Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Marius Trodahl

Verification of a collision avoidance algorithm in open sea and full visibility using fuzzy logic

Master's thesis in Marine Cybernetics
Supervisor: Dong Trong Nguyen
Co-supervisor: Tom Arne Pedersen, Azzeddine Bakdi
June 2021

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MSC THESIS DESCRIPTION SHEET

Name of the candidate:	Marius Trodahl
Field of study:	Marine Cybernetics
Thesis title (Norwegian):	Verifikasjon av en kollisjonsunngåelses algoritme i åpen sjø og full sikt ved bruk av fuzzy logic
Thesis title (English):	Verification of a collision avoidance algorithm in open sea and full visibility using fuzzy logic

Background
Autonomous surface vehicles have been a subject undergoing intense study. The autonomy provides a good potential regarding reducing the cost, increasing safety, reliability, efficiency and sustainability. The highest level of autonomous system is able to make decision itself. If the system is not tested and verified at an optimal manner it could lead to fatal consequences, e.g. crashing into another vessel, grounding or colliding with a quay. To trust the system, testing and verification of collision avoidance for autonomous vessels needs to be performed. However, there are still inadequate rule sets and methods for testing and verification.

The testing and verification of the system is a critical task; and this motivates the thesis considering the testing and verification of the collision scheme.

Work description
1. Perform a background and literature review to provide information and relevant references on:
   - Testing and verification of Autonomous systems
   - Different collision avoidance algorithms: Velocity obstacle, Model Prediction control (MPC and Simulation-based Model Prediction control (SBMPC)
   - Fuzzy logic
   - Navigational rules (COLREGs)
   - Closest point of approach
2. Design scenario-based testing for collision avoidance, focusing on head-on, overtaking and crossing situations
   a. Develop a fuzzy logic system to interpret COLREGs Rules, which are written for a human operator, by transforming vagueness to computer language.
   b. This fuzzy logic system is developed to evaluate COLREGs compliance in one score, i.e. one metric, in the range of $0-100\%$, to state the COLREGs compliance.
   c. This fuzzy logic system is developed to evaluate a one to one (a pair) vessel encounter.
   d. This fuzzy logic system is developed to evaluate multiple vessel encounters.
   e. The fuzzy logic system is developed to evaluate ownship evaluation and ownship + target ship evaluation
3. Using a simulator to obtain scenario data to evaluate the COLREGs compliance with Fuzzy logic

Specifications
The scope of work may prove to be larger than initially anticipated. By the approval from the supervisor, described topics may be deleted or reduced in extent without consequences with regard to grading.

The candidate shall present personal contribution to the resolution of problems within the scope of work. Theories and conclusions should be based on mathematical derivations and logic reasoning identifying the various steps in the deduction.

The report shall be organized in a logical structure to give a clear exposition of background, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Rigorous mathematical deductions and illustrating figures are preferred over lengthy textual descriptions. The report shall have font size 11 pts., and it is not expected to be longer than 60-80 A4 pages, from introduction to conclusion, unless otherwise agreed upon. It shall be written in English (preferably US) and contain the following elements: Title page, abstract, acknowledgements, thesis specification, list of symbols and acronyms, table of contents, introduction with objective, background, and scope and delimitations, main body with problem formulations, derivations/developments and results, conclusions with recommendations for further work, references, and optional appendices. All figures, tables, and equations shall be numerated. The original contribution of the candidate and material taken from other sources shall be clearly identified. Work from other sources shall be properly acknowledged using quotations and a Harvard citation style (e.g. *natbib* Latex package). The work is expected to be conducted in an honest and ethical manner, without any sort of plagiarism and misconduct. Such practice is taken very seriously by the university and will have consequences. NTNU can use the results freely in research and teaching by proper referencing, unless otherwise agreed upon.

The thesis shall be submitted with a printed and electronic copy to the main supervisor, with the printed copy signed by the candidate. The final revised version of this thesis description must be included. The report must be submitted according to NTNU procedures. Computer code, pictures, videos, data series, and a PDF version of the report shall be included electronically with all submitted versions.

Start date: 15 January, 2021 **Due date:** 21 June, 2021

Supervisor: Dong Trong Nguyen
Co-advisor(s): Tom Arne Pedersen, Azzeddine Bakdi

Trondheim, 20.06.2021

Dong Trong Nguyen
Supervisor

Preface

This thesis represents the final delivery for a Master of Science within Marine Cybernetics. The work was conducted from January to June 2021.

The work is motivated through the lack of evaluation of Convention on the International Regulations for Preventing Collisions at Sea (COLREGs) in one metric and for multi vessel encounters within the literature. The approach utilizes fuzzy logic as this method could handle vague terms and the fuzzy rules could be written with linguistic variables and values that could represent COLREGs in a great manner. The goal is to develop two evaluation systems, where one system could evaluate COLREGs compliance in an executed scenario in regard to how the Own-Ship (OS) and Target Ship (TS) behaved, while the latter was to only evaluate the OSs behaviour.

The methodology utilized in this thesis to incorporate COLREGs in a computer language manner and evaluate COLREGs compliance with fuzzy logic provided promising results. Several evaluations are conducted to validate the designed systems; the evaluation results were compared with the interpretation of the North-East trajectory, heading and speed plots.

Acknowledgments

I would like to acknowledge my supervisor, Prof. Dong Trong Nguyen for providing me with relevant literature, valuable discussions, reviewing my thesis and always taking time to help me, especially with MATLAB. I would also like to acknowledge my co-supervisor, Principal Researcher Tom Arne Pedersen (DNV) for valuable discussions upon COLREGs, relevant literature, always being available and reviewing my thesis and my second co-supervisor, Postdoctoral Azzeddine Bakdi for guiding me weekly with the designed evaluation systems with regard to fuzzy logic, valuable discussions on COLREGs and reviewing my thesis.

Last but not least i would like to thank Selina for always motivating me and my family for unconditional support.

Marius Trodahl

MT
June 21, 2021

Abstract

Autonomous Surface Vehicles (ASV) have been a subject undergoing intense study. The autonomy provides good potential regarding reducing the cost, increasing safety, reliability, efficiency and sustainability. The highest level of autonomous system is able to make decision itself. If the system is not tested and verified at an optimal manner it could lead to fatal consequences, e.g. crashing into another vessel, grounding or colliding with a quay. Therefore, testing and verification of the autonomous system needs to be performed to obtain trust, where the Collision Avoidance System (CAS) is a critical part of the control system. However, there are still vague rule sets and inadequate methods for testing and verification. This work focuses on evaluating COLREGs compliance which is central in performance verification and safety testing due to the central role of COLREGs.

The work conducted in this thesis was motivated through the lack in the literature of evaluation of a CAS in one metric for multi vessel encounters in regard to COLREGs. The approach utilizes fuzzy logic as this method could handle vague terms, could represent linguistic variables and values written in COLREGs in a quantitative mathematical form without introducing sharp assumptions or specifications to original COLREGs. The goal is to develop evaluation systems to test and verify the CAS in regard to COLREGs, and it is broken down into three objectives. The first system developed system, denoted as obj. 1, evaluates the COLREGs compliance of a finished scenario in regard to how OS and TS cooperatively behaved to evacuate the situation and avoid risk of collision. The second evaluation system, denoted as obj. 2, focuses on evaluating the COLREGs compliance of how the OS behaved in a situation with a risk of collision. Both pairwise evaluation systems, obj. 1 and obj. 2, are then extended to evaluate the compliance in multi vessel encounter scenarios in the third objective, denoted obj. 3.

Obj. 1 contributes to verifying how vessels should behave in a scenario to obtain COLREGs compliance. In testing and verification of a control system, Class societies only consider the OS, therefore obj. 2. With these systems obj. 1 could be utilized to determine what challenges are in the provided scenario, and then utilize this scenario to evaluate OSs compliance, i.e. obj. 2, e.g. a scenario where TS does not comply to COLREGs would be great to test the OSs control system on.

The designed systems are verified on a set of simulated scenarios, utilizing fuzzy

logic to firstly incorporate COLREGs in a computational algorithm, machine-executable software form and secondly evaluate COLREGs compliance for obj. 1, 2 and 3. The obtained results are validated against visual assessment of the North-East trajectory, heading and speed plots, where the evaluation systems provided variables that would be challenging or impossible to obtain by visual assessment.

Sammendrag

Autonome overflatefartøy er er et populært emne som det er blitt gjort mye forskning på. Ved bruk av autonome overflatefartøy kan man redusere kostnader, øke sikkerhet, pålitelighet, effektivitet og oppnå et mer bærekraftig fartøy. Det høyeste nivået av autonome systemer kan ta valg selv. Om et system ikke er testet og verifisert på en optimal måte, kan det føre til fatale konsekvenser, f.eks. kollisjon med et annet fartøy, grunne eller en kai. For å kunne stole på det autonome systemet er det viktig å teste og verifisere systemet. Kollisjonsunngåelsessystemet er en kritisk del av kontrollsystemet som må bli testet og verifisert, men det er fremdeles vage regler og utilstrekkelige metoder for testing og verfisering av denne delen. Derfor fokuserer denne oppgaven på å evaluere COLREGs samsvar, som er sentral i opptredende verifikasjon og sikkerhetstesting av kollisjonsunngåelsessystemet.

Arbeidet utført i denne oppgaven er motivert av mangelen i litteraturen på evaluering av kollisjonsunngåelsessystemet i en score for møter mellom flere fartøy i henhold til COLREGs. Metoden utført i oppgaven benytter seg av fuzzylogikk ettersom at fuzzylogikk kan håndtere vage beskrivelser og representere språklige variabler og verdier slik innholdet i COLREGs er. Dette gjør også at COLREGs blir implementert på en dataspråklig måte i en kvantitativ matematisk form, uten å innføre antagelser eller spesifikasjoner til originale COLREGs. Målet med oppgaven er å utvikle systemer som kan evaluere kollisjonsunngåelsessystemet i henhold til COLREGs. Systemene som er utviklet i denne oppgaven er delt inn i 3. Det første utviklede systemet evaluerer COLREGs samsvar med et utført scenario i henhold til hvordan OS og TS samarbeidende oppfører seg for å unngå kollisjon. Dette systemet er betegnet som obj. 1. Det andre utviklede systemet evaluerer OSs oppførsel i henhold til COLREGs, betegnet som obj. 2. Begge disse evalueringssytemene kan evaluere COLREGs samsvar med flere fartøy, det vil si når det er flere TS enn ett, og er betegnet som obj. 3.

