave velocities, respectively. Γ, ρ, and ϒ are a roll, pitch, and yaw displacement, respectively. m_x, m_y, and m_z terms denote the added mass with respect to x, y, and z axes respectively and $J_{xx}, J_{yy,}$ and J_{zz} represent the added moments of inertia with respect to x, y, and z axes, respectively. I_{pp}, Q_E, and Q_P denotes the moment of inertia of the propeller-shafting system, the propeller torque, and the main engine torque, respectively. The subscript FK, DF, and RF represent the Froude-Krylov, the diffraction and the rudder forces, respectively. Besides the set of equations given above, Fang et al. (2018) includes the Equation 3-40 in his model.

The set of equations in this system dynamic model can also be further simplified, for instance, if a vessel sailing in a constant velocity, the nonlinear constants in $\dot{\omega}$ are eliminated as such the relative speed ($\dot{v}$) is zero. Or, the model can assume that the principal axes of inertia of the ship are parallel to the chosen axis system (the ship is symmetric about its center plane), and the roll angles are small. In this case, heave and pitch can be ignored (Sariöz and Narli, 2003; Sarıöz et al., 2002).

The first-order model is practical, while the second-order model possesses a much better hydrodynamic derivation that can be used for tuning the full-mission models. Modeling the vessel dynamics using the first-order equation represents a simplification of the real vessel sailing behavior. Studies have shown that the parameter values of higher-order model are hard to identify and the magnitude effects of the resulting higher accuracy of the model system behavior are in the same order with the disturbance

(Zimmermann and Gilles, 2017). Therefore, in a model by Beschnidt and Gilles (2005), first-order differential equations are used to describe the vessel dynamics.

The paradigm can define the mode as an agent-based or adopt a modularity concept. The agent-based model is generic for all kind of vessels and all situation. For instance, if the model runs for a hundred times, the arrival behavior of a vessel in all simulations will be the same. Differently, in the model-based simulation, as shown by Sariöz and Narli (2003), the concept isolates the forces exerted by the separate components of the ship and accounting the interaction between various modules such as rudder and propeller into the equation of motion. Each module is designed by reference to the detailed physical analysis of the process being modeled. So, the system, in general, is modeled by combining the individual elements and expressing their interaction in a physical expression (ship motions). With this approach, the vessel movement, for instance, the arrival pattern of a vessel, can be different every time the model is run. Therefore, the system dynamic model can impose such detail movement behavior by considering the modularity of a ship.

3.6.2. Vessel Encounters in System Dynamics

The ship interaction during encountering maneuver needs to involve a complex hydrodynamic process which is difficult to predict in the simulation model. So instead, the interactions are employed in the simulation software based on a theoretical approach with empirical corrections based on model test results (Sariöz and Narli, 2003; Sarıöz et al., 2002). In the model by Fang et al. (2018), the maneuvering process is simplified by excluding environmental factors such as the wind, current, and waves. So instead of using Equation 3-41, the turning characteristic of a ship is defined in the second-order equation of motions proposed by Nomoto as shown in the Equation 3-42 and 3-43:

$$\boldsymbol{T_1 T_2 \ddot{R} + (T_1 + T_2)R + R = K\delta + KT_3\dot{\delta}} \qquad (3\text{-}42)$$

$$\boldsymbol{r(t) = K\delta\left\{1 - \frac{T_1 - T_3}{T_1 - T_2}\exp\left(-\frac{t}{T_1}\right) - \frac{T_3 - T_2}{T_1 - T_2}\exp\left(-\frac{t}{T_2}\right)\right\}} \qquad (3\text{-}43)$$

K, T_1 , T_2 and T_3 are the maneuvering indices and the formula is obtained from numerical simulation and regression technique for a specific type of vessel. The values are a function of the ship speed and rudder angle.

In avoiding the collision, the model by Fang et al. (2018) firstly compute the distance between two vessels and the heading angle of a target ship. Then the own ship will assume an initial rudder angle and calculate the maneuvering indices (K, T_1,T_2 and T_3) and these parameters become inputs to the Equation 4-43. After that, the model will create a sailing trajectory and predict if the own ship is collided with the target vessel in the fast time simulation. If there is a possible collision, the rudder angle will be increased; otherwise the effectivity of the chosen rudder angle will be processed further. With the chosen rudder angle, the safe distance generated between vessels should be over or equal to 300 m and not less than the 1 nautical mile; otherwise, the rudder angle needs to be further optimized. In addition, the time to start to maneuver is also predicted in this step.

In an encounter situation, only the own vessel will initiate an action; the other vessel is assumed to stay on a steady course. In a simple overtaking situation, the own ship may overtake the target ship from any side (port or starboard). In the crossing situation, a ship that approaching from the starboard side of another vessel will act to avoid a collision. Also, in head-on condition, only the own ship alter its course to starboard, so that each shall pass on the port side. With this helm order, the own ship starts to alter its course by changing the rudder. After the own ship safely passes the position at a safe distance, then the rudder angle will follow the helm order to turn back to its initial course using an autopilot algorithm. The course change is defined in detail in this model; however, the speed change in all encounters are predefined and to determine the encounter maneuvering indices.

With the information above, it can be concluded that the encountering process can be simulated with the highest level of details and accuracy. However, when the model involves a lot of vessels in an area, the ship-ship interactions are hardly incorporated due to the complexity of the hydrodynamic process, which is difficult to predict in the simulation. Also, this will cause a huge computational load. The SD paradigm that describes a lot of details in vessel movement and motion may have this problem. Therefore, some models use a theoretical approach with empirical correction based on the model test result. The simplification during encounter excludes the environmental factor. Since the coefficient is obtained by studying the behavior of a specific kind of vessel in a specific area, it indicates the limitation in applying such models for an area with various type of vessels due to lack of data for model parameter calibration.

3.7. Conclusion of The Paradigms

Based on the comparison of paradigms in this chapter, the models are indeed developed for different purposes and application areas. Although some models are developed in the same paradigm, the algorithms, modeling approaches, and rules are varied. The models that have a higher capability in describing vessel behaviors do not necessarily better than the other models in serving the modeling application purpose. Therefore, it is not justified to conclude that one model is better than the other because it depends on the modeling application purpose they serve. The summary of all models' capability in describing model application purpose requirement in this research is given in Table 3-1 to 3-6. The tables provide an assessment of what aspects and to which details the model describes the dynamic kinetic information and vessel encounter behaviors. The strip mark indicates that the models do not have the feature.

The dynamic kinetic information is manually defined or generated by historical distribution in most of the rule-based model and some mathematical-based models. The information is used for both, generates a traffic pattern for simulation, calibrate, and validation. The dynamic kinetic information is used in equations to change the vessel state; for instance: during a maneuver. The equation can be given in a simple kinematic equation, considering some detailed vessel modules, or including the hydrodynamical impacts. The equation details depend on the modeling purpose.

The difference between the rule and mathematical based models lies on how they control the vessel movement using the dynamic kinetic information. In general, the mathematical-based model has a higher potential in simulating all aspects of the dynamic kinetic information accurately compared to the rule-based paradigm. In rule-based model, the dynamic kinetic information is changed throughout the sailing process by behavior rules while in mathematical-based model it is controlled by functions. In CA paradigm, the information cannot be described accurately, and it approximates the information to the nearest value due to the discretization. The heading cannot be presented in CA paradigm since the vessel cells need to follow a straight discretized waterway route. The SRB and GRB paradigms have a higher potential in describing the information accurately because the space-state is continuous. For mathematical-based model, the functions can be controlled by sum of forces (APF), objective and constraint function (OC), and calculation of the whole sailing process factors (SD). So, for every time step, the vessel dynamic kinetic information can change flexibly. The accuracy and capability in describing the information depend on the modeling approach.

In describing the evasive maneuvering behavior, generally, all models assign the vessels to alter their course and speed. So, the mechanism and accuracy of the evasive maneuver relies on how the paradigms describe the dynamic kinetic information. Before performing a maneuver, usually several checks are done to determine what types of encounter a vessel faced and how to behave. The type of checking involved is varied depending on the modeler judgement. In general, the rule-based paradigm defines a simpler evasive maneuver behavior compared to the mathematical-based paradigm. The movement rules are often generic for every type of vessels and circumstances except for SRB paradigm. Due to the inclusion of the ship-ship interaction method such as CPA method, the paradigm can consider the vessels heterogeneity in the encounters. The rule-based paradigm can simulate more detailed maneuvering for specific vessels by adding more rules for a specific type of vessel. In the APF and OC paradigm, the models can simulate the maneuvering behavior between groups of vessels with similar inherent characteristics. In the APF paradigm, the vessel can choose its own course under the external impact; however, the unhindered vessel speed needs to be constructed from historical data. The OC paradigm can resemble human behavior in deciding an action to be taken during an encounter. This is obtained by setting an acceptable strategy considering the state of both vessels. The SD paradigm can describe the highest maneuvering detail in this research. The paradigm can integrate the hydrodynamic impacts into the vessel sub-modules. However, the specific maneuverability of a vessel in an area needs to be known beforehand, which is rarely known in most of the case. Also, due to high detail and complexity, especially when the model includes a variety of vessels, the computational time is huge. In the SD paradigm, integrating hydrodynamic force into ship-ship interaction is possible, but it is quite a challenge. In order to reduce that, the maneuvering equations are often simplified. The model often uses indices that obtained from numerical simulations of maneuvering histories and regression technique.

In summary, the rule-based paradigm is suitable to serve a model that does not need the maneuvering details and can simulate macroscopic traffic level that includes various kind of vessels. The mathematical-based is more suitable for a model that requires a higher level of vessel behavior description. In Chapter 4, the comparison between the paradigms is given to see the suitability of the paradigm in describing the modeling application purpose.

Table 3-1 Cellular automata model vessel dynamic behaviors and encounters summary

Model		Application Purpose	Dynamic Behavior				Vessels Encounters												
							Before			During									After
										Overtaking			Head-on			Crossing			
			P	S	C	H	Detection of The Encounter	Possibility To Manoeuvre	Time To Start a Manoeuvre	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic condition
	Cellular Automata																		
Cellular Automata	Qu and Meng (2012)	Traffic Flow Analysis	!	!	!	*	Safety Distance	Gap sufficiency (lateral and/or longitudinal)	Immediately after detection/no risk of collision	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with rules for overtaking vessel	-	-	-	Instant speed change	Vessel(s) manoeuvre to one specific side	Specified with rules for only give-way vessel	-
	Blokus-Roszkowska and Smolarek (2014)	Safety Assessment - Collision Probability and Risk	!	#	!	*	Safety Distance	-	-	-	-	-	-	-	-	No speed change	Vessel(s) manoeuvre to one specific side	Specified with rules for only give-way vessel	-
	Qi et al. (2017a,2017b)	Traffic Flow Analysis	!	#	*	*	Ship Domain	Gap sufficiency (lateral and longitudinal)	Immediately after detection/no risk of collision	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	Specified with rules for overtaking vessel	-	-	-	-	-	-	-

Table 3-2 Generic rule-based model vessel dynamic behaviors and encounters summary

Model		Application Purpose	Dynamic Behavior				Vessels Encounters												
							Before			During									After
										Overtaking			Head-on			Crossing			
			P	S	C	H	Detection of The Encounter	Possibility To Manoeuvre	Time To Start a Manoeuvre	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic condition
	Generic Rule Based																		
Generic Rule-Based Model	Thiers and Janssens (1998)	Traffic Flow Analysis	*	#	*	*	Safety Distance	Gap sufficiency forward and backward traffic check	Immediately after detection/no risk of collision	Target speed decelerates	No course change	Specified with rules for both vessels	-	-	-	Reduces speed for both vessels	-	Specified with rules for both vessels	*
	Almaz et al. (2006)	Traffic Flow Analysis	*	#	*	*	Safety Distance	Forward and backward traffic, vessel type	Immediately after detection/no risk of collision	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with rules for overtaking vessel	-	-	-	-	-	-	-
	Camci et al. (2009)	Traffic Flow Analysis	*	#	*	*	-	-	-	-	-	-	-	-	-	-	-	-	-
	Goerlandt and Kujala (2011)	Safety Assessment - Collision Probability and Risk	*	*	*	*	Safety Distance	Gap sufficiency (lateral)	Immediately after detection/no risk of collision	-	-	-	-	-	-	-	-	-	-
	Piccoli (2014)	Traffic Flow Analysis	*	#	*	*	Safety Distance	Gap sufficiency (lateral), rule of waterway section, vessel type	Immediately after detection/no risk of collision	No speed change/ own speed decelerate	No course change	Specified with rules for overtaking vessel	-	-	-	-	-	-	-
	Xu et al. (2015)	Traffic Flow Analysis	!	!	!	*	Safety Distance	Gap sufficiency (lateral)	Immediately after detection/no risk of collision	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with rules for both vessels	-	-	-	-	-	-	*
	Hasegawa (1990); Hasegawa et al. (2001, 2000)	Safety Assessment - Collision Probability and Risk	!	#	!	!	CPA	-	-	-	-	-	-	-	-	-	-	-	-

Table 3-3 Specific rule-based model vessel dynamic behaviors and encounters summary