Obj. 1 bidrar til å se hvordan fartøyene skal oppføre seg i et scenario for å oppnå COLREGs samsvar. I testing og verifisering av kontrollsystem bryr Klassifiseringsselskap seg kun om OSs oppførsel, derrav obj. 2. Med disse systemene kan man finne utfordringene i et scenario med obj. 1 for så å teste kontrollsystemet til OS med samme scenario med obj. 2. F.eks. vil et scenario hvor TS ikke følger COLREGs være en god test for OSs kontrollsystem.

De utviklede evalueringssystemene er testet og verifisert på flere simulerte scenarioer, ved å benytte fuzzylogikk til å implementere COLREGs på en dataspråklig måte og deretter evaluere COLREGs samsvar med obj. 1, 2 og 3. De oppnådde resultatene viser at å benytte fuzzylogikk gir gode muligheter. Resultatene er validert gjennom sammenligning av de utviklede evalueringssystemenes resultat og visuell analyse av Nord-Øst, retning og hastighets plot.

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Abbreviations

ASV = Autonomous Surface Vehicle
CAS = Collision Avoidance System
COG = Center Of Gravity
COLREGs = Convention on the International Regulations for Preventing Collisions at Sea
CPA = Closest Point of Approach
DPCA = Distance at Closest Point of Approach (between two vessels)
FMF = Fuzzy Membership Function
GVO = Generalized Velocity Obstacle
LOS = Line-Of-Sight
MPC = Model Predictive Control
OS = OwnShip
PID = Proportional–Integral–Derivative controller
SBMPC = Simulation-Based Model Predictive Control
TCPA = Time to Closest Point of approach
TS = Target Ship
VO = Velocity Obstacle
WP = WayPoint

Chapter 1

Introduction

1.1 Background

ASVs have been a subject undergoing intense study. Autonomy may reduce cost, increasing safety, reliability, efficiency and sustainability. The highest level of autonomous systems are able to make decision itself. Utne et al. (2017) defined autonomy in four levels, i.e. level one remote system, e.g. a remotely operated vehicle, level two management by consent, e.g. a system where consent by an operator is required to make an action such as dynamic positioning, level three semi autonomous (management by exception), e.g. an emergency shut-down safety system, and level four highly autonomous system, e.g. an autonomous underwater vehicle. There exists several different definitions of level of autonomy, e.g. Sheridan (1992) defined 10 levels of autonomy.

Testing and verification of an ASV is required to obtain trust and reduce the number of defects in the system. If the ASV is not tested and verified, the chances of fatal consequences are higher, e.g. a collision. However, there are still vague rule sets and inadequate methods for testing and verification. The main focus in this thesis is considering testing and verification of collision avoidance system (CAS) in regard to their compliance to the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs).

Antao and Soares (2008) and Rothblum (2002) stated that $75-96\%$ of marine accidents and causalities were by human errors. While Smierzchalski and Michalewicz (2000) stated that 56% of any marine accident and causality were due to violation of COLREGs. Woerner and Benjamin (2015) emphasized the lack of protocols of examination of COLREGs compliance for an ASV. Thereof, developing methods to evaluate a CAS for one to one and multi vessel encounters in regard to COLREGs is a great motivation for this thesis.

1.2 Literature review

This section provides a literature review on testing and verification of autonomous systems, collision avoidance, fuzzy logic, COLREGs and closest point of approach.

1.2.1 Testing and verification of autonomous systems

In Perez et al. (2019) there has been gathered information about system verification, process and testing of autonomous systems. It was stated that the complexity of an autonomous system makes it harder to verify and there is missing ethical guidelines and regulations. In this context the system verification process is an ongoing process, e.g. when an autonomous system has a software update there is required new testing and verification on the autonomous system. In the paper an intuitive example is given, i.e. a self-driving car is tested and verified in America, but the car could not operate in Scandinavia where the cars and pedestrians might behave differently.

The paper proposed a three-step testing and verification process and concluded with six main challenges and four main opportunities with autonomous system. Summarizing some of them are that autonomous systems might need assistance from operators and even in some certain scenarios with control handed over which is challenging to know when and how. If an autonomous system is verified it becomes easier to predict how the system will react compared to a human in the loop. Moreover, with the human out of the loop testing the system with simulations would be more time efficient compared to dependent on a operator.

A research by Helle et al. (2016) conducted by Airbus Group Innovation specified the challenges with testing an autonomous system. The study stated a consensus among researches: "*If testing complex systems is hard, then testing complex autonomous systems is even harder*" (Helle et al. (2016)).

Factors that cause the testing and verification process challenging are the complexity of the environment, complexity of the software, confidence in the system, dependence on the operational, non-deterministic behaviour, fault avoidance, fault removal and fault tolerance (Helle et al. (2016)). The paper proposed a synopsis to support autonomous system design and testing, and concluded that the testing and verification of autonomous system is a big challenge and requires more research.

1.2.2 Collision avoidance

Huang et al. (2020) conducted a review on existing collision avoidance methods for unmanned and manned vessels, which is the main read for this section. Collision preventing, i.e. techniques involved in collision avoidance, could be divided into three categories, i.e. route planning, path planning and reactive collision avoidance. Route planning develops a route on a large map, path planning develops a collision free path concerning static obstacles and the reactive collision avoidance, i.e. the relevant category for this thesis, is a technique to avoid moving obstacles. The paper defined collision avoidance as "*Collision Avoidance is a process in which one ship (manned or unmanned) departs from its planned trajectory to avoid a potential undesired physical contact at a certain time in the future.*" (Huang et al. (2020))

Moreover, the paper defined the collision avoidance as two sub-problems, i.e. conflict detection and conflict resolution. For a manned vessel the integrated navigational system detects a conflict, where the officer on watch does an evasive maneuver if necessary, i.e. the conflict resolution. For an unmanned vessel the guidance navigational control system executes both conflict detection and resolution.

The main CAS algorithms presented in this section are the Velocity obstacle (VO), Model Predictive Control (MPC) and the Simulation-based Model Predictive Control (SBMPC).

Kuwata et al. (2013) constructed a VO algorithm and conducted on-water demonstrations of their autonomous vessel. The VO calculates a velocity obstacle, if the velocity vector of the vessel is inside the velocity object it might lead to collision.

MPC is a controller which obtains the control inputs by solving an optimization problem at each time step (Foss and Heirung (2013)). The MPC has been used in several CAS with modifications, such as Abdelaal et al. (2018) developed a nonlinear MPC to obtain trajectory tracking and collision avoidance, Eriksen et al. (2020) used a hybrid three layered collision avoidance method with MPC for an ASV and Johansen et al. (2016) developed the SBMPC method.

The SBMPC simulates different control inputs to obtain estimates of different ship behaviours and selects the control input which gives the lowest risk. In Huang et al. (2020), the main read for this section, it is stated that the SBMPC incorporates the ship dynamics, offers the control input and trajectory to avoid a collision. The challenging part with the SBMPC is the balance between the effectiveness and efficiency. The VO offers the maneuvers to avoid a collision such as course, velocity and more. Therefore, for a manned vessel it might be better to use VO than SBMPC due to the fact that the interpretation of course and velocity is more comprehensible than a control input.

1.2.3 Fuzzy Logic

This section will review the fuzzy logic usage and its advantages in autonomy.

Fuzzy Logic used in collision avoidance

Kijima and Furukawa (2001) proposed a fuzzy logic system to obtain collision avoidance and control of the rudder to obtain the desired course change. The inputs to the collision avoidance fuzzy logic system were the time of closest point of approach (TCPA) and closest point of approach (CPA), which measure the collision risk. The fuzzy membership function (FMF) was constructed with triangular shapes. For the rudder controller the inputs were the lateral distance between initial and new course, difference between initial and new heading and yaw rate, also constructed with triangular FMFs. Four simulations were conducted to validate the algorithm, by this the paper concluded that the presented algorithm worked well. Perera et al. (2011) proposed a fuzzy logic system to obtain decision making for collision avoidance. The algorithm utilized collision distance, collision region, relative speed ratio and relative collision angle as input variables with trapezoidal FMFs and the outputs were the collision risk warning and a fuzzy decision. The paper concluded that the decision making fuzzy logic system performed well for a one to one encounter, but for a multiple vessel encounter the system should be updated.

Fuzzy logic in robotics

Peri and Simon (2005) proposed a fuzzy logic controller to obtain navigational behaviour for a fully autonomous robot to compete in an IEEE competition in 2004. The competition regarded covering the most area in the shortest amount of time. The fuzzy logic controller received the position and heading error as input to triangular FMFs. The paper argued that triangular FMFs would result in a faster controller. The fuzzy logic rules consisted of 18 rules to control two wheels on the robot, where the output was produced using the centroid fuzzy method. The paper concluded that the robot did as intended and there is a great potential of using fuzzy logic controllers for real world applications.

Nour et al. (2007) proposed a comparison of a fuzzy logic controller and a conventional Proportional–Integral–Derivative (PID) controller for an inverted pendulum robot. The aim of the robot was to obtain a vertical position of the pendulum, the inputs to the controller were the position of the cart and the falling angle of the pendulum. By these inputs the desired torque to obtain a vertical position of the pendulum was calculated. The inputs were given to a combination of triangular and trapezoidal FMFs, and the output was calculated by the centroid defuzzification method. The PID performed better than the fuzzy logic controller when the PID was tuned for a given mass. However, when changing the mass of the pendulum the PID totally failed while the fuzzy logic controller managed to keep the pendulum vertical. The paper concluded that the fuzzy logic controller is simpler and more robust than the PID.

Benefits with fuzzy logic

Peri and Simon (2005) and Sharma (2020) stated some of the benefits of fuzzy logic; it reasons more like a human, provides effective responses to complex inputs and ability to obtain a degree to truth, i.e. a value between 0 and 1, as compared to Boolean logic. Moreover, Peri and Simon (2005) stated it can accomplish great results with inexpensive hardware. The system could easily improve performance by adding new features or new fuzzy logic rules (Peri and Simon (2005), Sharma (2020)). Nour et al. (2007) stated fuzzy logic is robust, due to elimination of the complicated mathematical modeling process by use of control set rules, which also result in simpler implementation than modern control theory. Some real life applications given by Sharma (2020) are aircraft, satellites and spaceships to control the altitude, control and monitoring the speed and traffic for an automotive system, decision making support for large companies and controlling the acidity or basicity in chemical industries.

1.2.4 Literature review on COLREGs

This section will provide literature on COLREGs and CAS with COLREGs incorporated. By this the review will provide the interpretation of the difficulties when incorporating COLREGs into a CAS, and the lack of providing one overall score to evaluate COLREGs compliance, i.e. one metric to verify the compliance with regard to COLREGs. In this thesis an overall score is the evaluation of COLREGs as a whole.

Woerner (2016) developed an algorithm which evaluated how the vessel responded to avoid a collision in regards to COLREGs, with possibilities to perform online and post mission evaluation. The evaluation provided scoring for each active COLREGs Rule experienced in the scenario.

Benjamin and Curcio (2004) stated that COLREGs is written for humans and Naeem et al. (2012) stated that this leads to subjectivity. Moreover, Naeem et al. (2012) proposed examples of flexibilities in the Rules, such as when a Rule should apply. Rule 14 states to make a starboard alteration, but nothing about how much of an alteration. Another example is that Rule 16 states what the give-way (GW) vessel should do to avoid a collision, i.e. ”*take early and substantial action*” (IMO (1972)), where Naeem et al. (2012) stated that the action to avoid a collision should be assessed by a human operator, thereof it is challenging to incorporate COLREGs into a computer. The paper concluded that COLREGs are precise enough, but COLREGs flexibility could be exploited by humans.

Mohovic et al. (2016) presented data to identify gaps in the knowledge and learning of COLREGs, based on questionnaires given to nautical Bachelor of science students and experienced captains. The sample consisted of 1538 participants of which 46% were professional seafarers. Professional seafarers, students in nautical Bachelor of science and licensed watch officers answered a question about which Rules are the most difficult to understand, the paper received Rules 6, 10, 13, 14, 17, 18 and 19 as answers. Another question, only to the students, considered how it is to interpret the Rules, where 63% stated that it is difficult.

Since these regulations and Rules are written for humans to understand, a challenging task is to adopt them for computers. Several papers mentioned the dilemma of incorporating them into an ASV, where Woerner (2016) stated ”*The Rules are complex, vague, and full of nuances that must be considered*”. Woerner and Benjamin (2015) stated there is little literature on scoring protocol compliance in a metric manner, ”*protocol compliance is often asserted by authors in the collision avoidance realm*”. Johansen et al. (2016) noted that the main development of COLREGs has been for vessels operated by a crew and in a situation with only two vessels, i.e. one pair. Kuwata et al. (2013) stated the implementation of COLREGs into a computer is a challenging task, e.g. to determine if COLREGs apply for a simple scenario is not a trivial task since the Rules are written for human operators and often the interpretation of the Rules are by subjective measures.

An example by Kjerstad (2019) to illustrate the difficulties with COLREGs is given in Figure 1.1. The figure illustrates a scenario where Rule 13 Overtaking is applied to vessels A and C, while Rule 15 Crossing situation is applied to vessels A and B. Rule 13 states that vessel C which is overtaking vessel A shall keep out of the way and vessel A should keep her course and speed, i.e. vessel C should GW and vessel A should ”stand-on” (SO). In contrast, Rule 15 states that in a crossing situation the vessel (A) which has the other (B) on her own starboard shall keep out of the way, i.e. GW. By this vessel A should SO in the encounter with vessel C and GW in the encounter with vessel B. This example reveals one of the problem with COLREGs, that it is written for a vessel to vessel encounter and not for multi vessel encounters. In a real-life scenario there might be several vessels and the different roles, i.e. GW or SO, and actions to avoid a collision is based on the interpretation of the COLREGs by a human operator.

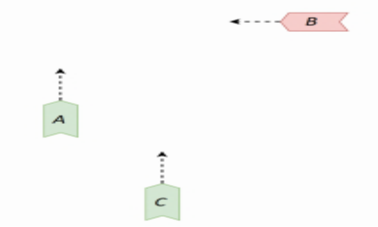


Figure 1.1: Scenario with three vessels (Kjerstad (2019))

1.2.5 Closest Point of Approach

Several COLREGs Rules, e.g. Rule 14 and 15, states something about the risk, but nothing about what parameter should be assessed nor the metric. In this context, Campbell et al. (2014) tried to relate the Closest Point of Approach (CPA) with risk by stating that if CPA is below 100 meters, risk is present. Bertaska et al. (2015) used a pre-determined CPA and TCPA to determine if the control primitive is in a collision situation. Moreover, the paper stated that these pre-determined parameters are dependent on the vessel size, maximum surge speed and maximum turning radius of the vessel. Kuwata et al. (2013) also used pre-determined values of CPA and TCPA to determine if COLREGs Rules should apply without stating how to obtain these pre-determined values. By this CPA measures are considered the assessment of risk for this thesis.

DCPA is the estimated distance between two vessels moving forward in time with constant speed and course, TCPA is the time until the DCPA will arise and CPA is the North-East coordinates for the CPA, e.g. useful to assess the pose. In the literature DCPA is often referred to CPA, e.g. looking at the section above where Bertaska et al. (2015) utilizes CPA. Moreover, some utilizes the notation DCPA as the distance to CPA, e.g. Vujičić et al. (2017) utilizes this notation, but for this thesis the notation DCPA is referred to the distance at CPA, thereof the author has changed the notation in the following to obtain the desired notation, i.e. DCPA for the distance to another vessel at CPA and CPA as the North-East coordinates.

The Faculty of Maritime studies in Rijeka conducted a research (Vujičić et al. (2017)) for the EU project ”Avoiding Collision at Sea”, to determine safe DCPA for an open sea situation. It contained a survey, with 256 respondents where 19.5% of them had less than 5 years of navigational experience, 16.5% had between 5 and 10 years of navigational experience and 64% had more than 10 years of navigational experience. The question to determine a safe DCPA in open sea gave additional information such as ship length and speed. The survey results concluded that a DCPA of 1.6 to 2.5 nautical miles was considered as a safe DCPA. The paper also included a table containing other studies conducted on DCPA, but highlighting that these studies did not included vessel parameters such as ship length and speed. A summarizing of the table stated that Goodwin (1975) determined a safe DCPA of 2.35 nautical miles, Davis et al. (1980) stated a safe DCPA of 1.8 nautical miles and Pietrzykowski and Uriasz (2009) stated a safe DCPA of 1.5 to 2.2 nautical miles.

As seen from the literature review, different DCPA safety limit parameters are incorporated for autonomous systems and methods to avoid a collision, while the COLREGs does not provide precises standards to implement the Rules in a computer language, but with fuzzy logic there are great possibilities represent this. The scoring of COLREGs compliance is often conducted by the authors of their subjective interpretation of a scenario or by scoring each active Rule in the scenario. The literature lacks a method to evaluate COLREGs compliance in one overall score, i.e. one unique metric that evaluates all active Rules in the scenario and evaluation of a multi vessel encounter.

1.3 Objective and scope

The objective of this thesis is to develop two fuzzy logic systems which will evaluate COLREGs compliance in one score, i.e. one metric, in the range of $0 - 100\%$, to state the COLREGs compliance. The evaluation system will use data from a completed simulation. The goal is to develop systems that will evaluate a one to one vessel encounter firstly, and modify this system to obtain evaluation on multiple vessel encounters. The first fuzzy logic system will evaluate the COLREGs compliance in regard to OS and TS, i.e. denoted as obj. 1, while the second fuzzy logic system will evaluate OS compliance only with regard to COLREGs, i.e. denoted as obj. 2. The multiple vessel encounter evaluation system is designed for both obj. 1 and 2 and is denoted as obj. 3. Fuzzy logic and fuzzy logic control theory are useful for uncertain information (variable measurement error) and lack of precise models. Uncertainty in this thesis is in COLREGs term, the Rules are expressed in human language and designed for human reasoning not computational algorithms. The Rules are therefore uncertain and the terms in the Rules are not specific. Even if input variables are numeric and accurate, their interpretation in COLREGs is uncertain and it varies according to the context and between users in academia and in application. COLREGs are international conventions, they cannot be tailored or honed by assuming sharp definitions of their terms. There are no sharp limits that all seafarers agree on. Therefore, fuzzy logic is utilized to incorporate COLREGs in a computer language.

Besides designing scenario compliance evaluation systems, the scope of this thesis covers the following:

1. Perform a background and literature review to provide information and relevant references on:
    - Testing and verification of Autonomous systems
    - Different collision avoidance algorithms: Velocity obstacle, Model Prediction control and Simulation-based Model Prediction control
    - Fuzzy logic
    - Navigational Rules (COLREGs)
    - Closest point of approach (CPA)
2. Design scenario-based testing for collision avoidance, focusing on head-on, overtaking and crossing situations
3. Using a simulator to obtain scenario data to evaluate the COLREGs compliance with fuzzy logic

1.3.1 Assumptions

This section contains assumptions used in the development of the evaluation system.

1. Several restricted waters and channels have national regulations (Perera et al. (2011)) in addition to COLREGs. This thesis considers only COLREGs.

2. All vessel encounters are assumed to be power-driven vessels. This is by reason of the different Rules for different types of vessel and other ship navigation status, e.g. sailing vessels and fishing boats have other regulations in COLREGs than power-driven vessels.

3. This work is limited to compliance evaluation in open waters, good sea and visibility conditions which cover the majority of traffic situations. This work need to be extended in order to cover Rules like Narrow channels, i.e. Rule 9, and Rule 19 Conduct of vessels in restricted visibility.