Model		Application Purpose	Dynamic Behavior				Vessels Encounters												
							Before			During									After
										Overtaking			Head-on			Crossing			
			P	S	C	H	Detection of The Encounter	Possibility To Manoeuvre	Time To Start a Manoeuvre	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic condition
	Specific Rule Based																		
Specific Rule-Based Model	Li (2013)	Safety Assessment - Collision Avoidance	!	#	*	*	Ship Domain, CPA	Forward and backward traffic check, rule of waterway section	Immediately after detection/no risk of collision	Acceleration/Deceleration	No course change	Specified with rules for overtaking vessel	-	-	-	No speed change	Vessel(s) manoeuvre to one specific side	Specified with rules for only give-way vessel	*
	Miyake et al. (2015)	Collision Avoidance Behavior	!	#	!	!	Safety Distance, CPA	-	-	-	-	-	-	-	-	-	-	-	-
	Huang et al. (2016,2013)	Traffic Flow Analysis	!	!	*	*	CPA	Gap sufficiency (lateral and/or longitudinal)	Immediately after detection/no risk of collision	Instant speed change	Vessel(s) manoeuvre to one specific side	Specified with rules for overtaking vessel	Instant speed change	Two vessels alter the course to one specific side	Specified with same rules for both vessels	Instant speed change	Vessel(s) manoeuvre to one specific side	Specified with rules for only give-way vessel	*
	Aarsaether (2011)	Safety Assessment - Collision Avoidance	!	#	!	*	Safety Distance, CPA	Gap sufficiency (lateral and/or longitudinal)	Immediately after detection/no risk of collision	No speed change	Vessel(s) manoeuvre to one specific side	Specified with rules for overtaking vessel	No speed change	Two vessels alter the course to one specific side	Specified with same rules for both vessels	No speed change	Vessel(s) manoeuvre to one specific side	Specified with rules for only give-way vessel	*
	Watanabe et al. (2008)	Safety Assessment - Collision Avoidance	!	#	!	*	CPA	Gap sufficiency (lateral and/or longitudinal)	Immediately after detection/no risk of collision	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with rules for both vessels	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with same rules for both vessels	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with rules for both vessels	*

Table 3-4 Artificial potential model vessel dynamic behaviors and encounters summary

Model		Application Purpose	Dynamic Behavior				Vessels Encounters												
							Before			During									After
										Overtaking			Head-on			Crossing			
			P	S	C	H	Detection of The Encounter	Possibility To Manoeuvre	Time To Start a Manoeuvre	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic condition
	Artificial Potential																		
Artificial Potential Field Model	Xiao (2014)	Safety Assessment	!	#	!	*	Ship Domain	-	Determined by a specific parameter	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with rules for both vessels	Acceleration/Deceleration	Two vessels alter the course to one specific side	Specified with same rules for both vessels	-	-	-	*
	Rong et al. (2015)	Safety Assessment	!	#	!	*	Ship Domain	-	Determined by a specific parameter	Acceleration/Deceleration	Vessel(s) manoeuvre to one specific side	Specified with rules for both vessels	Acceleration/Deceleration	Two vessels alter the course to one specific side	Specified with same rules for both vessels	-	-	-	*
	Cheng et al. (2017)	Collision Analysis	!	#	!	!	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 3-5 Optimal control model vessel dynamic behaviors and encounters summary

Model		Application Purpose	Dynamic Behavior				Vessels Encounters												
							Before			During									After
										Overtaking			Head-on			Crossing			
			P	S	C	H	Detection of The Encounter	Possibility To Manoeuvre	Time To Start a Manoeuvre	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic condition
	Optimal Control																		
Optimal Control Model	ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	Safety Assessment - Collision Avoidance	!	#	!	!	Safety Distance, CPA	Safe trajectory prediction	Determined by a specific parameter	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	Specified with rules for both vessels	Acceleration/Deceleration	Two vessels alter the course to one specific side	Both vessels cooperate to take actions	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	Specified with rules for both vessels	*
	Shu et al. (2015a,2015b,2018)	Safety Assessment - Collision Avoidance	!	#	!	*	Ship Domain	-	Immediately after detection/no risk of collision	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	-	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	-	-	-	-	*
	Lisowski (2016)	Safety Assessment - Collision Avoidance	!	#	!	*	Ship Domain, CPA	Safe trajectory prediction	Determined by a specific parameter	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	Specified with rules for both vessels	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	Both vessels cooperate to take actions	Acceleration/Deceleration	Flexibility of choosing manoeuvring courses	Specified with rules for both vessels	*

Table 3-6 System dynamic model vessel dynamic behaviors and encounters summary

Model		Application Purpose	Dynamic Behavior				Vessels Encounters												
							Before			During									After
										Overtaking			Head-on			Crossing			
			P	S	C	H	Detection of The Encounter	Possibility To Manoeuvre	Time To Start a Manoeuvre	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic condition
	System Dynamic																		
System Dynamic Model	Beschnidt and Gilles (2005)	Ship Maneuvering	!	#	!	!	-	-	-	-	-	-	-	-	-	-	-	-	-
	Sariöz et al. (1999); Sariöz and Narli (2003)	Ship Maneuvering	!	!	!	*	-	-	-	-	-	-	-	-	-	-	-	-	-
	Fang (2018)	Safety Assessment - Collision Avoidance	!	#	!	!	Safety Distance	Safe trajectory prediction	Determined by a specific parameter	Instant speed change	Flexibility of choosing manoeuvring courses	Specified with rules for both vessels	Instant speed change	Flexibility of choosing manoeuvring courses	Both vessels cooperate to take actions	Instant speed change	Flexibility of choosing manoeuvring courses	Specified with rules for both vessels	*

4

DISCUSSION OF THE PARADIGMS

In this chapter, the paradigms will be discussed and compared to assess the suitability of the paradigms in serving a given modeling application purpose. For each application purpose from Subchapter 4.1 to 4.3, a recommendation of which paradigms suits the application purpose the most is given. Although a paradigm has a high capability of simulating the nautical traffic model does not necessarily mean it suits a particular modeling application purpose. Therefore, the paradigms are compared based on its capability in fulfilling the requirement and the suitability in describing specific modeling purpose. In Subchapter 4.4, the conclusion of this discussion is provided. A table of recommended paradigm to serve each modeling application purpose is provided based on the justification given in the previous subchapters.

4.1. Comparison of Paradigms for Port Authority

There are several paradigms that can be used by the port authority for a different model application purpose requirement. The paradigm includes all range of paradigms from the rule-based to the mathematical-based paradigm.

4.1.1. Traffic Flow Analysis

Since a high accuracy in describing vessel behavior is not necessary, a simple rule-based paradigm is a suitable option. The rule-based model is chosen due to its simplicity in describing the movement rules and a low computational load. The rule-based paradigm can simulate traffic in a wide and complex area and including a variety of vessels without going into unnecessary individual vessel behavior detail. Among the three paradigms, the CA and GRB. paradigms are advisable. The SRB paradigm is more suitable to serve a collision-related modeling purpose due to its capability in describing a better ship-ship interaction. The ability to embed the interaction is not necessary for this analysis.

The only thing that differs CA and GRB paradigm is the discretized space state in CA models. The discretization creates a huge impact on every aspect of vessel behavior representation, as mentioned in Chapter 3. The geometry of vessels and waterways and the maneuvering behavior in CA models will always be approximated. So, accuracy wise the GRB is more recommended to use if the detail in space state is needed. For efficiency, the CA paradigm provides a faster simulation output since it does not exhibit an extensive detail of vessel behavior. However, due to an increasing computation ability, the weight factor for computation time is lowering. Therefore, the GRB paradigm is chosen to be the best paradigm for a model that aims to analyze the traffic flow.

4.1.2. Safety Assessment – Collision Probability and Risk

In this assessment, the evasive maneuver does not necessarily have to be simulated. If the simulation shows that there is a near-miss collision, it is counted as one collision probability event. Therefore, the paradigm that is suitable for this purpose is the one that can detect the possibility of an encounter and quantify the degree of risk. In this research, it is found that all paradigms have the capability to do so. Since a detail of evasive maneuvering is not necessary, the rule-based paradigm (CA, GRB, SRB) is a good option.

The difference between those mentioned recommended paradigms are their capabilities in quantifying the collision probability and risk. The CA paradigm is only able to define a safety distance. Even though the safety distance can be a function of the target vessel state, the other two paradigms are better in quantifying the relative motion between two vessels. The GRB and SRB paradigms are capable of calculating the CPA method to quantify the collision probability and risk. With calculating CPA, the interaction between both vessels is considered. Thus, the detection of an encounter and the quantification of the degree of risk involved can be more accurate. Both the GRB and SRB are selected to be the most promising paradigms for assessing the safety of port area by computing the collision probability and risk.

4.1.3. Safety Assessment – Collision Avoidance

As mentioned in Chapter 2, the vessel behavior representation and evasive maneuvering behavior details are required in high details. Moreover, since it is important to take into account the heterogeneity between vessels in the encounter maneuvering, the mathematical-based paradigm (APF, OC, SD) is recommended to assess port safety.

Compared to the other paradigms, SD provides the highest accuracy in simulating vessel behavior. The paradigm is able to include the impact of forces (ex: hydrodynamic or waterway bank suction force) on different modules of vessels. However, due to high vessel behavior details that SD possess, the computational load is huge. To reduce the load, the models often involves several vessels only in a specific area. Also, since there are a lot of parameters involved, it is a challenge to calibrate the model, since the maneuverability of each individual vessel in an area need to be known. Differently, in the OC and APF, the maneuvering parameters are relatively simple, so more vessels can be analyzed in the broader area. The OC and APF paradigms are also capable of describing the vessel behavior variation between groups of vessels, although with similar inherent characteristics. The OC paradigm has the potential to describe human behavior on an encounter maneuver by setting up the most optimum strategy of both vessels considering their states. This potential can reflect the bridge team choice in deciding how to avoid a collision. Based on the elaboration above, considering the paradigms efficiency, accuracy, and its potential, the OC paradigm is selected to be the most suitable paradigm to analyze the collision avoidance model to assess port area safety.

4.2. Comparison of Paradigms for Bridge Team

The bridge team needs the highest accuracy of vessel behavior compared to the other model application purpose. Usually, the ship handling is used as a main simulator for the bridge team. This kind of simulator needs to have the highest detail of vessel maneuvering behavior and able to integrate the hydrodynamic impacts and other environmental factors to the vessel. In this research, there is no model that serves such an application purpose. However, for the ship handling simulators, only the SD paradigm has the potential to serve the modeling application purpose.

4.3. Comparison of Paradigms for Research and Development

For research and development, the paradigm should be able to describe more functionality compared to the simulation for the port authority, and it also should be easy to be extended. The R&D department is meant to develop further a model for the port authority. The difference with the previous application purpose is that the users need to conduct a more thorough analysis due to external factors (environment, encounter, a complex traffic condition).

4.3.1. General Model for Traffic Flow Analysis

As mentioned in Chapter 3, for further research and development in the traffic flow analysis model, the paradigm should have the potential to describe more functionality and easy to be extended. Also, in the traffic flow analysis, the extension is mainly focused on the increment of waterway complexity, traffic management change, or adding the impact due to traffic increment such as encountering or speed change. For this purpose, the detail of individual vessel behavior is not necessary.

According to Chapter 4, the model that easy to be extended without an intricate complexity in describing vessel behavior is the rule-based model. Therefore, the suitable paradigms are the rule-based paradigm: CA, GRB, SRB. The paradigm can be extended further by adding more maneuvering behavior rule. The SRB paradigm can be used for a model that needs a further study about the impact of collision in an area in collective manners. This paradigm is meant for a model that requires a higher accuracy result due to a significant encounter impact on the analysis output. The other two paradigms can be an option when the modeler wants to analyze the traffic flow in a complex waterway geometry. Therefore, the selection of the paradigm is relative to what kind of extension that the modeler specifically needs.

4.3.2. General Model for Safety Assessment

The paradigms selected for this purpose need to possess high potential in describing the vessel behavior representation and encountering behavior. The main difference between this model and the safety assessment model for the port authority is the ability to separate course and heading in simulating the collision avoidance. The separation is important to accommodate the model extension, for instance: to assess the vessel safety at the sharp turn or when the environment factor plays a big role. Therefore, only the mathematical-based paradigm (APF, OC, SD) can meet the requirement. However, the best paradigm for this purpose highly depends on the specific modeling purpose.

The SD paradigm is the most suitable paradigm when the research team needs a model to assess the vessel(s) maneuvering safety considering the hydrodynamic details and its impact on vessels modules. The vessel behavior representation can be defined with the highest detail far beyond this research modeling requirement criteria. The SD is able to simulate individual vessel behavior in detail considering the whole sailing process. However, due to the lack of maneuvering data of a vessel in a specific area, this paradigm can only involve several vessels.

For a larger area and involving a variety of vessels, the OC and APF paradigm are good options. Both paradigms can describe the behavior variation between groups of vessels with similar inherent characteristics. Also, the paradigms can be used for a nautical traffic model for an area without a strict requirement on individual behavior accuracy. Both paradigms do not lack capability in describing real-sailing environment and compared to SD paradigm they are easier to be extended. The choice between OC and APF paradigm depends on what kind of specific simulation that the developer needs. The OC paradigm has the potential to integrate more aspects that impacting vessel encounter behavior by changing the objective function and constraints. The paradigm shows potential to consider human behavior on sailing by setting up the most optimum encounter strategy. This can be beneficial for a multi-vessel encounter. In the APF paradigm, more aspects can be integrated by adding more artificial forces. The paradigm is suitable if a modeler wants to include the hydrodynamic impact during an encounter. It can be done by defining the impact as a repulsive force. So, in conclusion, the suitability of the paradigm depends on the output and specific application purpose that the research and development needs.

4.4. Conclusion of The Discussion of The Paradigms

Although a paradigm can meet the all functionalities in modeling application purpose requirement, it does not necessarily mean that the paradigm is suitable to describe them. In Table 4-1, some paradigms are recommended based on their capability and suitability in describing modeling application purposes requirements. The summary of the recommended paradigms for each modeling application purpose is given in Table 4-1.

Table 4-1 Recommended paradigms for each modeling application purpose

Model Application Purpose		Paradigm					
		CA	**SRB**	**GRB**	**APF**	**OC**	**SD**
Port Authority	Traffic Flow Analysis (capacity assessment, forecasting, performance assessment, traffic management)	√	√				
Port Authority	Safety Assessment - Collision Probability and Risk	√	√	√			
Port Authority	Safety Assessment - Collision Avoidance				√	√	√
Bridge Team	Safety Analysis - Collision Avoidance (Real-Time)						√
Research and Development	General Model Development for Traffic Flow Analysis	√	√	√			
Research and Development	General Model Development for Safety Assessment				√	√	√

In the next chapter, a model to assess the safety in the port area will be chosen to be extended further to serve the modeling application purpose better. Therefore, one of the models from the OC paradigm will be chosen by a comparison method.

5

EXTENSION OF A NAUTICAL TRAFFIC MODEL

This chapter is dedicated to answering objective 2 regarding the nautical traffic model extension. Subchapter 5.1 provides a selection of models from OC paradigm to be extended further to serve as the safety assessment model for the port authority. The selection is made by comparing the OC models in detail. In Subchapter 5.2, a feature in the model by Shu et al. (2015a, 2015b, 2018) is selected to be extended further and the benefit of adding the extension is given. Subchapter 5.3 elaborates a functional description of the model. Subchapter 5.4 explains the theoretical approach of the improvement in the aggregate level of how the overtaking maneuver can be extended further in the model. Subchapter 5.5 elaborates the overtaking maneuver sequences in more detail. Subchapter 5.6 provides an analysis of the model to see which of the existing feature need to be improved or be kept in order to support the new extension. Subchapter 5.7 elaborates the theoretical approach of the extension in more detail. It explains an extended overtaking maneuver sequence algorithm and mathematical formulations. Lastly, Subchapter 5.8 provides a conclusion of this chapter.

5.1. Selection of a Model in Optimal Control Paradigm

As mentioned in Chapter 4, the best paradigm to serve this purpose is the OC paradigm. Among the three models studied in this research, one model will be selected through a comparison study to get the most promising model to serve as the safety assessment model for the port authority.

In the OC paradigm, as elaborated in Chapter 3, the model by Lisowski (2014, 2016) and ten Hove and Wewerinke, (1990) involve quite a lot of parameters in the vessel's state equation. With those parameters, both models are able to give the vessel sailing behavior details. Compared to the model by Shu et al. (2015a, 2015b, 2018), the two models provide more functionality in describing vessel maneuvering encounters. The collision simulation in both models is advance. Both models are able to set the most optimum strategy for both vessels when facing an encounter, including the strategy on the multi-vessels encounter (Lisowski, 2014, 2016). The optimum maneuvering strategy includes predicting a safe trajectory of a vessel and the time to start a maneuver. This can be achieved by minimizing the risk involved, considering DCPA and TCPA value as extensively elaborated in Subchapter 4.5. Moreover, the traffic rule is already embedded in the models. The summary of the OC model's capability in simulating the collision avoidance for safety assessment by the port authority is given in Table 5-1.

Table 5-1 The OC models capability in simulating the collision avoidance for safety assessment by the port authority

Application Purposes		Vessel Dynamic Behavior				Vessels Encounters												
						Before / After			During									After
									Overtaking			Head-on			Crossing			
		P	S	C	H	Detection of The Encounter	Possibility to Maneuver	Time to Start Manuever	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Speed	Course	Traffic Rule	Adjust the initial course and speed to initial or a new traffic condition
Port Authority	Safety Assessment - Collision Avoidance	!	#	!	*	!/#	!	*	!	!	!	!	!	!	!	!	!	*
Shu et al. (2015a,2015 b,2018)	Safety Assessment - Collision Avoidance	!	#	!	*	*		*	!	!		!	!					*
ten Hove and Wewerinke (1990); Wewerinke et al. (1989)	Safety Assessment - Collision Avoidance	!	#	!	!	!	#	!	!	!	!	!	!	!	!	!	!	*
Lisowski (2012,2014)	Safety Assessment - Collision Avoidance	!	#	!	*	!	#	!	!	!	!	!	!	!	!	!	!	*

In selecting the best model in the OC paradigm to assess the safety in a port area, one of the most important things is the applicability of the model in the narrow waterway. The applicability is important because unlike in the open water, the vessel maneuvering in the narrow waterway is limited due to the waterway bank. Therefore, the model needs to ensure that the limitation has taken into account. The applicability of the model by Lisowski (2014, 2016) and ten Hove and Wewerinke, (1990) in the narrow waterway is questionable. Both models do not include the discomfort factor due to the bank. Moreover, the model by ten Hove and Wewerinke (1990) is a conceptual model. Since it is only a concept, the model applicability in a real sailing situation has not been proven. Unlike those models, the model by Shu et al. (2015a, 2015b, 2018) is specially dedicated to the port water area. The model considers the disutility cost due to the surrounding infrastructure of the waterway, such as the bank. Since this research will not perform the implementation of the models by means of simulation, this research could not say that the model by Lisowski (2014, 2016) and ten Hove and Wewerinke, (1990) cannot perform well in the narrow waterway. Another research should be done to prove that indeed such a model could work in the narrow waterway. Therefore, the model by Shu et al. (2015a, 2015b, 2018) is chosen to be the most promising OC model analyzed in this research to serve as a safety assessment model for the port authority.

5.2. Selection of Features to be Extended

In order to better serve as a safety assessment model by the port authority, the model by Shu et al. (2015a, 2015b, 2018) needs to meet the modeling requirement. As shown in Table 4-1, there is some room for the model to be improved in order to serve the modeling application purpose better. The detection of the encounter does not meet the criteria. Also, the possibility checks to maneuver, and the traffic rule should be added.

The model by Shu et al. (2015a, 2015b, 2018) states that the cost function for vessel influence in the model does not work well for head-on vessel encounter. According to the description in the model, compared to head-on, the cost function works better in the overtaking encounter. The existing feature in the model supports the overtaking encounter to be extended further in order to obtain a more accurate simulation result. Therefore, in this research, the sequence of the overtaking maneuver will be improved.

In the current model by Shu et al. (2015a, 2015b, 2018) the possibility check to maneuver and the traffic rule are not exist in the model. The vessel will choose the most optimum side to maneuver during overtaking, to port or starboard with an assumption that the maneuvering during an encounter is always possible. Such an arbitrary choice of maneuver causes the simulated encountering may happen on the other side than the real one, so there will be an error in predicting the nautical traffic safety. The scheme to determine the maneuvering side for overtaking encounter is essential to improve the accuracy of the model by Shu et al. (2015a, 2015b, 2018). This can be achieved by adding the traffic rule and the possibility to maneuver check. By adding these, a better vessel overtaking trajectory can be generated, so the safety assessment will be more accurate.

5.3. Study of The Nautical Traffic Model by Shu et al. (2015a, 2015b, 2018)

The operational control model by Shu et al. (2015a, 2015b, 2018) comprises of two parts; there are a tactical level model (route choice) and an operational level (dynamics of vessel behavior). Both models are based on disutility or cost minimization. In the tactical level, the preferred route of the vessel is generated. This route is chosen considering the discomfort of the infrastructure, such as distance to the waterway bank and expected sailing time. The optimization for the vessel route will yield the optimized velocity choice and preferred route at the tactical level. The vessel course and speed are included in the optimized velocity. This route choice model provides a basis for predicting vessel behavior at the operational level. The operational level determines the sailing model of the vessels. The behavior of sailing is determined by the bridge team behavior with reference to the speed and course in tactical level. The behavior such as accelerating and turning is executed to force the vessel to sail with the desired speed and course. Also, the encounters are considered at this level.

As mentioned in the previous section, the overtaking encounter will be extended by adding the maneuvering side preference. In the model by Shu et al. (2015a, 2015b, 2018), the vessel will choose an arbitrary side to maneuver. This is because the overtaking encounter is not considered at the tactical level. The vessel will not be preferred one side over the other side due to any condition (traffic rule, width sufficiency, vessel position, etc.). Therefore, in order to embeds the overtaking maneuver side preference, the encounter should be embedded in the tactical level. By this approach, the preferred speed and course will consider the traffic rule. The overall concept of the model by Shu et al. (2015a, 2015b, 2018) and its extension (red box) is shown in Figure 5-1.

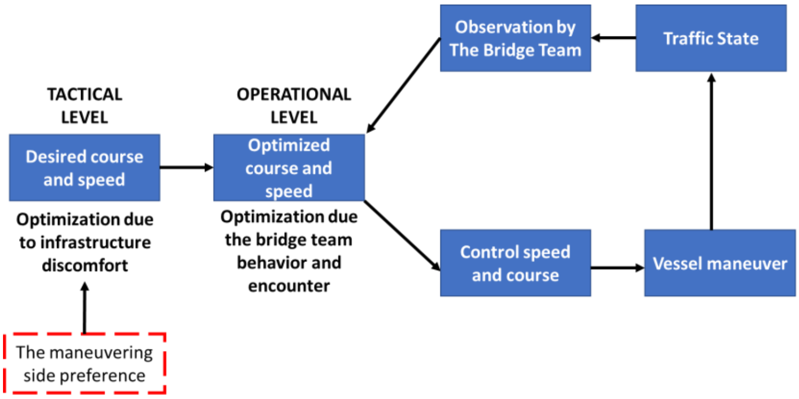

Figure 5-1 The overall concept of the model by Shu et al. (2015a,2015b,2018) and its extension (red box)

5.4. Theoretical Approach at an Aggregate Level

As mentioned in the previous section, the overtaking maneuver should be considered at the tactical level in order to overrule the preferred speed and course. In order to achieve that, the model should detect an encounter at the tactical level. In the model by Shu et al. (2015a, 2015b, 2018), the sailing mode is controlled at the operational level. The vessel will keep sailing, and when the operational time is more significant than the tactical level time step, it will check the possibility of an encounter. If an encounter is detected, the vessel will proceed to check the possibility to maneuver; otherwise, it will continue to sail. The aggregate level of this continuous process is given in Figure 5-2.

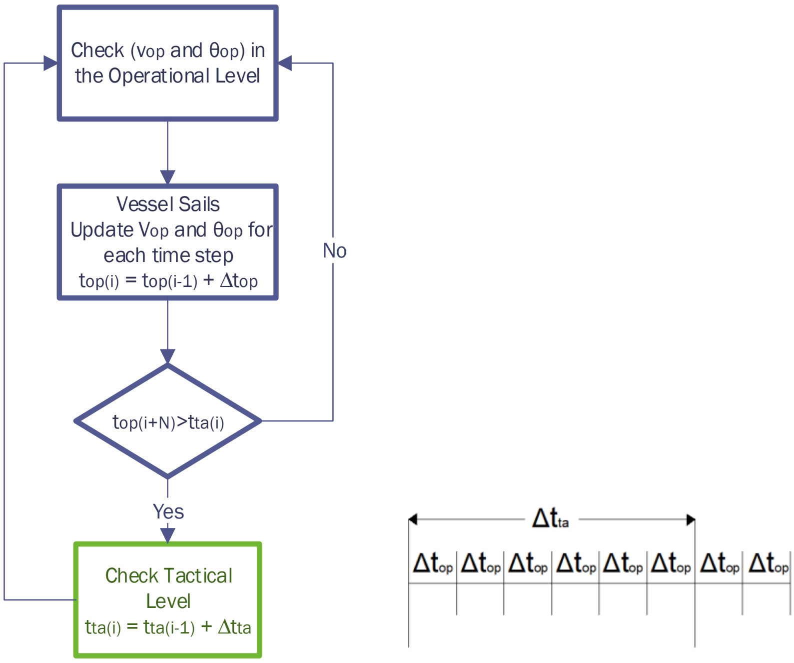

Figure 5-2 The aggregate level of model improvement

As mentioned before, when the operational time is bigger than the tactical time step, the model will check the possibility to maneuver. According to the modeling application requirement in Chapter 3, the possibility check to maneuver includes the gap sufficiency, vessel maneuverability, forward and backward traffic check. The traffic rule determines the role of a vessel in an encounter (overtaking or overtaken vessel) and to which side the vessel(s) should maneuver. Figure 5-3 shows the overruling process of speed and course in the model. The blue boxes exist at the operational level, while the other boxes are at the tactical level. The purple box indicates the detection of an encounter and identification of the role of a vessel in an encounter. The yellow indicates the possibility to maneuver checks. In this mechanism, the vessel safety to maneuver before, during, and after the encounter needs to be guaranteed. If there is no possibility to maneuver, the vessel will keep the sailing behavior or decelerate (red box). The green box is the overruling process of vessel speed and course. Either the model needs to overrule the vessel speed or course or keep its sailing behavior, the vessel needs to continue sailing in the operational mode.