4. The propulsion command and heading angle offset values from the CAS system for both the OS and the TSs are assumed known. This will simplify the desire to test for ”early action” and ”succession of small alterations” which are a part of Rule 8 and 16 in COLREGs. This will be highlighted more in the Section 3.1.3.

5. Finally the parameters that are proposed in the design of the FMFs, fuzzy rules and DCPA parameters are assumed valid. These may be different from subjective measures, e.g. Rule 14 Head-on situation uses ”reciprocal or nearly reciprocal courses” and this could be defined differently. The presented design is generic and the parameters can be easily modified or tuned if needed or tailored to specific applications

Even though this thesis uses simulation generated data, the evaluation methods developed in this thesis can be used on any data, e.g. real AIS data if available. In the following the COLREGs Rules are refereed to with a capital ”R”, while the fuzzy rules are not.

1.4 Contribution

The main contribution for this thesis is given in the following:

- Contribution to classification societies to provide a systematic verification of compliance of vessel encounter scenarios in open water, good sea and visibility conditions utilizing fuzzy logic.
- Provide a method that could evaluate AIS data, which will provide a score on OS and TSs behaviour, that could be utilized in OS CAS evaluations.
- Investigate the power of fuzzy logic, due to fuzzy logic can be used to interpret COLREGs Rules, which are written for a human operator, by transforming vagueness to computer-executable/ computational algorithms.
- Several evaluation results of different scenarios, for one TS and multi-vessel encounter scenarios, where COLREGs considers only pair scenarios.

To the knowledge of the author, the implementation of COLREGs with fuzzy logic to obtain an ASV CAS compliance has not been done before.

1.5 Organization of thesis

The thesis is dived into five chapters. Chapter 2 provides the necessary theory to understand the development of the system, i.e. the simulator developed by Kjerstad (2019), collision avoidance notation and fuzzy logic theory. Chapter 3 develops the methods to evaluate the system to obtain one overall score. Chapter 4 provides results obtained by the evaluation models and discussions among these results. Finally, Chapter 5 provides a conclusion and further work.

Chapter 2

Background theory

This chapter will give a brief introduction to marine control theory, general collision avoidance notation and finally fuzzy logic theory with an example to obtain comprehensive understanding. If there is need for more details regarding marine control theory the reader is referred to Fossen (2011).

2.1 Marine control system

A marine control system consists of several components and devices, which may vary largely depending on the marine vehicle, desired operation and more. This section will provide the reader with a brief introduction to the control system incorporated into the vessels used in the simulator which is used in this thesis to generate data for evaluation. For more details on the relevant control system, the reader is referred to Kjerstad (2019).

The OS and TSs have identical parameters, see Table 2.1.

Parameter	**Value**	**Unit**
Mass	15524000	kg
Length	116	m
Width	25	m

Table 2.1: Vessel parameters

The vessels control system consist of Line-Of-Sight (LOS) guidance, reference models, collision avoidance, feedback linearizing controller and a process plant which will simulate the real dynamics and kinetics of the vessel.

The LOS guidance ensures that the vessel follows a straight-line path between the WayPoints (WP) given by the human operator. The reference models are for the heading and the speed, where its assignment is to smooth out the input given by the LOS guidance block, because the LOS guidance output signal is given in steps and have to be smoothened before the feedback linearizing controller receives it as input, due to the slow dynamics of the vessels can not follow the step signal and smoothing this signal will reduce the wear and tear on the actuators. The feedback linearizing controller consists of two controllers where the assignment of this component is to make the vessel achieve the desired heading and speed obtained from the reference model. This is sent to the vessel as a control force which is adopted to how the actuators should react. Then there are measures on the vessel which sends back the ship states to the LOS guidance to verify if the vessel is doing as intended. The collision avoidance block gets the WP from the LOS Guidance, TSs states and sends out a propulsion command and heading angle offset to the controllers in case of risk of collision. By this the controllers will gain more inputs, i.e. the propulsion command and heading angle offset, if there exists a situation of collision. In Figure 2.1 the control system for OS is provided.

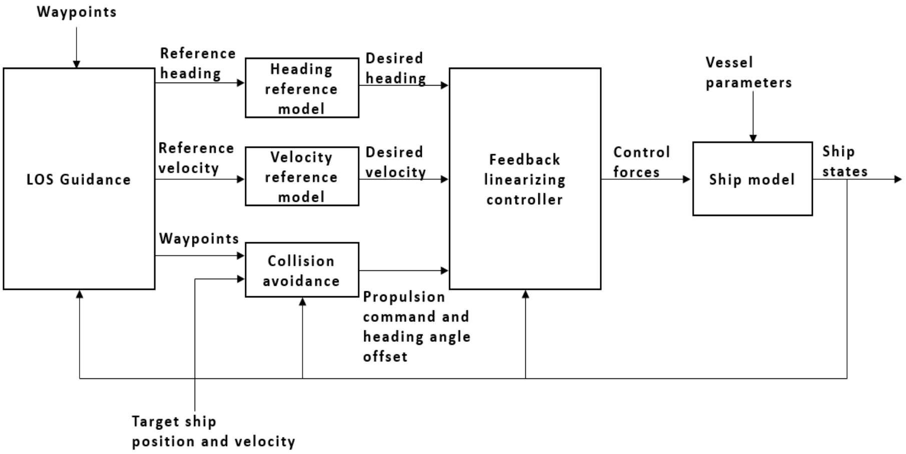


Figure 2.1: Components of OS, inspired by Kjerstad (2019)

The simulator has the ability to use one or more TSs. The OS has the SBMPC method for CAS in the control system and the TSs could be defined with and without SBMPC method for CAS in the control system. The simulator might provide unrealistic behaviours, e.g. when there is a heading change it is expected that there is also a speed change which is not the case in some scenarios, and some fast increase or decrease in speed and/or heading, i.e. also unrealistic, but the simulator is out of the scope of this thesis, therefore only a few comments on these unrealistic behaviours will be provided in Chapter 5.

2.2 General collision avoidance notation

This section describes general notation used in collision avoidance, inspired by Benjamin (2017). As stated ownship is denoted OS and target ship is denoted TS. The OS will avoid TS by active control. Figure 2.2 illustrate the notation for OS and TS with the position, heading and speed.

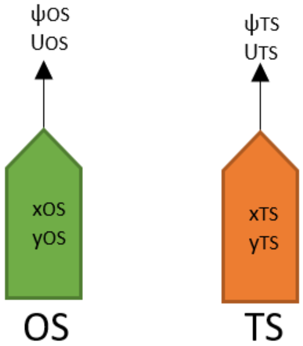


Figure 2.2: Notation for own ship and target ship inspired by Benjamin (2017)

- Current position of OS: x_{OS}, y_{OS}
- Current speed and heading OS: U_{OS}, ψ_{OS}
- Current position of TS: x_{TS}, y_{TS}
- Current speed and heading of TS: U_{TS}, ψ_{TS}

A useful operator in collision avoidance and in general ship notation is a mathematical operator which converts the heading to be inside the domain $\psi \in [0, 360)$. This is useful when the heading e.g. is $[\psi]^{360} = [405]^{360}$ which is actually 45 degrees. This is shown in Equation 2.1.

$$\psi = mod(\psi, 360) \tag{2.1}$$

mod is the modulus operator. The heading could also be specified in the domain $\psi \in [-180, 180)$, see Equation 2.2 given by Fossen (2011).

$$\psi = mod(\psi + 180, 360) - 180 \tag{2.2}$$

A way to describe the relative heading difference between the OS and TS is using the smallest absolute value, e.g. the difference between a heading of 340 and 10 is 30 degrees, not 330 degree. Provided in Equation 2.3, where 180 denotes that it is $\in [0, 180)$.

$$\Delta(\psi_1, \psi_2) = \mid [\psi_1 - \psi_2]^{180} \mid \tag{2.3}$$

Three methods to obtain a vessel position in relation to another vessel is the range, bearing angle and relative bearing angle. The range from OS to TS is the linear distance between OS and TS. The bearing from OS to TS is the angle from OSs North to the the linear distance to TS. The relative bearing from OS to TS is the angle from OSs heading to the linear distance to TS. Range is given in meters and the two others are given in degrees. The angle is given as $\in [0, 360)$ (clockwise direction) with North as 0° for the bearing angle and 0° at OS heading for the relative bearing angle.

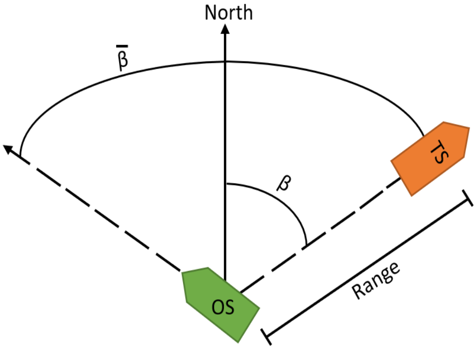


Figure 2.3: Range, bearing and relative bearing inspired by Benjamin (2017)

In Figure 2.3 the range, bearing and relative bearing angle are given as:

- Range between OS and TS: r_{TS}^{OS}
- Bearing from OS to TS: β
- Relative bearing from OS to TS: $\bar{\beta}$

The range from is the same, i.e. $r_{TS}^{OS} = r_{OS}^{TS}$, the bearing from TS to OS is denoted as the contact angle, α, and the relative bearing from TS to OS is denoted the relative contact angle, $\bar{\alpha}$.

The range could be found using Pythagorean theorem, given in Equation 2.4.

$$r_{TS}^{OS} = \sqrt{(x_{OS} - y_{OS})^2 + (x_{TS} - y_{TS})^2} \tag{2.4}$$

The bearing angle is given in Equation 2.5.

$$\beta = atan2(y_{TS} - y_{OS}, x_{TS} - x_{OS}), \tag{2.5}$$

with this the relative bearing angle is defined in Equation 2.6.

$$\bar{\beta} = \begin{cases} 360 - abs(\beta - \psi_{OS}) & \beta - \psi_{OS} < 0 \\ \beta - \psi_{OS} - 360 & \beta - \psi_{OS} \geq 360 \\ \beta - \psi_{OS} & else \end{cases} \tag{2.6}$$

The contact angle is calculated by the same manner as shown in Equation 2.5 by swapping the OS and TS with each other and the relative contact angle is calculated as the same manner as shown in Equation 2.6 by simply swapping the $\bar{\beta}$ with $\bar{\alpha}$, β with α and ψ_{OS} with ψ_{TS}.