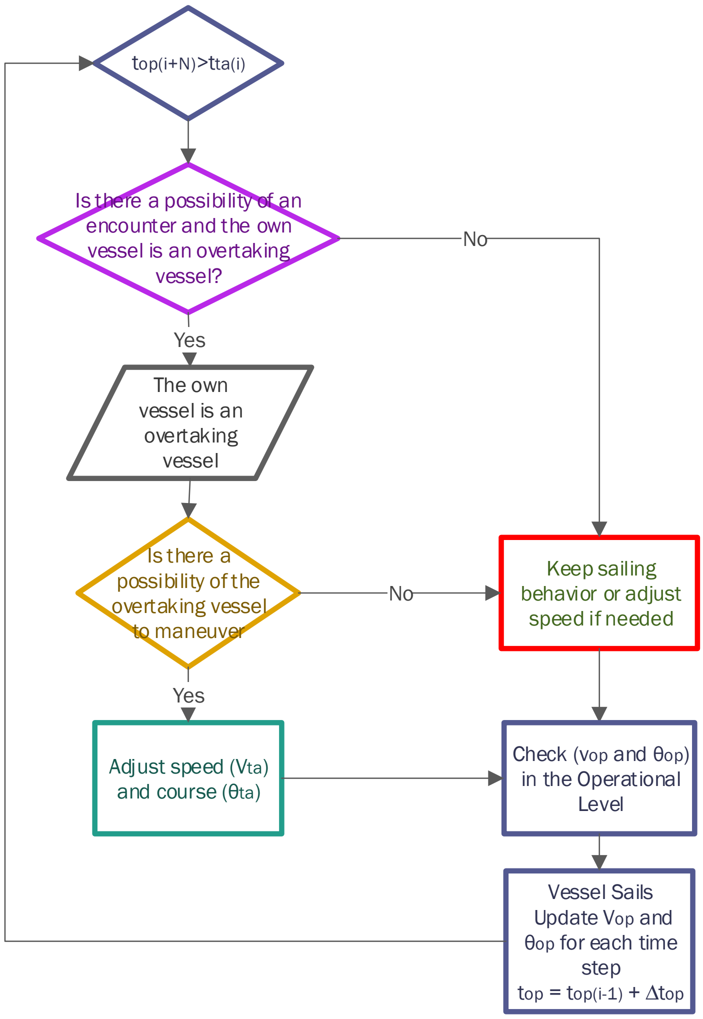

Figure 5-3 The process to overrule the tactical level speed and course

In Subchapter 5.5 and 5.6, the purple, yellow, green, and red box will be elaborate more in detail.

5.5. An Overtaking Encounter Maneuver Sequence Details

The general overtaking encounter maneuver sequences are elaborated in more detail in Figure 5-4. The next paragraphs elaborate the boxes shown in the figure.

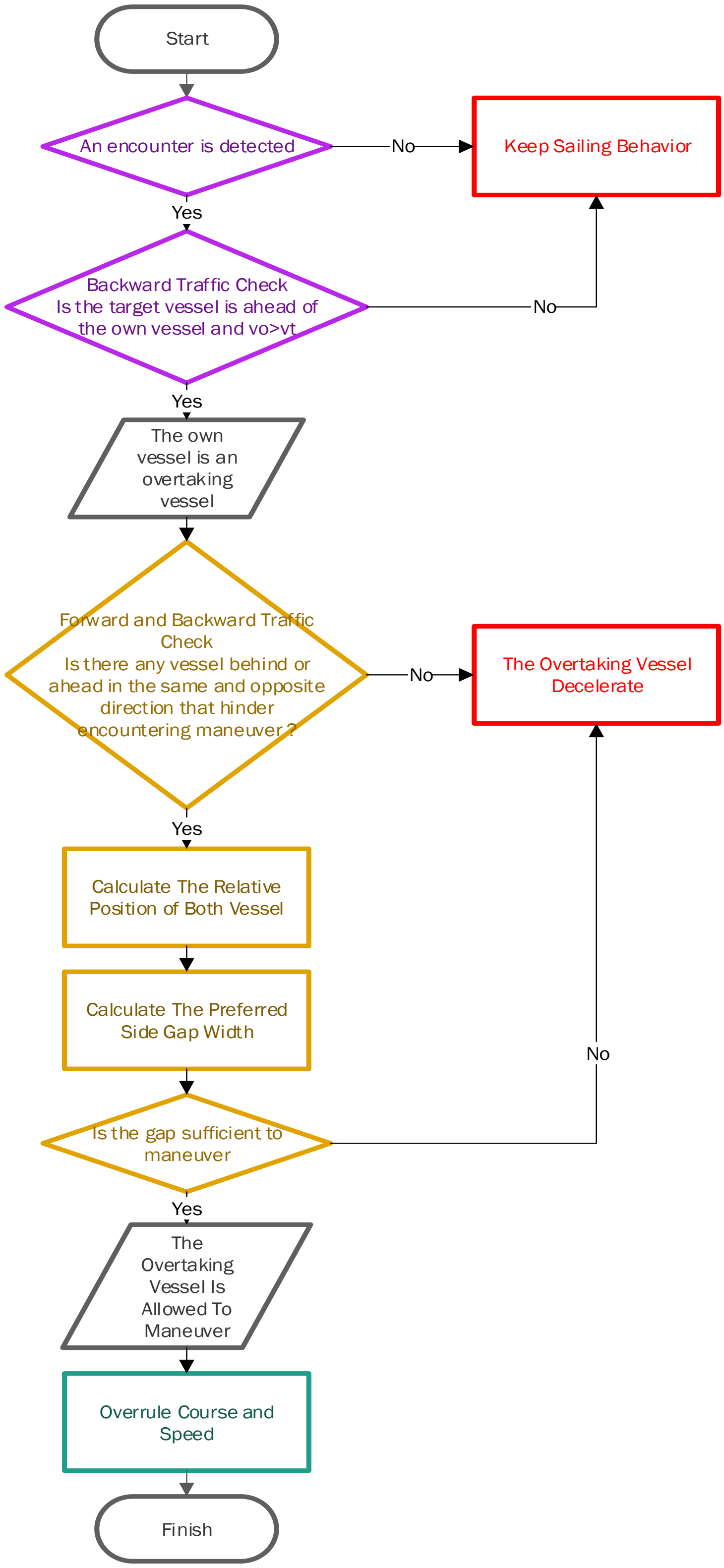

Figure 5-4 Overtaking encounter second-base mechanism

The purple boxes indicate the detection of an encounter, vessels speed check, and the backward traffic check. The model needs a feature to detect the risk of encounter as a parameter for a vessel to decide what action (if needed) should be taken. After detecting the risk of an encounter, the vessel will check the backward traffic to see the position and speed of the target vessel. The check is meant to identify the role of a vessel if the own vessel is overtaking or the overtaken vessel. If it is found that the target vessel is behind the own vessel, then it is either there is no risk of collision $(v_o > v_t)$ or the vessel is an overtaken vessel $(v_o < v_t)$. In this research, only the overtaking vessel performs a maneuver, while the overtaken vessel is assumed to maintain its current speed and course. When there is no target vessel behind, it means that the target vessel is ahead of the own vessel. If the own vessel speed is bigger than the target vessel, then the own vessel is an overtaking vessel.

The yellow boxes check the possibility of the own vessel to maneuver. This mechanism consists of a forward traffic check and gap width sufficiency check. The forward traffic check will ensure the safety of the vessel during the overtaking maneuver. The vessel should check if there is no vessel ahead of it both in the same and opposite direction. The next check is the relative position of both vessels checks. In this mechanism, the relative position between both vessels will be calculated and represented by the relative bearing between both vessels. The relative position of vessels decides the preferred maneuvering side. In the gap width sufficiency check, the vessel will measure the preferred available gap and seek the possibility to perform maneuvering with the available gap. The width should be sufficient for a vessel to evade the target vessel, considering its maneuverability. If the vessel passes all the checks, then the vessel will perform the last mechanism, which is maneuvering by overruling the preferred speed and course. The detail of these mechanisms will be elaborated further in the next chapter.

5.6. An Analysis of The Existing Features in The Model by Shu et al. (2015a, 2015b, 2018)

In this chapter, the existing feature in the model by Shu et al. (2015a, 2015b, 2018) will be analyzed to see if the model has those checking sequence mentioned in Subchapter 5.5 and to see which of the existing feature need to be improved or kept to support the new extension.

The model only has the mechanism to detect an encounter by so-called influence area at the operational level, as shown in Figure 5-5. This influence area has an elliptical shape with the longitudinal side two times larger than the lateral side. The distances at the lateral side are equal for both directions as shown in Figure 5-5. This area is used as a safety zone for overtaking and head-on encounter. The smaller the ratio between the distance to the influence area radius, the bigger the deviation of vessel speed and course from the preferred one in the tactical level. Thus, this concept is similar to the ship domain concept. According to Jingsong et al. (1993) and Pietrzykowski (2008), the concept of ship domain is practically useful in restricted areas such as narrow waterway. Also, according to a review by

Szlapczynski and Szlapczynska (2017) the elliptical ship domain area suits overtaking encounter the most. In COLREG rule for the overtaking encounter, passing from both sides (port and starboard) are allowed. Although in a narrow waterway, overtake to the port side is more desirable. In addition, the model also defines the time to start maneuvering when the vessel detects an encounter. This assumption is valid since, in the real-life situation, the bridge team would start negotiating even before the need for an actual maneuver.

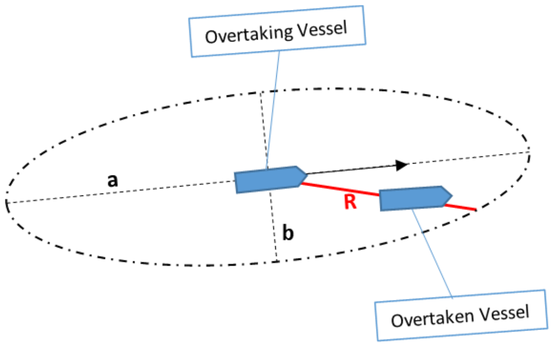

Figure 5-5. The relative distance between the two vessels (d) is smaller than the ship domain (R) (Reference: Shu et al. (2015a, 2015b, 2018))

5.7. A Theoretical Approach Details Elaboration

In this subchapter, the mechanisms in Figure 5-3 and 5-4 (purple, yellow, green, and red box) will be further elaborated. The details are also provided in flowcharts and mathematical equations.

5.7.1. Check the Possibility of Encounter

This mechanism comprises checking the possibility of an encounter and identifying the role of the vessel either it is an overtaking or an overtaken vessel. The overall process in this section is given in Figure 6-5.

a. Checking the Possibility of Encounter

As mentioned in the previous section that the existing influence area will be maintained in this model. A possibility of encounter is detected when the distance between vessels (d) is smaller than the ship domain radius (R). If the distance is indeed smaller, then it will proceed to identify its role in the overtaking encounter; otherwise, there is no encounter situation.

b. Identifying the Role of a Vessel

According to Thiers and Janssens (1998), the allowance from the forward and backward traffic is essential in an encountering situation. The backward traffic check is conducted to check the role of the vessel. If the target vessel is behind the own vessel, then it is either the own vessel is the overtaken vessel, or there will be no risk of an encounter. In both situations, the own vessel needs to keep its sailing behavior. If the target vessel is ahead, the own vessel should check whether its speed (v_o) is larger than the target speed (v_t). If the own speed is larger than its target vessel, it will check the possibility to maneuver. Otherwise, there is no risk of collision. The overall process is given in Figure 5-6.

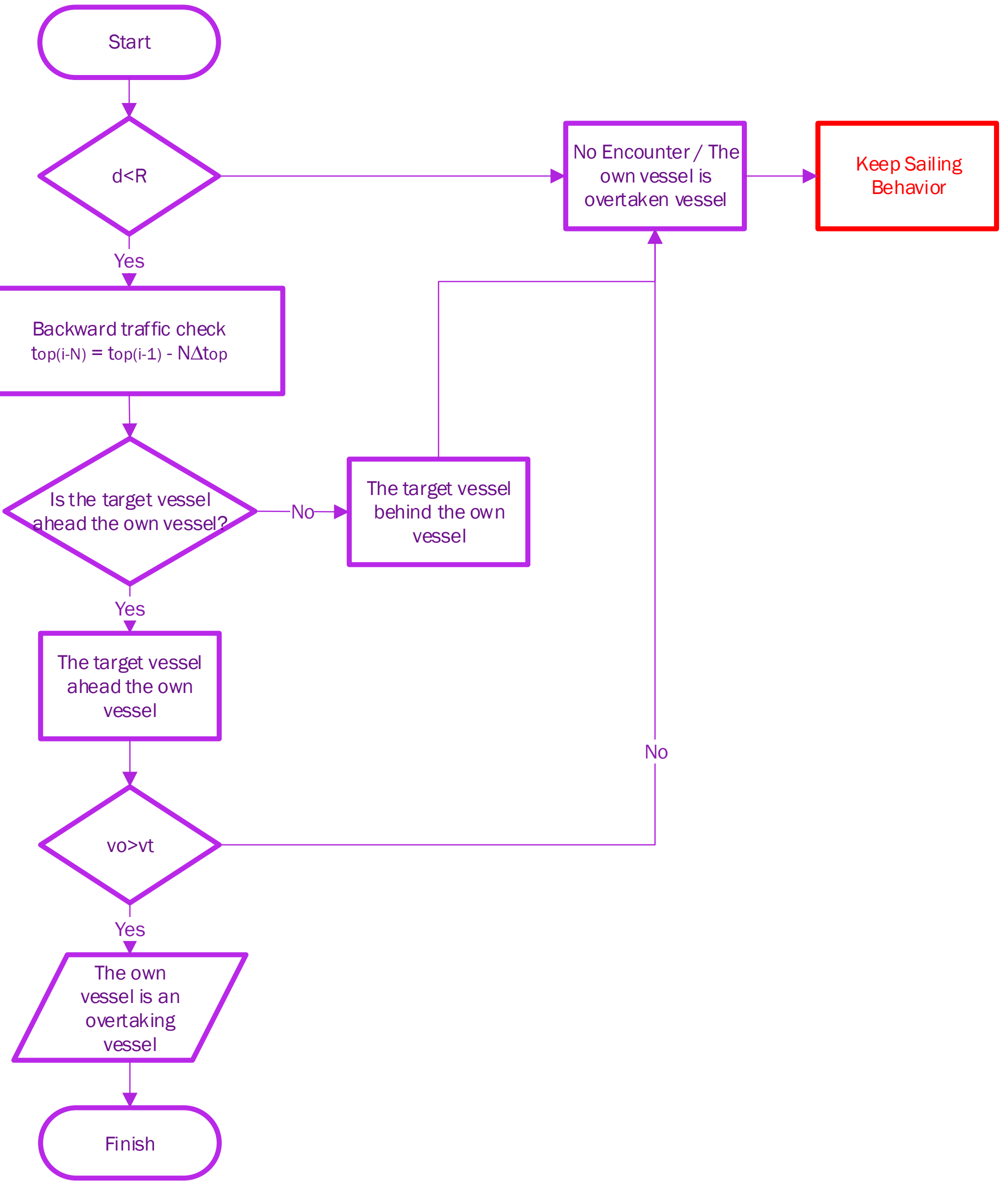

Figure 5-6 Checking process of the possibility of an encounter

The backward traffic check formula is given in the Equation 5-1. The value N is the steps back taken by the own vessel to check if there is a vessel with a higher speed approaching from the backward direction.

$$t_{op\,(i-N)} = t_{op\,(i-1)} - N\Delta t_{op} \qquad (5\text{-}1)$$

5.7.2. Check the Possibility to Maneuver

The possibility to perform maneuvering depends on the allowance from forward traffic the vessel maneuverability, the width of the waterway and the position of both vessels (Ni et al., 2019; Xiao, 2014; Li, 2013; Thiers and Janssens, 1998). The flowchart to check the possibility to maneuver is depicted in Figure 5-7.

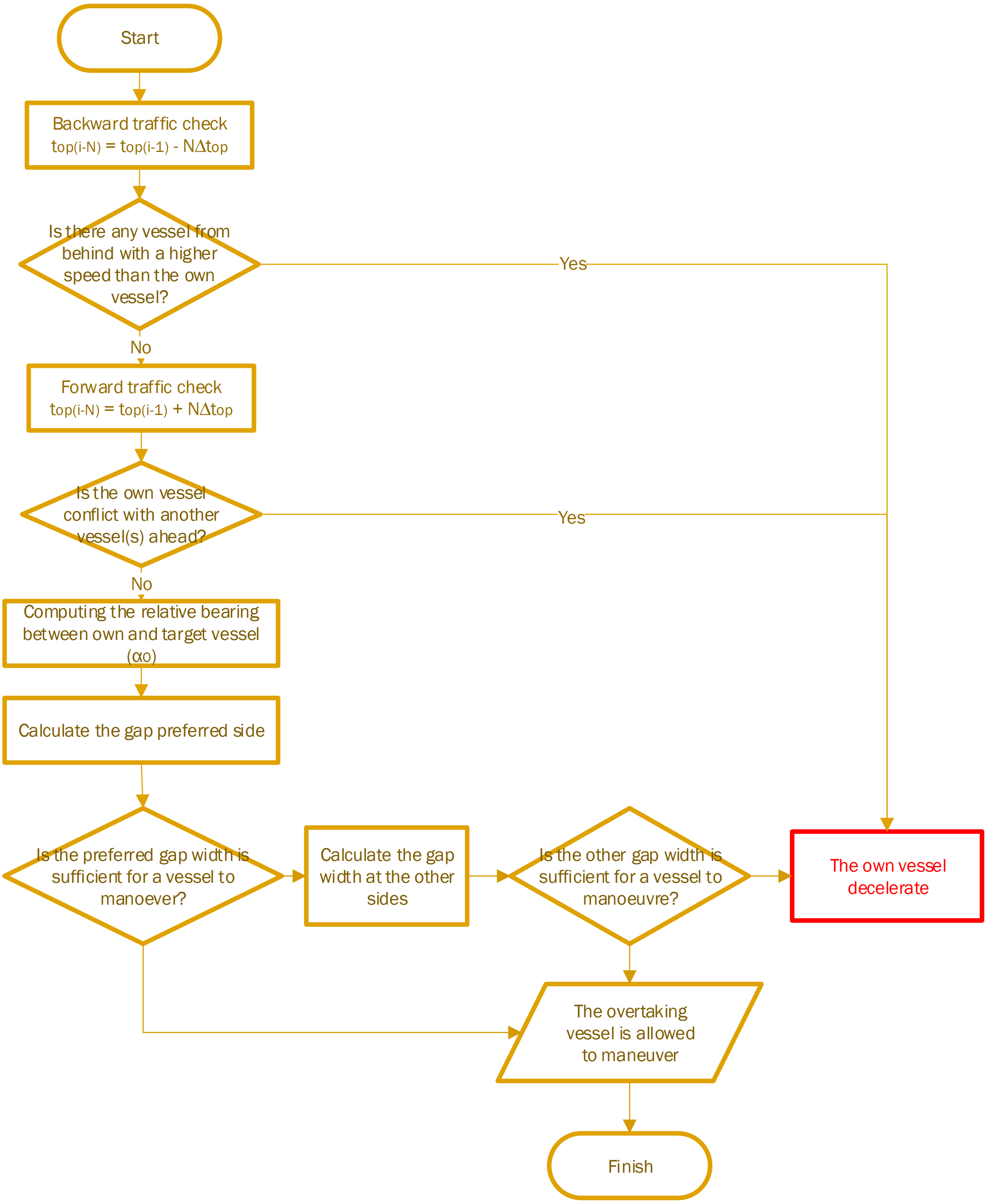

Figure 5-7 Checking the possibility to maneuver based on the lateral gap sufficiency

Firstly, the model conducts the forward and backward traffic check. The backward traffic check makes sure there will be no vessel from behind with high speed. The formula of this checking is given in Equation 6-1. The coefficient N is bigger than in the previous section because in this checking to cover a larger distance. The forward traffic check attests the safety of the own vessel by making sure that there will be no vessel conflicted with the own ship from the opposite and same sailing direction during the maneuvering process. The forward traffic check formula is shown in Equation 5-2. If the prediction shows that there will be future conflict, then maneuvering is not allowed, and the own vessel needs to decelerate with a deceleration formula shown in Equation 5-3. The vessel needs to decelerate to the target vessel speed. (Camci et al., 2009; Almaz et al., 2006; Thiers and Janssens, 1998).

$$\boldsymbol{t_{op\,(i+N)} = t_{op\,(i-1)} + N\Delta t_{op}} \tag{5-2}$$

$$\boldsymbol{a_{o\,(i)} = max(\frac{v_{o(i-1)} - v_{t(i-1)}}{\triangle\, t_{op}}, a_{max})} \tag{5-3}$$

Secondly, the width sufficiency of the waterway is checked to decide to which side the vessel should maneuver. In a real sailing situation, the bridge team prefers a bigger lateral space to conduct maneuvering for a safety reason. However, it also depends on the position of the own vessel relative to the target vessel. If the own vessel position is at the starboard side of the target vessel, it will be easier to maneuver to starboard. Moreover, the gap width should be big enough to allow a vessel to pass, considering its maneuverability. If both gap widths are not possible to perform maneuvering, the vessel should decelerate to the target vessel speed. The value of the deceleration is given in the Equation 6-3. The width sufficiency is checked based on the assumptions as follow:

- An own vessel changes speed with a constant acceleration and has a maximum limit speed (v_{max})
- An own vessel has a course maneuverability limit $(\Delta\theta_{max})$
- It is assumed that the vessel will maneuver with a maximum course alteration allowed (θ_{max}). This parameter depends on the position of the own vessel relative to the bank and to the target vessel. The maximum course alteration is given in the Equation 5-9.
- A target vessel will maintain its speed and course during the maneuvering process. Usually, in real sailing, the vessels cooperate with each other, and the target vessel reduces its speed to accelerate the overtaking process. So, maintaining the target vessel's course and speed is assumed as the worst scenario in overtaking (Xu et al., 2013).

A sufficient width is checked using the Equations 5-4 up to 5-7. Figure 5-8 describes the parameter used for the width sufficiency formula. The relative positions between vessels are represented by the relative bearing (α_o). If the relative bearing is between $0^\circ \leq \alpha_o \leq 22.5^\circ$, the vessel will seek the possibility to maneuver to port. The vessel will check the possibility to maneuver to starboard if the relative bearing is between $337.5^{\circ} < \alpha_o < 360^{\circ}$. If the preferred side width is not sufficient, then the vessel will check the width sufficiency at the alternative side.

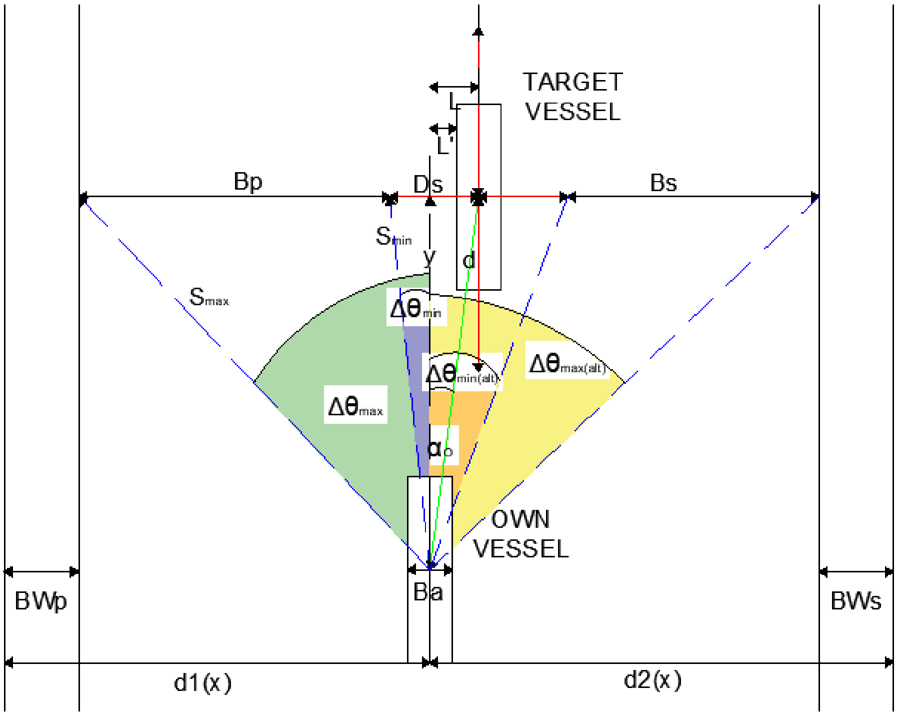

Figure 5-8 Illustration of the parameters used

a. The vessel is located at $0^{\circ} \leq \alpha_o \leq 22.5^{\circ}$. The own vessel prefers to maneuver to port

   i. Alter to port

$$\boldsymbol{d_1(x) - B_{Wp} > \int_{t_{i-1}}^{\frac{\theta_{max}}{\omega}} \left(v_{o(i-1)} + at\right) \sin(\omega t)\, \Delta t_{op}} \quad (5\text{-}4)$$

   ii. Alter to starboard

$$\boldsymbol{d_2(x) - B_{Ws} - B_B > \int_{t_{i-1}}^{\frac{\theta_{max}}{\omega}} \left(v_{o(i-1)} + at\right) \sin(\omega t)\, \Delta t_{op}} \quad (5\text{-}5)$$

b. The vessel is located at $337.5^{\circ} < \alpha_o < 360^{\circ}$. The own vessel prefers to maneuver to starboard

   i. Alter to port

$$\boldsymbol{d_1(x) - B_{Wp} - B_B > \int_{t_{i-1}}^{\frac{\theta_{max}}{\omega}} \left(v_{o(i-1)} + at\right) \sin(\omega t)\, \Delta t_{op}} \quad (5\text{-}6)$$

ii. Alter to starboard

$$d_2(x) - B_{Ws} > \int_{t_{i-1}}^{\frac{\theta_{max}}{\omega}} \left(v_{o(i-1)} + at\right) \sin(\omega t)\, \Delta t_{op} \tag{5-7}$$

$$\theta_{max} = \tan^{-1} \frac{d \sin(\alpha_o)}{d_1(x) - B_{Wp}}; for\ port\ side \tag{5-8}$$

$$\theta_{max} = \tan^{-1} \frac{d \sin(\alpha_o)}{d_2(x) - B_{Ws}}; for\ starboard\ side$$

After all of the checks are done, and the own vessel is allowed maneuver, the vessel will perform maneuvering through three stages. The next section explains how the vessel changes its speed and course to overtake the target vessel.

5.7.3. The Overtaking Maneuver (Overruling the Preferred Speed and Course)

There are three stages of the overtaking maneuver, as shown in Figure 5-9. The first stage is course alteration and speed change to avoid the target vessel. The second stage is when both vessels sail in parallel. The last stage is when the vessel tries to maneuver back its course and decelerate. The detail maneuvering process is given in the flowchart in Figure 5-10. In the following sections, each stage will be further elaborated.