Another useful parameter, provided in the literature review, see Section 1.2.5, is the DCPA which is calculated as given in Equation 2.7.

$$DCPA = r(t_{cpa}) = \sqrt{k_2 t_{cpa} + k_1 t_{cpa} + k_0} \tag{2.7}$$

The TCPA is calculated as given in Equation 2.8.

$$\frac{d}{dt} r^2 = 2k_2 t + k_1 \tag{2.8}$$

k_0, k_1 and k_2 are given in the following:

$$\begin{aligned} k_2 =& \cos^2(\theta_{os}) v_{os}^2 - 2\cos(\theta_{os}) v_{os} \cos(\theta_{cn}) v_{cn} + \cos^2(\theta_{cn}) v_{cn}^2 + \sin^2(\theta_{os}) v_{os}^2 - \\ & 2\sin(\theta_{os}) v_{os} \sin(\theta_{cn}) v_{cn} + \sin^2(\theta_{cn}) v_{cn}^2 \\ k_1 =& 2\cos(\theta_{os}) v_{os} y_{os} - 2\cos(\theta_{os}) v_{os} y_{cn} - 2y_{os}\cos(\theta_{cn}) v_{cn} + 2\cos(\theta_{cn}) v_{cn} y_{cn} + \\ & 2\sin(\theta_{os}) v_{os} x_{os} - 2\sin(\theta_{os}) v_{os} x_{cn} - 2x_{os}\sin(\theta_{cn}) v_{cn} + 2\sin(\theta_{cn}) v_{cn} x_{cn} \\ k_o =& y_{os}^2 - 2y_{os} y_{cn} + y_{cn}^2 + x_{os}^2 - 2x_{os} x_{cn} + x_{cn}^2 \end{aligned} \tag{2.9}$$

For a more detailed description on collision avoidance notations, good illustrations and calculations, see Benjamin (2017).

2.3 COLREGs

This section will provide the essential parts of the COLREGs used in the developed evaluation systems. See Appendix A for the direct citation. The rules considered in this thesis are given in the following:

- Rule 8 - Action to avoid collision
- Rule 13 - Overtaking
- Rule 14 - Head-on situation
- Rule 15 - Crossing situation
- Rule 16 - Action by give-way vessel
- Rule 17 - Action by stand-on vessel

Rule 8 considers what action a vessel should do to avoid a collision. The action, course and/or speed, should be large enough such that another vessel could observe this action on the radar or visually. This action should not be a succession of small alterations. Course alteration might be the most effective, if there is sufficient sea-room. The action should be made in ample time and result in passing at a safe distance. A vessel might slacken her speed or stopping or reversing to obtain more time to assess the situation.

Rule 13 considers an overtaking situation, where it states that when a vessel is overtaking another vessel she shall keep out of the way (GW). An overtaking scenario is considered when a vessel is coming up towards another vessel from a direction more than 22.5 degrees abaft the overtaken vessels beam. It also states when the overtaking vessel is in doubt if she is overtaking she shall assume such.

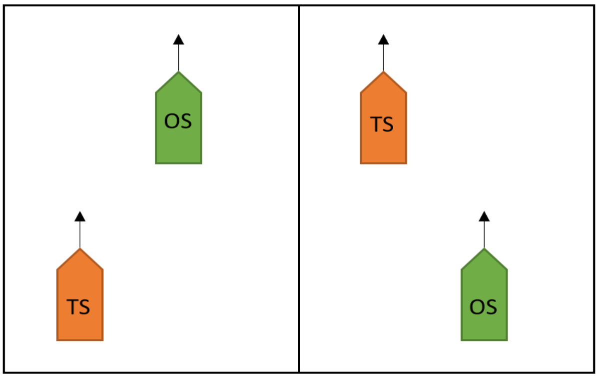


Figure 2.4: Illustration of overtaking scenarios

Figure 2.4 illustrates two overtaking situations. In the left the TS is overtaking the OS, therefore the TS should GW and the OS should SO, in the right the OS is overtaking the TS, therefore the OS should GW and the TS should SO.

Rule 14 considers a head-on situation, where it states that a head-on situation is considered when two vessels are meeting on reciprocal/nearly reciprocal courses and risk is present. If two vessels are in a head-on situation both vessels shall GW by altering course to starboard to obtain a portside passing. It also states when a vessel is in doubt if there is a head-on situation she shall assume such.

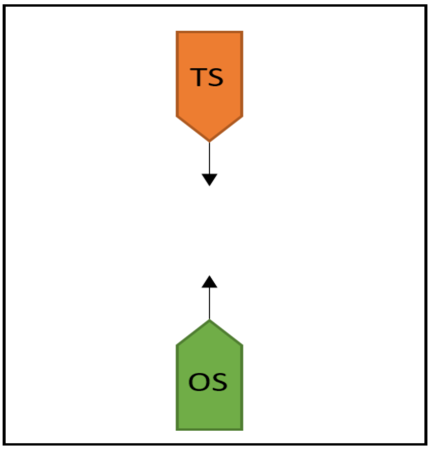


Figure 2.5: Illustration of a head-on scenario

Figure 2.5 illustrates two vessels in a head-on situation, by this both vessels shall GW by altering course to starboard to obtain a portside passing.

Rule 15 considers a crossing situation, where it states when two vessels are crossing and risk is present the vessel which has the other on her own starboard side shall GW.

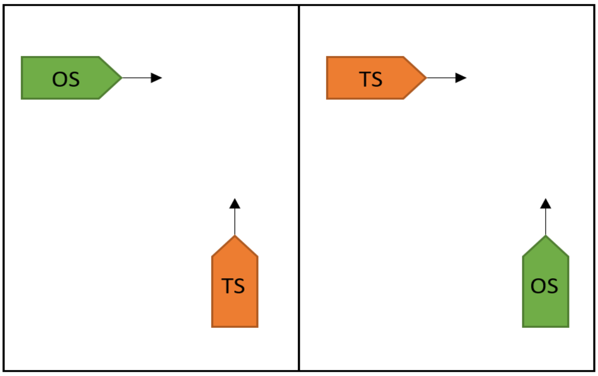


Figure 2.6: Illustration of crossing scenarios

Figure 2.6 illustrates two crossing situations. In the left the OS has the TS on her own starboard side and by this the OS shall GW. In the right the TS has the OS on her own starboard side and by this the TS shall GW.

Rule 16 considers the action by the GW vessel, where it states that the GW vessel shall take early and substantial action to avoid a collision.

Rule 17 considers the action by the SO vessel, where it states that the SO vessel shall keep course and speed, but if the GW vessel does not do appropriate action or the SO vessel experiences that collision cannot be avoided by the GW vessels actions alone the SO vessel must take actions to avoid a collision. Moreover, if the SO vessel must take actions to avoid a collision and the scenario is a crossing situation the SO vessel shall not alter course to portside for a vessel on her own portside.

2.4 Fuzzy logic

This section will provide fuzzy logic theory and an example of its use.

2.4.1 Introduction to fuzzy logic

Fuzzy logic is a branch of Artificial Intelligence that mimics the humans ability of reasoning under uncertainty and partial information. With Boolean logic, there is no such a partial degree of truth, a statement takes a binary state, i.e. either true or false denoted by 1 or 0, respectively. Fuzzy logic is an extension of the fuzzy sets introduced by Zadeh (1965), where fuzzy logics intention is to model logical reasoning with imprecise or vague statements (Cintula et al. (2017)).

A fuzzy set is defined by Zadeh (1965): ”*A fuzzy set (class) A in X is characterized by a membership (characteristic) function* $\mu_A(x)$ *which associates with each point in X a real number in the interval* $[0\ 1]$*, with the value of* $\mu_A(x)$ *at x representing the ”grade of membership” of x in A.*”

$$A = \{x, \mu_A(x) | x \in X\} \tag{2.10}$$

Equation 2.10 defines a fuzzy set, X denotes the universe of discourse and x is an element. Moreover, the equation gives a fuzzy set A in X where $\mu_A(x)$ is the membership function which maps each element in the universe of discourse, X, to a membership value between 0 and 1 (a degree of truth) (MathWorks (2020)).

Fuzzy logic provides mathematical tools that bridge between a linguistic value to the universe of discourse (Tizhoosh (2019)). Fuzzy reasoning includes three main processes fuzzification, inference and defuzzification, see Figure 2.7. A variable is linguistic if its values are linguistic, i.e. the values are words or sentences (Zadeh (1975)). E.g. $COLREGs\ compliance$ is a linguistic variable if its values are linguistic, e.g. $medium\ good$, $good$, $medium\ bad$ or bad instead of numerical values.

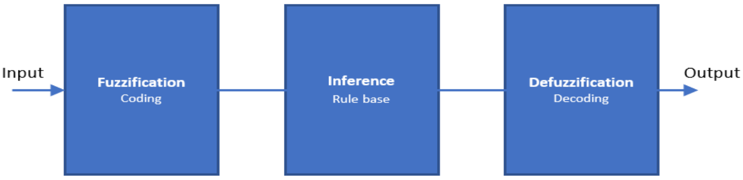


Figure 2.7: Simple flowchart of fuzzy logic, inspired by Tizhoosh (2019)

The linguistic variables and linguistic values are modeled mathematically by fuzzy variables and fuzzy values, respectively. Moreover, a fuzzy variable can include multiple fuzzy values.

To clarify the concept of fuzzy logic in COLREGs, an example will be provided in the following. This example is not a complete evaluation and it is not the actual design used to develop the evaluation systems, but it is to explain fuzzy logic. The example considers Rule 14 and 15 from COLREGs to determine what the role of OS is. This example will illustrate the power of fuzzy logic, as COLREGs provides vague statements when these situations applies, e.g. ”*two power-driven vessels are meeting on* ***reciprocal or nearly reciprocal*** *courses*”(IMO (1972)), but COLREGs do not provide any form of numerical value. The separation between crossing and head-on sectors is not precisely defined, where one vessel can be either or between SO and GW, i.e. the different roles OS could obtain. The inputs for the fuzzy logic example are the relative contact angle $\bar{\alpha}$ and the relative bearing angle $\bar{\beta}$.