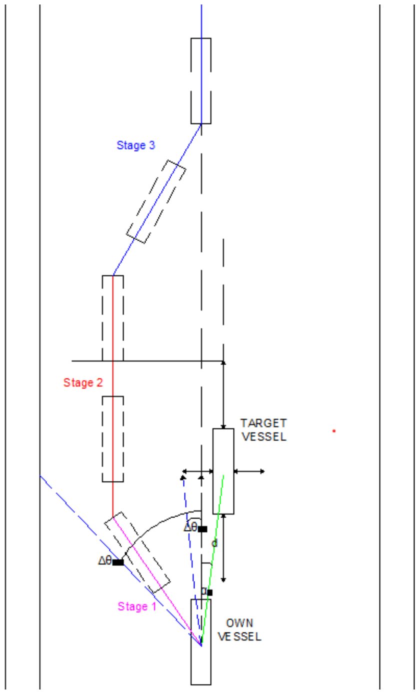

Figure 5-9 Overtaking processes

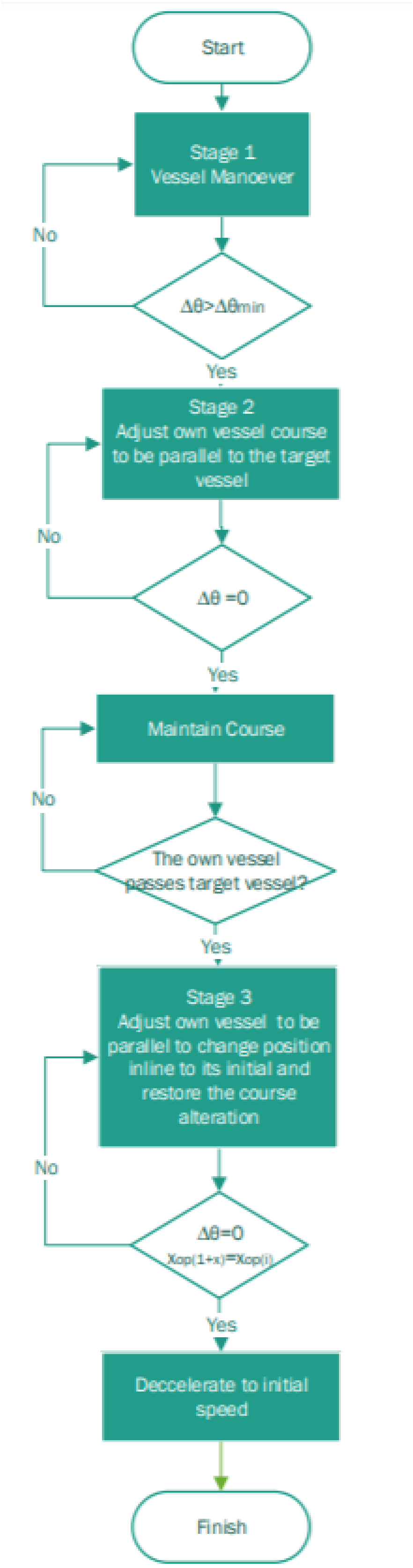

Figure 5-10 Overall processes of the overtaking maneuver

- **Stage 1: Course Alteration and Acceleration**

The first stage is the course alteration and accelerate. The vessel will try to alter its course for each time step until the course deviation is more significant than the minimum course alteration. The detail process of this overtaking maneuver is given in Figure 5-11. This detailed process holds for every stage in the overtaking maneuver.

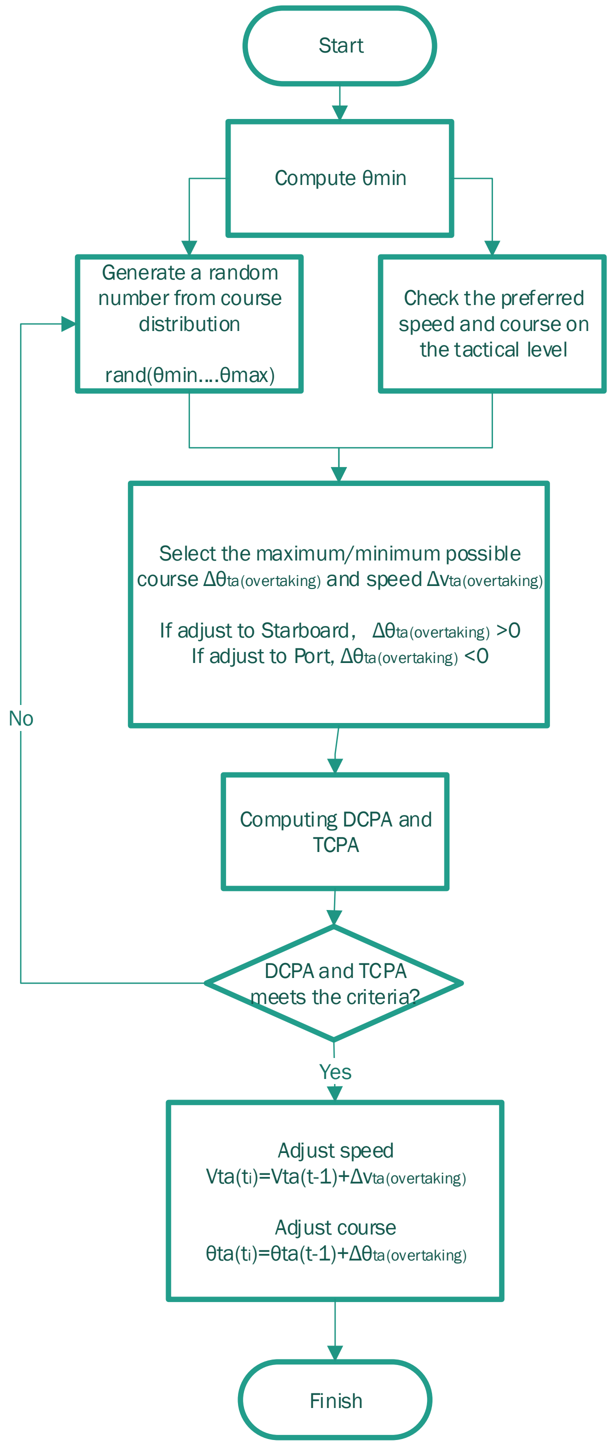

Figure 5-11 Speed change and course alteration for each stage

The vessel will alter the course as optimum as possible. The optimum course means that the vessel deviates wide enough to maintain the safe distance between both vessels but also small enough for the fuel efficiency. The optimum course deviation should be kept as close as possible to the minimum course alteration at the preferred maneuvering side (θ_{min}) if the vessel intends to maneuver at its preferred side. If the vessel intends to maneuver to the other side/alternative side, the minimum course deviation is denoted with $\theta_{\min(alt)}$. The minimum course alteration is given in Equation 5-9.

$$\boldsymbol{\theta_{min} = \tan^{-1}\frac{y}{D_s - L} = \tan^{-1}\frac{d\,sin\,(90-\alpha_o)}{D_s - L}} \qquad (5\text{-}9)$$

$$\boldsymbol{\theta_{\min(alt)} = \tan^{-1}\frac{y}{D_s - L} = \tan^{-1}\frac{d\,sin\,(90-\alpha_o)}{D_s + L}}$$

Where:

$$\boldsymbol{\frac{d}{\sin 90} = \frac{L}{sin\,\alpha_o} = \frac{y}{sin\,(90-\alpha_o)}}$$

$$\boldsymbol{L = \frac{d\,sin\,\alpha_o}{sin\,90} = d\,sin\alpha_o}$$

$$\boldsymbol{y = \frac{d\,sin\,(90-\alpha_o)}{sin\,90} = d\,sin\,(90-\alpha_o)}$$

The course alteration change is given in the range $\theta_{min} < \theta_{dist} < \theta_{max}$, so the alteration is not a fixed value. The range value is presented in a course distribution, and a random number will be drawn from this distribution. The model will compare the maximum/minimum course alteration value between the course in the tactical level $\Delta\theta_{ta}(t_i)$ and the generated random number $\Delta\theta_{dist}$. The course alteration change value is given in Equation 5-10 and 5-11.

The model will select the most significant absolute course alteration. When the vessel alters its course to starboard, the delta is positive while if it is to the port, the delta is negative. The course alteration formula is given in the Equation 5-12.

$$\boldsymbol{\theta_{dist} = rand[\theta_{min} \ldots \theta_{max}]} \qquad (5\text{-}10)$$

$$\boldsymbol{\Delta\theta_{dist} = \theta_{dist} - \theta(t_{i-1})}$$

$$\boldsymbol{\Delta\theta_{ta}(t_i) = \theta_{ta}(t_i) - \theta(t_{i-1})}$$

$$\Delta\boldsymbol{\theta}_{ta(overtaking)} = \begin{cases} \max\left(\Delta\boldsymbol{\theta}_{dist}, \Delta\boldsymbol{\theta}_{ta}(\boldsymbol{t}_i)\right), \boldsymbol{if}\,\Delta\boldsymbol{\theta}_{ta} > \mathbf{0} \quad (\boldsymbol{alter\ course\ to\ starboard}) \\ \min\left(\Delta\boldsymbol{\theta}_{dist}, \Delta\boldsymbol{\theta}_{ta}(\boldsymbol{t}_i)\right), \boldsymbol{if}\,\Delta\boldsymbol{\theta}_{ta} < \mathbf{0} \quad (\boldsymbol{alter\ course\ to\ port}) \end{cases} \tag{5-11}$$

$$\boldsymbol{\theta}_{ta(overtaking)}(\boldsymbol{t}_i) = \boldsymbol{\theta}_{ta}(\boldsymbol{t}_{i-1}) + \Delta\boldsymbol{\theta}_{ta(overtaking)} \tag{5-12}$$

The acceleration will also be generated from the speed distribution. The vessel will check the speed in the tactical level and if the speed has not reached the maximum value (v_{max}), the vessel will keep accelerating. If the speed at the tactical level is the maximum speed, then the vessel will keep the speed. The course alteration change value is given in Equation 5-13 and 5-14. The speed change formula is given in the Equation 5-15.

$$\Delta\boldsymbol{v}_{max} = \boldsymbol{v}_{max} - \boldsymbol{v}(\boldsymbol{t}_{i-1}) \tag{5-13}$$

$$\Delta\boldsymbol{v}_{ta}(\boldsymbol{t}_i) = \boldsymbol{v}_{ta}(\boldsymbol{t}_i) - \boldsymbol{v}(\boldsymbol{t}_{i-1})$$

$$\Delta\boldsymbol{v}_{ta(overtaking)} = \max\left(\Delta\boldsymbol{v}_{max}, \Delta\boldsymbol{v}_{ta}(\boldsymbol{t}_i)\right) \tag{5-14}$$

$$\boldsymbol{v}_{ta(overtaking)}(\boldsymbol{t}_i) = \boldsymbol{v}_{ta}(\boldsymbol{t}_{i-1}) + \Delta\boldsymbol{v}_{ta(overtaking)} \tag{5-15}$$

In the model, an influence area is an approach used by the model to quantify the course and speed change of the vessels. In this new overruling process, a method to quantify the ship-ship interaction is needed. Modifying the influence area or add a new cost function to support the new extension is not an easy job. For simplicity without lack of accuracy, the CPA approach is used to quantify the ship-ship interaction. The CPA represents an easy-to-implement parameter of collision determination and assists with decision making in collision avoidance. This is because the calculation of CPA assumes that vessels are simplified to geometrical points. These arguments to justify CPA methods in quantifying ship-ship interactions are also implemented in the most of the SRB paradigm models that can be applied in the narrow waterway (Huang et al., 2016; Xu et al., 2013; Aarsæther, 2011; Watanabe et al., 2008).

As mentioned in Chapter 3, the application area of the CPA is more suitable in open water. In a narrow water area, the ship maneuverability is limited. Therefore, the CPA in this research needs to be limited to a certain value is used to ensure that the vessel position change due to the course and speed alteration will not exceed the waterway bank limit, but bigger than the vessel safety distance. The closest point of approach should be bigger than the safety distance to the target vessel (D_s) but should be smaller to not hitting the waterway bank. The TCPA should be kept to bigger than a certain value ($t_{threshold}$), so the vessel will not violate the DCPA value too soon. The TCPA threshold depends on the maneuverability, visibility, and can be configured by an operator. The CPA parameters and the criteria used in this research are shown in Equation 5-16.

The criteria of DCPA and TCPA are given as follow:

$$D_s < DCPA < d_1(x) - B_{wp}\ ;alter\ to\ port \qquad (5\text{-}16)$$

$$D_s < DCPA < d_2(x) - B_{ws};\ ;alter\ to\ starboard$$

$$TCPA > t_{threshold}$$

$d_1(x)$ and $d_1(x)$ are the distances of the own vessel's center to the edge of the waterway bank at port and starboard side respectively. B_{wp} and B_{ws} is the safety distance at the waterway bank at port and starboard side respectively.

DCPA and TCPA are computed every time the new value and the course and speed are chosen. If the value does not match the DCPA and TCPA criteria, the model will try to generate another value. Otherwise, the model will overrule the speed and course change at the tactical level.

- **Stage 2: Both Vessels Sail in Parallel**

After the first stage finish, the vessel sails parallel to the target vessel. In the second stage, the vessel will start to alter its course parallel to the target vessel. The course alteration process uses the process in Figure 5-12. In this thesis research, the initial courses of both vessels are assumed to be 0°. So, the deviation of the initial course to the present course is zero in this stage ($\Delta\theta' = 0$). The vessel will continue to sail in parallel until its stern passing the safety distance of the target vessel's bow. The criteria for passing is given in the relative bearing. The criteria and illustration of the vessel passing is given in Figure 5-12 and Equation 5-17

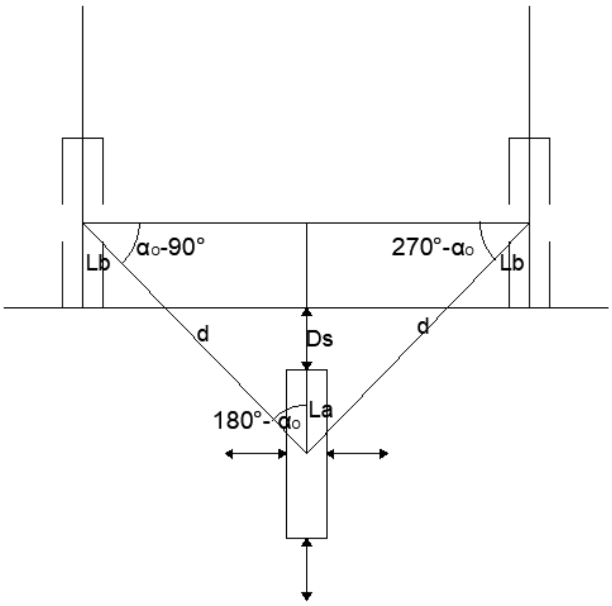

Figure 5-12 Vessel passing criteria

$$\alpha_{o(passing\ port)} = \sin^{-1}\left(\frac{0.5\,L_a + 0.5\,L_b + D_s}{d}\right) + 90 \qquad (5\text{-}17)$$

$$\alpha_{o(passing\ starboard)} = 270 - \sin^{-1}\left(\frac{0.5\,L_a + 0.5\,L_b + D_s}{d}\right)$$

- **Stage 3: Maneuvering Back and Deceleration**

In the last stage, the vessel tries to maneuver back to adjust its position to the preferred course in a new traffic condition. The course alteration process is similar to Stage 1 by using the process given in Figure 5-11, but the course alteration side is the other way around. This process will continue until the current, and the initial lateral position of the vessel is the same. In the end, the own vessel will keep sailing, and the existing cost minimization function will adjust to its preferred speed and course.

5.8. Conclusion of Extension of a Nautical Traffic Model

The room for extension of an encounter can be checked by ensure the availability of each maneuvering sequence and see if it meets the modeling application purpose requirement. The extension should fulfill the application purpose but also compatible with the existing features in the model. In order to serve as a safety assessment model for the port authority, the traffic rule and the maneuvering possibility checks in overtaking encounter are added in the OC model by Shu et al. (2015a, 2015b, 2018). By adding the extension, an overtaking vessel will consider the traffic rule. Therefore, the overtaking vessel trajectory result output will better match the AIS data analysis.

In order to embed the extension, a study of a model in the functional level needs to be done. A strategy at an aggregate level must be set in order to add an extension. In improving the encounter details of a model, there are several features that need to be presents: the detection of an encounter check, the possibility to maneuver check (available gap width check, relative position of vessels, vessel maneuverability, forward and backward traffic check), the time to maneuver, the maneuvering action (course and speed change), and the traffic rule (assigning the role of vessel in an encounter and choosing the maneuvering side of vessel). Therefore, in supporting the traffic rule extension, it is essential to make sure that the model has those mentioned features.

In the model by Shu et al. (2015a, 2015b, 2018), the overtaking encounter is simulated to create an overtaking trajectory at the tactical level. The traffic rule will be added in this tactical level, so a more accurate preferred overtaking vessel trajectory is generated. The traffic rule extension includes assigning which ship to take action and to which side it should maneuver. In the detection of encounter check, if a ship sails faster than its succeeding and it violates a safe distance, then it is an overtaking ship. The ship can overtake if the time and distance to maneuver are enough considering the vessel maneuverability. It is also essential to get the allowance from backward and forward traffic by checking several time steps ahead and backward respectively. When the overtaking ship is allowed to maneuver, the interaction between both ships should be quantified. In a narrow waterway, it is important to limit vessel maneuverability to avoid a collision with another vessel and waterway bank. Therefore, in this case, both the CPA calculation and the distributions of speed and course are limited. The speed and course are selected from distributions as such, so the DCPA value is higher than the safe distance between both vessels but lower than the distance of the vessel to the waterway bank minus the waterway bank safe width. The minimum and maximum course value consider a safe distance between the overtaking ship to another ship and to the waterway bank respectively. There are three stages of maneuvering; there are: course alteration and acceleration, both vessels sail in parallel, and maneuvering back and deceleration. Depending on the stages that the overtaking vessel sails, the maximum or minimum value of the speed and course between the tactical level values and the distributions are chosen (overruling process). The CPA calculation, the speed, and course choice, and the overruling process will be done for each tactical level time step. By this method of extension, the traffic rule is considered in the overtaking vessel preferred route.

6

CONCLUSION AND RECOMMENDATION

This chapter describes the conclusions and recommendations of this research. The conclusion includes a summary of the key finding, outcome, and other relevant information in this research. By recalling the objectives, the conclusion makes sure that all objectives have been obtained during this research. In the next subchapter, future works are given. Also, the recommendations are provided in order to address limitations and give suggestions on how the limitations may be overcome in future work.

6.1. Conclusion

This subchapter concludes the results and findings of this research.

➢ ***What are the basic algorithms of the paradigms?***

- Cellular Automata is a discrete computational system that can represent the complex behavior of a system. An object defined in this paradigm is composed of a finite set of homogenous cells. These cells contain information (in this case: individual vessel state) that evolve in space and time. The behavior of the information in the cell is influenced by the neighborhood's cells around it and deterministic rules.
- Generic Rule-Based is an approach that assumes a system can be understood as a model with interrelated parts that perform predictable behavior. In the nautical traffic model, the vessels are defined as agents. The behavior of vessel maneuvering (for instance: during a maneuver) is simplified as generic movement rules for all agents. The rules for different vessels are defined as the same under any circumstances. It does not differentiate the vessel behavior based on type nor situations.
- Specific Rule-Based is basically similar to the GRB paradigm in terms of defining the movement rules. However, in this paradigm, the difference between vessels in different circumstances can be described. The impact of the geographical layout is considered by giving more rules. Also, the vessel behavior differences during an encounter can be taken into account by situation-based calculation.
- Artificial Potential Field is a modeling paradigm that assumes an object is moving in an abstract artificial force field. This field consists of an attractive and repulsive potential field, which can be derived as forces. The sum of these forces becomes an input to change the object. In the

nautical traffic model, the object is a vessel. So, the individual vessel behavior change is controlled by the generated forces.

- Optimal Control is a paradigm that describes an object in the state consist of differential functions. The change of this state is driven by control functions such as the minimization tasks and constraints. The minimization tasks and constraints generate the most optimum maneuvering variables of a vessel.
- System Dynamics is a method for modeling and simulating dynamic, complex issues/systems that are characterized by feedback and accumulation effects. The paradigm controls the movement of an object based on the accumulation effects of the external factors on its sub-modules.

➢ ***How are vessel dynamic kinetic information such as position, speed, course, and heading modeled in the paradigms?***

The dynamic kinetic information is manually defined or generated by historical distribution (AIS data) in most of the rule-based and some mathematical based models. The information is used in a nautical traffic model to generate a traffic pattern, calibration, and validation. The information becomes an input to change a ship state through mathematical equations. The complexity of the vessel state equations can vary depending on the application's purpose. It can be defined in a simple kinematic equation or an advance equation considering an external impact on ship modules.

The paradigms control a ship movement using the dynamic kinetic information in different ways. The rule-based models control the maneuver by rules based on the modeler judgment. The CA paradigm has the lowest precision in representing the information due to the discretization. All value in the information is approximated, and the precision of this approximation depends on the cell size. Moreover, heading cannot be presented in CA paradigm. The incapability is because the paradigm defines a vessel as (a) squared cell (s), and the cells move straight following the discretized route. The SRB and GRB paradigms have a higher potential in describing the information accurately due to continuous space-state. The capability of the paradigms in simulating all aspects of the dynamic kinetic information depends on the approach that the model used. Heading can be presented if a model simulates the information of an individual ship in a time-space state. In most of the approaches that the models used, such as nodes and links concept, heading cannot be presented. A ship needs to follow a straight link and change its state in a node only. So, in this approach, the heading is deemed as course. The mathematical-based paradigm has the potential to describe all aspects of the dynamic kinetic information with the flexibility (the highest level of detail set up in this research modeling criteria). For every time and space step a ship is continuously exposed by mathematical functions that controlled the vessel movement. By this approach a ship can maneuver flexibly through the journey.

- ***How are vessel encounters such as head-on, overtaking, and crossing modeled in the paradigms?***

The encountering maneuver is characterized by vessel state change, often by altering its speed and course. Therefore, the potential in showing the degree of accuracy of the vessel maneuvering behavior in the simulation depends on the accuracy of the paradigms in describing the vessel behavior representation. The value of alteration in the encounter maneuvering behavior is controlled by rules in the rule-based paradigm and mathematical functions in the mathematical-based paradigm. So, the details of the maneuver will rely on how the modeler constructs the rules / the mathematical function. The rules and mathematical functions are constructed based on study and analysis of the historical distribution data, for instance, the AIS data. The controlling function is different among mathematical-based paradigm. It can be by the sum of artificial forces (APF), objective function and constraints (OC), and the calculation of external impact in whole sailing process (SD). The rules and mathematical functions control the encountering sequence before until after the maneuvering is performed. This includes the detection of an encounter, possibility of maneuvering check, the time to maneuver, the maneuvering action, assigning the vessel role and choosing the maneuvering side.

The evasive maneuvering behavior is controlled by rules which rely on the modeler judgment. The rule-based paradigm hardly distinguishes the heterogeneity in the vessels encounter. The rules are often described in generic for any type of vessel and circumstances, except in SRB paradigm. The rules of course and speed change usually given in a fixed value or in a simple kinematic equation. Differently, the SRB paradigm considers the differences between vessel behavior during an encounter. This is due to the addition of ship-ship interaction feature, for instance: the CPA method. In the node and link concept that often used by rule-based model, the collision avoidance is quantified by the CPA without considering the difference between the course and heading. This information is important if the heading plays a big role in the traffic area.

The mathematical-based paradigm can describe a greater detail of encounter maneuvering behavior compared to the rule-based paradigm. In the APF and OC paradigm, the models can simulate the maneuvering behavior between groups of vessels with similar inherent characteristics. In the APF, the encountering sequences are controlled by the sum of forces. For instance, the maneuvering side, which vessel(s) to maneuver, and the degree of alteration is controlled by external forces exerted to the vessel. The OC paradigm can resemble human behavior in deciding an action to be taken during an encounter. The evasive action of a vessel is determined by optimizing the encounter maneuvering strategy. The strategy considers the state of both vessels. The SD paradigm can describe the highest encounter maneuvering detail in this research. Besides considering the other vessel state in the encounter maneuvering equation, it also includes the vessel modularity and the hydrodynamic factors.

In summary, the rule-based paradigm is suitable to serve a model that does not need the maneuvering details and can simulate macroscopic traffic level that includes various kind of vessels. The mathematical-based is more suitable for a model that requires a higher level of vessel behavior description.

- ***How can the level of detail in (an) encounter (s) be improved based on the potential of the model(s) given a modeling application purpose ?***

The detail of an encounter can be improved by fulfilling the modeling application purpose requirement given in this research. In this research, the model by Shu et al. (2015a, 2015b, 2018) is extended by adding the traffic rule. The traffic rule is an essential addition to serve the safety assessment model for the port authority. The traffic rule addition will generate a more similar overtaking vessel trajectory compared to AIS data. It means that the accuracy of the simulation output can be improved. The modeler needs to ensure that the other encountering features are existed and compatible with the new extension. For instance, in this research, the traffic rule of choosing the maneuvering side is chosen as the encounter extension. The overtaking maneuvering side can be present by adding the possibility to maneuver check. The check includes the available gap width check considering overtaking ship maneuverability and relative position of both ships. By adding this check, the ship will maneuver to the safest side as preferred by the bridge team.

In further extending a model, it is important to realize how the model works and the new extension approach limitation. The model has simulated the preferred overtaking trajectory without considering the traffic rule. Therefore, the current preferred speed and course will be overruled. To overrule those aspects, the new speed and course during an encounter are calculated by the CPA method. The approach is learned from another model. However, since the CPA method has a limitation to be applied in narrow waterways, other measures are taken to tackle the limitation. In this research, the CPA is limited as such so it will be bigger than the vessel safety distance but smaller than the distance between the vessels and waterway bank. In conclusion, the approach to extend a model can be taken by looking into other models approaches. The modeler should ensure that the approach is compatible with the model's existing features and the limitation should be addressed.

6.2. Recommendation and Future Work

In this subchapter, some recommendations are given to conduct better research. This subchapter also recommends some future works that can be done following this research to have a better understanding of the individual vessel behavior in a nautical traffic model.

6.2.1. Recommendation

- *Compare the paradigms in serving a modeling application purpose by simulation*

The potential of the paradigm that is revealed from the theoretical approach is used to assess which paradigms are recommended for each modeling application purpose. The recommended paradigms then further compared based on their potential in serving the modeling purpose. Since the comparison is based on the theoretical approach, the accuracy of the models can only be predicted. In order to compare the accuracy and precision, the comparison by simulation can be performed. So, a model is taken as the representation from each recommended paradigm and compared to see how each functionality / overall performance works. The simulation outputs then compared with the data to see which paradigm works better from the others.

- *Use a snowball approach to find nautical traffic models or use documentation that is not publicly available for the literature review*

The snowball method is a way of finding literature by using a key document on your subject as a starting point. It can be conducted by searching all of the relevant articles in the references or in the co-authors' articles.

6.2.2. Future Work

Several future works that need to be done after this research are given in this section.

- *Implementation of the theoretical approach extension in a model by Shu et al. (2015b, 2015a, 2018)*

In this research, the development of the model by Shu et al. (2015b, 2015a, 2018) is limited to the theoretical approach. Implementation by Simulation needs to be done in order to validate the developed algorithm and to see whether the model can work by means of simulation. For this action, AIS data is needed in order to validate and calibrate the model

- *Add the head-on traffic rule in the model by Shu et al. (2015b, 2015a, 2018)*

The model by Shu et al. (2015b, 2015a, 2018) has the potential to develop the head-on encounter by adding the traffic rule since the model has simulated the encounter. There are several modifications that can be made in order to better integrate the traffic rule in the model. For instance, by changing the shape of the ship domain as suggested by Szlapczynski and Szlapczynska (2016, 2017). For head-on, the area is recommended to be wider at the starboard side.