2.4.2 Fuzzification

Fuzzification is the process of partial decomposition of a crisp quantity or characteristic into linguistic values. Based on the designed fuzzy variables, numerical inputs are mapped into fuzzy subsets through FMFs.

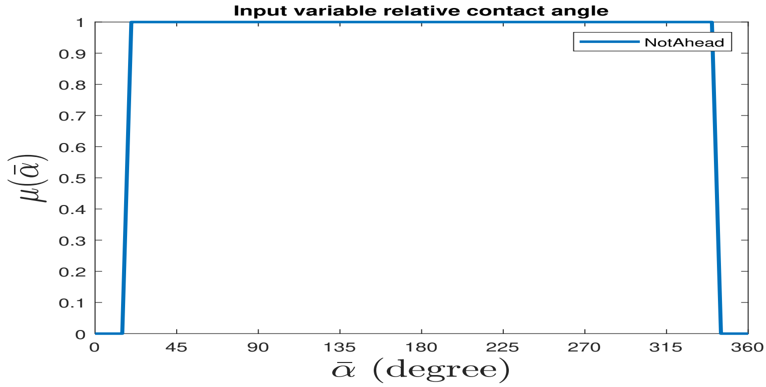


Figure 2.8: FMF for relative contact angle for R14

In Figure 2.8, the fuzzy variable $\bar{\alpha}$ is provided to the fuzzy value *NotAhead*, where the rule to determine head-on situation utilizes the "NOT" *NotAhead* to obtain the fuzzy value *Ahead*, where $\mu_{Ahead}(\bar{\alpha})$=$\mu_{NOT\ NotAhead}(\bar{\alpha})$=$1-\mu_{NotAhead}(\bar{\alpha})$. This is used to simplify the rules and avoid utilizing two fuzzy values instead of one, due to $\bar{\alpha} \in [0\ 360]$ and *Ahead* would be in both directions, i.e. in the lower and upper part, but not in-between. This fuzzy value is to determine if TS is travelling ahead OS. By the same manner the determination if OS is travelling ahead TS is obtained by the fuzzy variable $\bar{\beta}$ provided to the same fuzzy value.

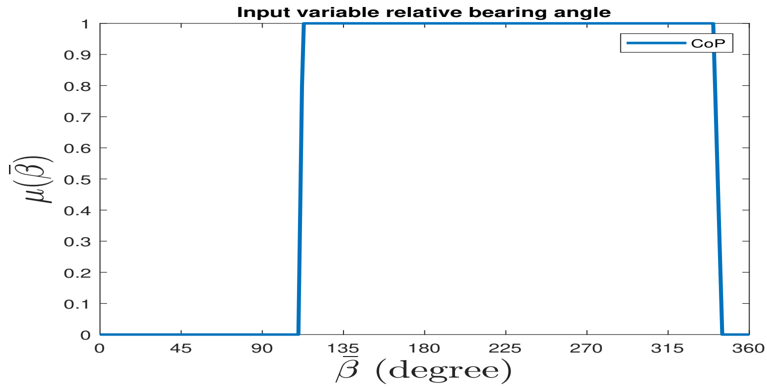


Figure 2.9: FMF for relative bearing angle for R15

In Figure 2.9, the fuzzy variable $\bar{\beta}$ is given to the fuzzy value *CoP*, i.e. Crossing on Portside. This is to assess if OS is crossing TS on portside. The universe of discourse is $[0, 360)$ for these two fuzzy variables, i.e. the possible values for the fuzzy variables.

In summary, the fuzzification is a method that converts the numerical values, crisp numbers, into fuzzy sets (GeeksforGeeks (2019)).

2.4.3 Inference

The inference executes the designed fuzzy rules, the if then rules. The rules for the previous example are given in the following:

e_1 : If $\bar{\alpha}$ is ”NOT” *NotAhead* and $\bar{\beta}$ is ”NOT” *NotAhead* then RoleOfOS is GW

e_2 : If $\bar{\beta}$ is *CoP* then RoleOfOS is SO

As seen from the rules they consists of antecedents, i.e. the if statement, and consequent, i.e. the then statement, where the degree of a consequent is the aggregated antecedents.

Consider the evaluation of a particular situation, $\bar{\beta}$=344, i.e. it has a fuzzy value of both ”NOT” *NotAhead* and *CoP*, and $\bar{\alpha}$=344.5, i.e. it has a fuzzy value of ”NOT” *Ahead*. Table 2.2 provides the degree of memberships of these fuzzy variables.
There are some fuzzy operations to provide which values should be mapped to the output fuzzy value, coupling between the rules and coupling the antecedents. These are the ”AND” and the ”OR” operation. The ”AND” operator between two values is often implied using the minimum operation between their fuzzy values

Fuzzy variable	**Crisp value**	**Membership function**	**Membership value**
$\bar{\alpha}$	344.5	$\mu_{NOTNotAhead}(\bar{\alpha})$	0.8
$\bar{\beta}$	344	$\mu_{NOTNotAhead}(\bar{\beta})$	0.9
$\bar{\beta}$	344	$\mu_{COP}(\bar{\beta})$	0.1

Table 2.2: Membership

and the ”OR” is often implied using the maximum operation between their fuzzy values. Since the two antecedents are connected with an ”AND” logic at e_1 (first rule), the value mapped to the output fuzzy value is obtained by $min(\mu(\bar{\alpha}), \mu(\bar{\beta})) = min(0.8, 0.9) = 0.8$. For e_2 (second rule) there is only one input fuzzy variable, i.e. $\bar{\beta}$ with the $\mu(\bar{\beta}) = 0.1$. These values are mapped to the same FMF output, but for different fuzzy values, see Figure 2.10. The first rule provide 0.8 belongings to the fuzzy value *GW* and the second rule with the value 0.1 provides belongings to the fuzzy value *SO*.

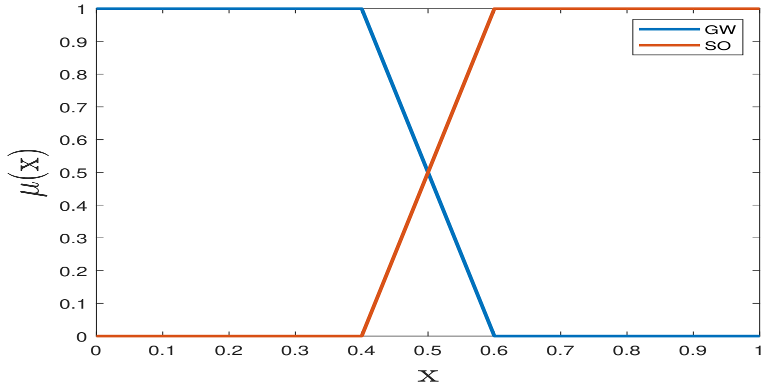


Figure 2.10: FMF to determine role of OS

Through fuzzy inference, the implication of each rule will result in a fuzzy subset.

2.4.4 Defuzzification

The final step is the defuzzification process, where the fuzzy subsets derived in the fuzzy inference are aggregated to a fuzzy set, through which the defuzzification process calculates a crisp output value. There are several defuzzification methods, but a common method is by the center of gravity method (Tizhoosh (2019)).

The center of gravity method to obtain the defuzzified value is calculated by Equation 2.11, where N is the number of subareas, x_i is the x-coordinate of the centroid of the area and A_i is the area.

$$COG = \frac{\sum_{i=1}^{N} A_i \times x_i}{\sum_{i=1}^{N} A_i} \tag{2.11}$$

The defuzzification of the example would then give a crisp value of approximately 0.308 by the center of gravity for the areas $\mu(GW) = 0.8$ and $\mu(SO) = 0.1$. In Figure 2.11 the aggregation of these two fuzzy subsets is provided and a red vertical line denoting where the center of gravity is, i.e. the defuzzified value.

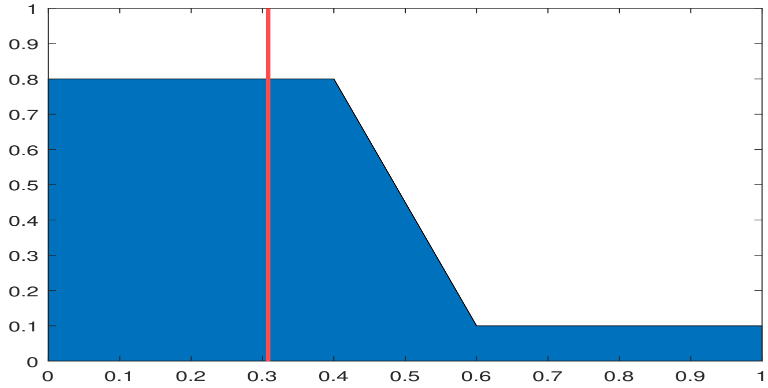


Figure 2.11: Aggregation of fuzzy subsets

The crisp (defuzzified) value is 0.308 which entitles a strong degree for OS to GW in this example.

In summary, the defuzzification converts the fuzzy sets implied from the inference to a numerical value (GeeksforGeeks (2019)).

2.4.5 Additional information on fuzzy Logic

The FMF could be of several geometrical shapes, e.g. trapezoidal (as used in the example), triangle, Gaussian, sigmoid and many others. Designing the trapezoidal FMF, which is the geometrical shape utilized in this thesis, takes a four-values parameter vector. For example the fuzzy value *NotAhead* in Figure 2.8 is defined by the parameters $[15\ 20\ 340\ 345]$, i.e. $\mu(x) = 0$ for $x \leq 15$; $\mu(x) = (x - 15)(20 - 15)$ for $15 < x \leq 20$; $\mu(x) = 1$ for $20 < x \leq 340$; $\mu(x) = (345 - x)(345 - 340)$ for $340 < x \leq 345$; $\mu(x) = 0$ for $345 < x$. The "OR" and "AND" operator are as stated often implied by the maximum and minimum, respectively, i.e. $\mu_{A\ OR\ B}(x, y) = max(\mu_A(x), \mu_B(y))$ and $\mu_{A\ AND\ B}(x, y) = min(\mu_A(x), \mu_B(y))$. The ”NOT” operator is $\mu_{NOT\ A}(x) = 1 - \mu_A(x)$. These are based on the standard Truth table and adjusted to comply with fuzzy Logic (MathWorks (2020)).