- *Do a study of nautical traffic paradigms comparison in representing individual vessel behavior due to other aspects*

This research is only focused on the vessel dynamic kinetic information and encounters. However, there are more aspects that can be compared among the paradigms, such as environmental impact (wind, wave, current, tide). Comparing how well the paradigm simulates the environmental condition is beneficial for an area where the impact plays a significant role in changing the traffic analysis output.

References

Aarsæther, K. G. (2011) ‘Modelling and analysis of ship traffic by observation and numerical simulation’, *Norwegian University of Science and Technology*.

Almaz, A., Or, İ. and Özbaş, B. (2006) ‘Investigation of transit maritime traffic in the strait of Istanbul through simulation modeling and scenario analysis’, *International Journal of Simulation: Systems, Science and Technology*, vol. 7, no. 7, pp. 1–9.

Bellsolà Olba, X., Daamen, W., Vellinga, T. and Hoogendoorn, S. P. (2018) ‘State-of-the-art of port simulation models for risk and capacity assessment based on the vessel navigational behaviour through the nautical infrastructure’, *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 5, no. 5, pp. 335–347 [Online]. DOI: 10.1016/j.jtte.2018.03.003.

Beschnidt, J. and Gilles, E. D. (2005) ‘“ Virtual Waterway ” – a traffic simulation environment for inland and coastal waterways’, vol. 79, pp. 351–360.

Blokus-Roszkowska, A. and Smolarek, L. (2014) ‘Maritime traffic flow simulation in the Intelligent Transportation Systems theme’, *Safety and Reliability: Methodology and Applications*, no. September, pp. 265–274 [Online]. DOI: 10.1201/b17399-40.

Camci, F., Eldemir, F., Uysal, O. and Ustun, I. (2009) ‘Istanbul Strait Marine Traffic Simulation Using Multiple Serially Connected Machinery Concept’, *Proceedings of the 2009 Summer Computer Simulation Conference*, pp. 424–429.

Cheng, T. T., Ma, F. and Wu, Q. (2017) ‘An artificial potential field-based simulation approach for maritime traffic flow’, *2017 4th International Conference on Transportation Information and Safety, ICTIS 2017 - Proceedings*, pp. 384–389 [Online]. DOI: 10.1109/ICTIS.2017.8047793.

Colley, B. A., Curtis, R. G. and Stockel, C. T. (1984) ‘A Marine Traffic Flow and Collision Avoidance Computer Simulation’, *Journal of Navigation*, vol. 37, no. 2, pp. 232–250 [Online]. DOI: 10.1017/S0373463300023389.

COLREGs (2009) *COLREGS -International Regulations for Preventing Collisions at Sea*,.

van Dorp, J. R. and Merrick, J. R. W. (2011) ‘On a risk management analysis of oil spill risk using maritime transportation system simulation’, *Annals of Operations Research*, vol. 187, no. 1, pp. 249–277 [Online]. DOI: 10.1007/s10479-009-0678-1.

Fang, M. C., Tsai, K. Y. and Fang, C. C. (2018) ‘A Simplified Simulation Model of Ship Navigation for Safety and Collision Avoidance in Heavy Traffic Areas’, *Journal of Navigation*, vol. 71, no. 4, pp. 837–860 [Online]. DOI: 10.1017/S0373463317000923.

Goerlandt, F. and Kujala, P. (2011) ‘Traffic simulation based ship collision probability modeling’, *Reliability Engineering and System Safety*, Elsevier, vol. 96, no. 1, pp. 91–107 [Online]. DOI: 10.1016/j.ress.2010.09.003.

Gucma, L., Bąk, A. and Sokołowska, S. (2018) ‘Stochastic Model of Ships Traffic Capacity and Congestion — Validation by Real Ships Traffic Data on Świnoujście — Szczecin Waterway’, *Annual of Navigation*, vol. 24, no. 1, pp. 177–191 [Online]. DOI: 10.1515/aon-2017-0013.

Hasegawa, K. (1990) ‘An Intelligent Marine Traffic Evaluation System for Harbour and Waterway Designs’, *4th International Symposium on Marine Engineering Kobe*.

Hasegawa, K., Shigemori, Y. and Ichiyama, Y. (2000) ‘Feasibility Study on Intelligent Marine Traffic System’, *IFAC Proceedings Volumes*, vol. 33, no. 21 [Online]. DOI: 10.1016/s1474-6670(17)37094-5.

Hasegawa, K., Tashiro, G., Kiritani, S. and Tachikawa, K. (2001) ‘Intelligent Marine Traffic Simulator For Congested Waterways’, *7th IEEE International Conference on Methods and Models in Automation and Robotics*, pp. 632–636.

ten Hove, D. and Wewerinke, P. H. (1990) ‘A man-machine system approach to model vessel traffic’, *Proceedings of 9th Ship Control Systems Symposium*, pp. 355–368.

Huang, S. Y., Hsu, W. J., Fang, H. and Song, T. (2016) ‘MTSS - A Marine Traffic Simulation System and Scenario Studies for a Major Hub Port’, *ACM Transactions on Modeling and Computer Simulation*, vol. 27, no. 1, pp. 1–26 [Online]. DOI: 10.1145/2897512.

Jingsong, Z., Zhaolin, W. and Fengchen, W. (1993) ‘Comments on Ship Domains’, *Journal of Navigation*, vol. 46, no. 3, pp. 422–436 [Online]. DOI: 10.1017/S0373463300011875.

Li, Q. (2013) ‘Simulation of conflict risk for marine traffic within a seaport’, Nanyang Technological University.

Lisowski, J. (2012) ‘Game control methods in avoidance of ships collisions’, *Polish Maritime Research*, vol. 19, no. SPEC. ISSUE, pp. 3–10 [Online]. DOI: 10.2478/v10012-012-0016-4.

Lisowski, J. (2014) ‘Comparison of Dynamic Games in Application to Safe Ship Control’, *Polish Maritime Research*, vol. 21, no. 3, pp. 3–12 [Online]. DOI: 10.2478/pomr-2014-0024.

Lisowski, J. (2016) ‘The Sensitivity of State Differential Game Vessel Traffic Model’, *Polish Maritime Research*, vol. 23, no. 2, pp. 14–18 [Online]. DOI: 10.1515/pomr-2016-0015.

Miyake, R., Fukuto, J. and Hasegawa, K. (2015) ‘Procedure for Marine Traffic Simulation with AIS Data’, *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, vol. 9, no. 1, pp. 59–66 [Online]. DOI: 10.12716/1001.09.01.07.

Mou, J. M., Tak, C. van der and Ligteringen, H. (2010) ‘Study on collision avoidance in busy waterways by using AIS data’, *Ocean Engineering*, Elsevier, vol. 37, no. 5–6, pp. 483–490 [Online]. DOI: 10.1016/j.oceaneng.2010.01.012.

Ni, S., Liu, Z. and Cai, Y. (2019) ‘Ship Manoeuvrability-Based Simulation for Ship Navigation in Collision Situations’, *Journal of Marine Science and Engineering*, vol. 7, no. 4, p. 90 [Online]. DOI: 10.3390/jmse7040090.

Piccoli, C. (2014) ‘Assessment of port marine operations performance by means of simulation’, Delft University of Technology.

Pietrzykowski, Z. (2008) ‘Ship’s Fuzzy Domain – a Criterion for Navigational Safety in Narrow Fairways’, *Journal of Navigation*, vol. 61, no. 3, pp. 499–514 [Online]. DOI: 10.1017/s0373463308004682.

Qi, L., Zheng, Z. and Gang, L. (2017a) ‘A cellular automaton model for ship traffic flow in waterways’, *Physica A: Statistical Mechanics and its Applications*, vol. 471, pp. 705–717 [Online]. DOI: 10.1016/j.physa.2016.12.028.

Qi, L., Zheng, Z. and Gang, L. (2017b) ‘Marine traffic model based on cellular automaton: Considering the change of the ship’s velocity under the influence of the weather and sea’, *Physica A: Statistical Mechanics and its Applications*, vol. 483, pp. 480–494 [Online]. DOI: 10.1016/j.physa.2017.04.125.

Qu, X. and Meng, Q. (2012) ‘Development and applications of a simulation model for vessels in the Singapore Straits’, *Expert Systems with Applications*, Elsevier Ltd, vol. 39, no. 9, pp. 8430–8438 [Online]. DOI: 10.1016/j.eswa.2012.01.176.

Rayo, S. (2013) ‘Development of A simulation Model for The Assessment of Approach Channels - The Taman Seaport Case’,.

Rong, H., Teixerira, A. . and Soares, C. . (2015) ‘Simulation Model for the Assessment of Maritime Traffic in the Tagus River using AIS Data’, *Maritime Technology Engineering*, pp. 185–193 [Online]. DOI: https://doi.org/10.1128/MCB.00875-13.

Sariöz, K. and Narli, E. (2003) ‘Assessment of manoeuvring performance of large tankers in restricted waterways: A real-time simulation approach’, *Ocean Engineering*, vol. 30, no. 12, pp. 1535–1551 [Online]. DOI: 10.1016/S0029-8018(02)00142-7.

Sarıöz, K., Kükner, A. and Narlı, E. (2002) ‘A Real-Time Ship Manoeuvring Simulation Study for the Strait of Istanbul (Bosporus)’, *Journal of Navigation*, vol. 52, no. 3, pp. 394–410 [Online]. DOI: 10.1017/s0373463399008498.

Shu, Y., Daamen, W., Ligteringen, H. and Hoogendoorn, S. (2015a) ‘Operational model for vessel traffic using optimal control and calibration', *Scientific Journals of the Maritime University of Szczecin*, vol. 42, no. 114, pp. 70–77.

Shu, Y., Daamen, W., Ligteringen, H. and Hoogendoorn, S. (2015b) 'Vessel Route Choice Theory and Modeling', *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2479, no. 1, pp. 9–15 [Online]. DOI: 10.3141/2479-02.

Shu, Y., Daamen, W., Ligteringen, H. and Hoogendoorn, S. P. (2017) 'Influence of external conditions and vessel encounters on vessel behavior in ports and waterways using Automatic Identification System data', *Ocean Engineering*, Elsevier, vol. 131, no. July 2016, pp. 1–14 [Online]. DOI: 10.1016/j.oceaneng.2016.12.027.

Shu, Y., Daamen, W., Ligteringen, H., Wang, M. and Hoogendoorn, S. (2018) 'Calibration and validation for the vessel maneuvering prediction (VMP) model using AIS data of vessel encounters', *Ocean Engineering*, Elsevier Ltd, vol. 169, no. June, pp. 529–538 [Online]. DOI: 10.1016/j.oceaneng.2018.09.022.

Szlapczynski, R. and Szlapczynska, J. (2016) 'An analysis of domain-based ship collision risk parameters', *Ocean Engineering*, Elsevier, vol. 126, pp. 47–56 [Online]. DOI: 10.1016/j.oceaneng.2016.08.030.

Szlapczynski, R. and Szlapczynska, J. (2017) 'Review of ship safety domains: Models and applications', *Ocean Engineering*, Elsevier Ltd, vol. 145, no. January, pp. 277–289 [Online]. DOI: 10.1016/j.oceaneng.2017.09.020.

Thiers, G. F. and Janssens, G. K. (1998) 'A Port Simulation Model as a Permanent Decision Instrument', *Simulation*, vol. 71, no. 2, pp. 117–125 [Online]. DOI: 10.1177/003754979807100206.

Thomas, B. S. and Sclavounos, P. D. (2007) 'Optimal-control theory applied to ship maneuvering in restricted waters', *Journal of Engineering Mathematics*, vol. 58, no. 1–4, pp. 301–315 [Online]. DOI: 10.1007/s10665-006-9130-6.

Unctad (2013) *World Investment Report Global Value Chains: Investment and Trade For 2013 New York and Geneva*,.

Wang, T., Yan, X., Wang, Y. and Wu, Q. (2019) 'A collision risk-based ship domain method approach to model the virtual force field', *PSAM 2018 - Probabilistic Safety Assessment and Management*, no. September.

Watanabe, S., Hasegawa, K. and Rigo, P. (2008) 'Inland Waterway Traffic Simulator', *Compit'2008*, pp. 578–588.

Xiao, F. (2014) *Ships in an Artificial Force Field: A Multi-agent System for Nautical Traffic and Safety*,.

Xiao, F., Ligteringen, H., Gulijk, C. Van and Ale, B. (2013) ‘Nautical traffic simulation with multi-agent system’, *International Workshop on Nautical Traffic Models*, no. Itsc, pp. 1245–1252.

Xu, W., Chu, X., Chen, X. and Li, Y. (2013) ‘Method of generating simulation vessel traffic flow in the bridge areas waterway’, *Proceedings - 2013 International Conference on Computer Sciences and Applications, CSA 2013*, pp. 808–812 [Online]. DOI: 10.1109/CSA.2013.193.

Xu, W., Liu, X. and Chu, X. (2015) ‘Simulation models of vessel traffic flow in inland multi-bridge waterway’, *ICTIS 2015 - 3rd International Conference on Transportation Information and Safety, Proceedings*, pp. 505–511 [Online]. DOI: 10.1109/ICTIS.2015.7232136.

Zhou, Y., Daamen, W., Vellinga, T. and Hoogendoorn, S. (2019) *Review of nautical traffic models from vessel behavior modelling perspective*,.

Zimmermann, R. and Gilles, E.-D. (2017) ‘State Estimation and System Identification of Inland Vessels’, *IFAC Proceedings Volumes*, Elsevier, vol. 31, no. 30, pp. 251–256 [Online]. DOI: 10.1016/s1474-6670(17)38448-3.