Chapter 3

Verification method for collision avoidance

This section presents the developed COLREGs-compliance evaluation models. The models receives a simulated scenario and gathers relevant information to evaluate compliance with respect to the COLREGs Rules. The evaluation systems are firstly developed for a one to one pairwise vessel encounter. The second part is an extension of the first evaluation systems to obtain evaluation of multiple vessel encounter scenarios, i.e. when $N \geq 2$ vessels and risk is present for all vessels.

For this chapter it is important to separate the COLREGs Rules and the fuzzy rules. The goal with the fuzzy logic systems is to reconstruct the COLREGs Rules in a fuzzy logic manner. The rules listed in the following sections are the fuzzy rules implemented in the fuzzy logic system, while referring to e.g. Rule 13 this means Rule 13 in COLREGs.

To obtain a broader overview in the figures, fuzzy rules and descriptions for the one to one evaluation system, the notation presented in Table 3.1 is utilized in the following.

Fuzzy variable	**Description of linguistic variable**	i, n
R_i	Role of vessel i	i=TS,OS
$\mathrm{R}_{i,n}$	Role of vessel i from COLREGs Rule n	i=TS,OS n=13,14,15
ts_i	Time at first deviation for vessel i	i=TS,OS
$\mathrm{TCPA}(\mathrm{ts}_i)$	Earliness of change for vessel i	i=TS,OS
$\lvert\Delta\chi_i\rvert$	Magnitude of course alterations for vessel i	i=TS,OS
$\lvert\Delta U_i\rvert$	Magnitude of speed alterations for vessel i	i=TS,OS
$\Delta\chi_i$	Course change for vessel i	i=TS,OS
ΔU_i	Speed change for vessel i	i=TS,OS
$\#\mathrm{SC}_i$	Succession of change for vessel i	i=TS,OS
C_i	Compliance under role i	i=GW,SO
$\Delta\chi$	Relative course from OS to TS	-
$\bar{\alpha}$	Relative contact angle	-
$\bar{\beta}$	Relative bearing angle	-

Table 3.1: This works designed fuzzy variables

3.1 Evaluation system for a one to one encounter

This section will provide the methodology of the one to one vessel encounter evaluation of OS and TS, i.e. obj. 1, and how it is developed.

3.1.1 Overview of the system

Obj. 1 is developed as a combination of three subsystems, i.e. system A, B and C, as illustrated in the diagram, given in Figure 3.1.

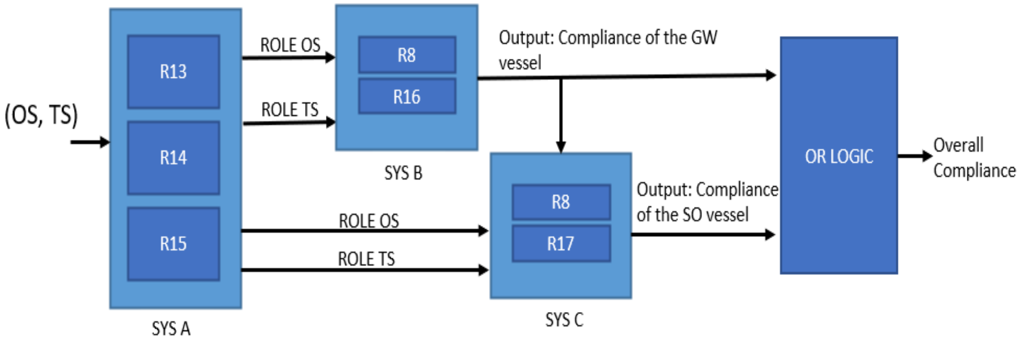


Figure 3.1: Diagram of system

In Figure 3.1, R stands for the evaluation system of a COLREGs Rule, e.g. R13 is the reconstruction of COLREGs Rule 13 in a fuzzy logic manner. The goal of system A is to determine the role of OS and TS based on variables calculated at the first time when the two vessels become in sight of one another, it is approximated by the time when a pre-determined range and TCPA value are present, since any subsequent alteration does not change the type of the situation. System B and C are based on variables estimated from the patterns of traffic of both vessels during the entire scenarios time-window from entrance to exit, where system B determines the compliance of the GW vessel and system C determines the compliance of the SO vessel. The final ”OR” logic is a combination of the GW and SO compliance score to obtain an overall compliance score, i.e. Overall Compliance $=\max(\mu(C_{GW}), \mu(C_{SO}))$, since a vessel should comply to COLREGs by executing the right maneuver, i.e. either SO or GW.

Table 3.2 lists where the different variables are given as input.

Variable	**System**
$\Delta\chi$	System A
$\bar{\beta}$	System A
$\bar{\alpha}$	System A
DCPA	System A
TCPA(ts$_i$)	System B
R$_i$	System B and C
$\lvert\Delta\chi_i\rvert$	System B and C
$\lvert\Delta$U$_i\rvert$	System B and C
#SC$_i$	System B and C
C$_{GW}$	System C

Table 3.2: Inputs to the evaluation systems

3.1.2 System A

System A covers three COLREGs Rules, i.e Rule 13, 14 and 15 constructed by the fuzzy logic systems R13, R14 and R15 respectively. The inputs to system A are $\Delta\chi$, $\bar{\beta}$, $\bar{\alpha}$, a variable to estimate risk, i.e. DCPA, and a variable to denote that the vessels Travel in the Same Direction, i.e. TSD.

The equation for the relative course for OSs perspective is given in equation 3.1.

$$\Delta\chi = mod(\chi_{OS} - \chi_{TS}, 360) \tag{3.1}$$

The relative bearing angle, $\bar{\beta}$, is calculated by equation 2.6, for simplicity it is repeated below:

$$\bar{\beta} = \begin{cases} 360 - abs(\beta - \psi_{OS}) & if \quad \beta - \psi_{OS} < 0 \\ \beta - \psi_{OS} - 360 & if \quad \beta - \psi_{OS} \geq 360 \\ \beta - \psi_{OS} & if \quad otherwise \end{cases} \tag{3.2}$$

$\bar{\beta}$ is the angle between the LOS vector from OS to the TS and OS heading (Woerner (2016)). The relative contact angle, $\bar{\alpha}$,is obtained in the same manner as $\bar{\beta}$, but from the TS perspective.

DCPA is calculated as given in 2.7. Repeated below for simplicity. For k_1, k_2 and k_3 see Equation 2.9.

$$DCPA = r(t_{cpa}) = \sqrt{k_2 t_{cpa} + k_1 t_{cpa} + k_0} \tag{3.3}$$

R13 receives $\bar{\beta}$ and $\bar{\alpha}$ to determine where each vessel is with respect to the other and DCPA to determine risk. Figure 3.2 illustrates the FMF for the fuzzy value *TSOvertakingOS* of the fuzzy variable $\bar{\beta}$.

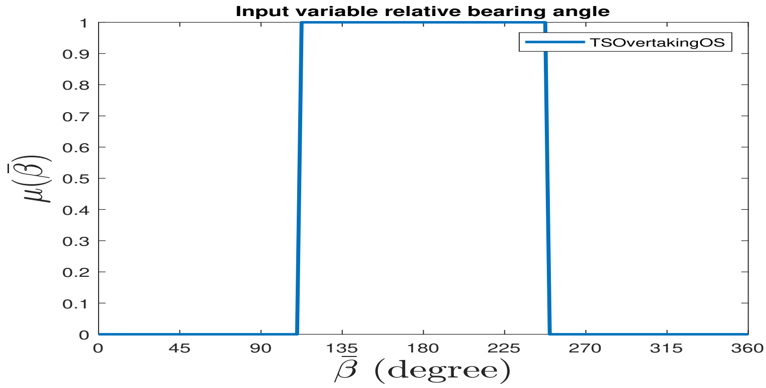


Figure 3.2: FMF for relative bearing angle for R13

The same FMF as given in the figure above is used for *OSOvertakingTS*, i.e. the fuzzy value of the fuzzy variable $\bar{\alpha}$. $\bar{\beta}$ determines if TS is overtaking OS and $\bar{\alpha}$ determines if OS is overtaking TS. The trapezoidal FMFs are designed with parameters $[110\ 112.5\ 247.5\ 250]$ as given in the figure above. Rule 13 specifies "*A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees abaft her beam*" (IMO (1972)) and Rule 13 part c states that if in any doubt if it is an overtaking situation the vessel shall assume an overtaking situation. Thereof, 2.5 degrees is added as a region of uncertainty on each side of the fuzzy values (*TSOvertakingOS* and *OSOvertakingTS*) to tolerate "if in any doubt". Also a MATLAB script is developed to determine if "*coming up with another*", i.e. from COLREGs Rule 13, is true or not, i.e. the variable TSD.

Risk is a variable used in COLREGs, but COLREGs do not provide a standard precise measure of this quantity. From the literature review, see Section 1.2.5, DCPA is a measure that several papers have utilized to measure risk. Therefore, the risk is approximated by the DCPA and provided as input to the FMF given in Figure 3.3. The trapezoidal FMF parameters are set to $[0\ 0\ 2960\ 2960]$, where 2960 meters=1.6 nautical miles.

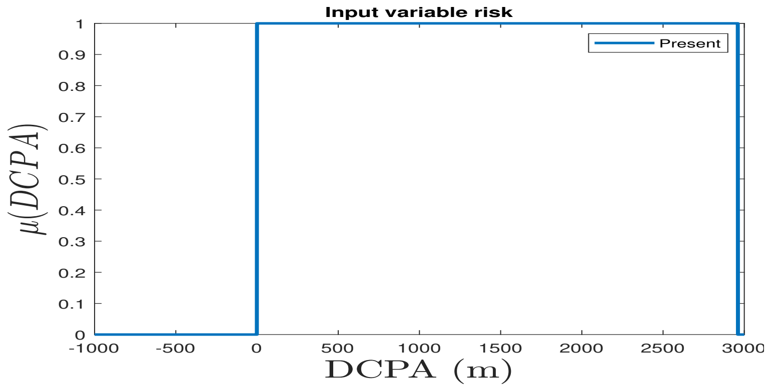


Figure 3.3: FMF for determination of risk

These values are inspired by the literature review on CPA, see section 1.2.5, where a study on DCPA proposed that a DCPA of 1.6 to 2.5 nautical miles are considered as a safe DCPA at open sea. This limit corresponded to a vessel with length overall (LOA) of 200 meters and at a speed at 15 knots. The vessels used in the simulator has a LOA of 116 meters, therefore the lower bound given in the study on DCPA is implemented in the evaluation system.

By this the rules are specified in a fuzzy logic manner as given below:

A$_1$: If $\bar{\beta}$ is *TSOvertakingOS* and TSD is *true* and Risk is *Present* then R$_{OS}$ is *SO* and R$_{TS}$ is *GW*

A$_2$: If $\bar{\alpha}$ is *OSOvertakingTS* and TSD is *true* and Risk is *Present* then R$_{OS}$ is *GW* and R$_{TS}$ is *SO*

The MATLAB script to determine TSD is added to the design because the $\bar{\beta}$ and $\bar{\alpha}$ only considers OS and TSs heading respectively, i.e. the $\bar{\beta}$ and $\bar{\alpha}$ may provide values in the fuzzy value *TSOvertakingOS* and *OSOvertakingTS* while the vessels are actually travelling apart from each other.

R14 uses $\Delta\chi$, $\bar{\beta}$, $\bar{\alpha}$ and DCPA (risk) as inputs. DCPA is utilizing the same FMF as presented for R13, see Figure 3.3.

Figure 3.4 illustrates the fuzzy value *NotAhead* for the fuzzy variable $\bar{\alpha}$. To obtain *Ahead* the fuzzy rules specifies "If $\bar{\alpha}$ is "NOT" *NotAhead*", i.e. $\mu_{Ahead}(\bar{\alpha}) = \mu_{NOTNotAhead-no}(\bar{\alpha}) = 1 - \mu_{NotAhead}(\bar{\alpha})$, where *Ahead* is the fuzzy value for the *ahead or nearly ahead* from Rule 14 in IMO (1972). "NOT" *NotAhead* is utilized to avoid having two subsets for the fuzzy value *Ahead* which eventually increases the number of rules (4 times). The Figure 3.4 depicts this fuzzy variable for TS. The fuzzy value *Ahead* is obtained for OS in the same manner, but with the fuzzy variable $\bar{\beta}$. The trapezoidal FMF for the fuzzy value *NotAhead* is designed with parameters $[15\ 20\ 340\ 345]$ for both TS and OS.

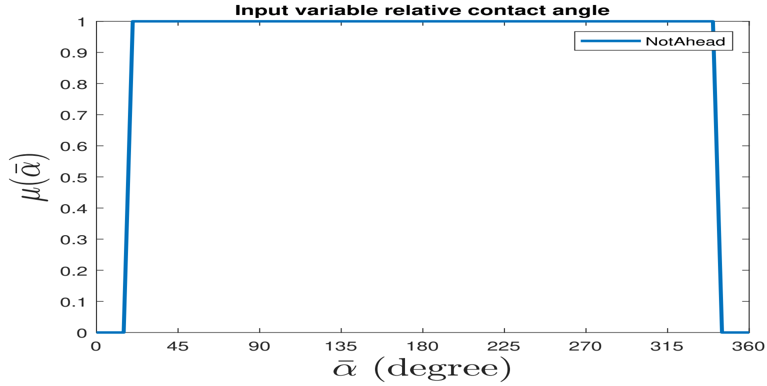


Figure 3.4: FMF for relative contact angle for R14

Given by the parameters and Figure 3.4 the FMFs, i.e. for both TS and OS, are developed with a range of uncertainty modelled by partial membership for the FMFs, due to Rule 14c from COLREGs states *when a vessel is in any doubt* (IMO (1972)).

$\Delta\chi$ is another input fuzzy variable to determine if the courses are reciprocal or nearly reciprocal. This is achieved by constructing $\Delta\chi$'s fuzzy value *ReciprocalNearReciprocal* designed by $[168\ 170\ 190\ 192]$ (also designed with a range of uncertainty) with a trapezoidal FMF, see Figure 3.5.

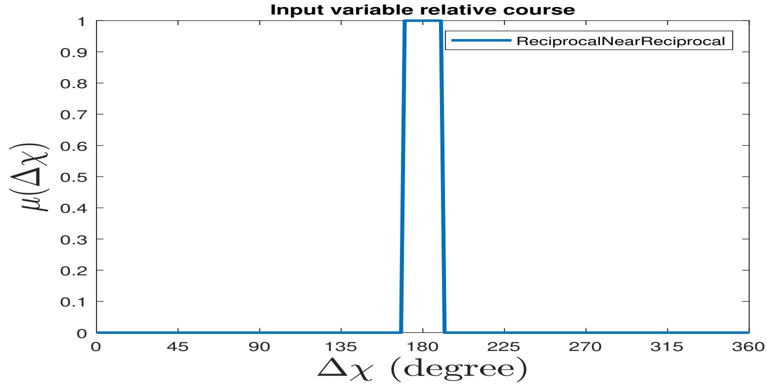


Figure 3.5: FMF for relative course for R14

Rule 14 specifies that "*When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard*" and part b states that "*Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead*" and part c states "*When a vessel is in any doubt as to whether such a situation exists she shall assume that it does*" (IMO (1972)). By this the fuzzy rules for both vessels, i.e. i=TS,OS, are developed and given as:

A$_3$: if $\Delta\chi$ is *ReciprocalNearReciprocal* and risk is *Present* then R$_i$ is GW

A$_4$: if $\bar{\alpha}$ is NOT *NotAhead* and $\bar{\beta}$ is NOT *NotAhead* and risk is *Present* then R$_i$ is GW

The fuzzy rule also specifies that both vessels shall GW if one or both of the if-then fuzzy rules are true, which is correct by the Rule 14 from COLREGs. Rule 14 specifies what action the vessels should do to obtain compliance, which is considered in system B.

For R15 the inputs are $\bar{\beta}$, $\bar{\alpha}$ and DCPA. The risk is defined by the same FMF and same fuzzy variable (input) as given in R13 and R14, see Figure 3.3, while $\bar{\beta}$ and $\bar{\alpha}$ use different FMFs than given in the previous.

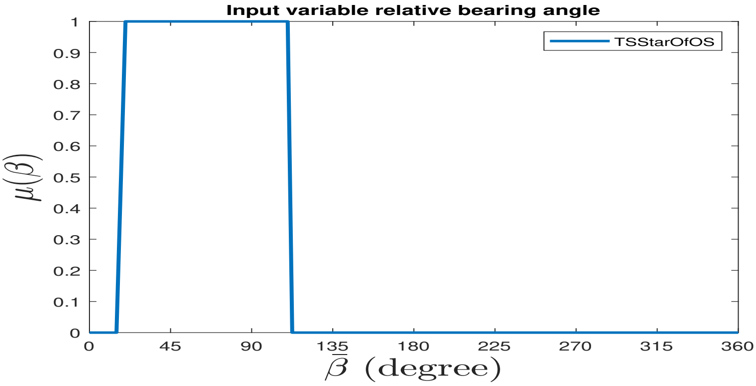


Figure 3.6: FMF to determine if TS is on starboard of OS

In Figure 3.6 the FMF for the fuzzy variable $\bar{\beta}$ is given to the fuzzy value *TSStarOfOS*, i.e. to obtain if TS is on starboard side of OS. In Figure 3.7 the same FMF parameters are utilized, but with different fuzzy variable and value, i.e. $\bar{\alpha}$ and *OSStarOfTS*, respectively. The fuzzy value *OSStarOfTS* is to determine if OS is on starboard side of TS.

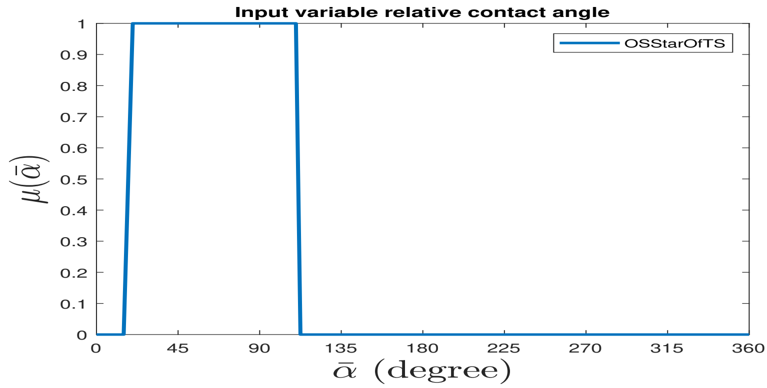


Figure 3.7: FMF to determine if OS is on starboard of TS

As seen in Figure 3.6 and 3.7 the trapezoidal FMFs are designed with the parameters [15 20 110 112.5]. By these parameters there are designed a range of uncertainty here too. The rules for the fuzzy logic are designed as:

A_5 : If $\bar{\beta}$ is *TSStarOfOS* and risk is *Present* then R_{OS} is *GW* and R_{TS} is *SO*

A_6 : If $\bar{\alpha}$ is *OSStarOfTS* and risk is *Present* then R_{OS} is *SO* and R_{TS} is *GW*

In Figure 3.8 all fuzzy values for $\bar{\beta}$ are given, looking into them they would sum to one for all points. The fuzzy variable $\bar{\alpha}$ would provide a similar figure, but with different fuzzy values, which are given in the previous. Thereof, the evaluation system will entitle R_i for all possible positions OS has in relation to TS and opposite when there is a risk of collision.

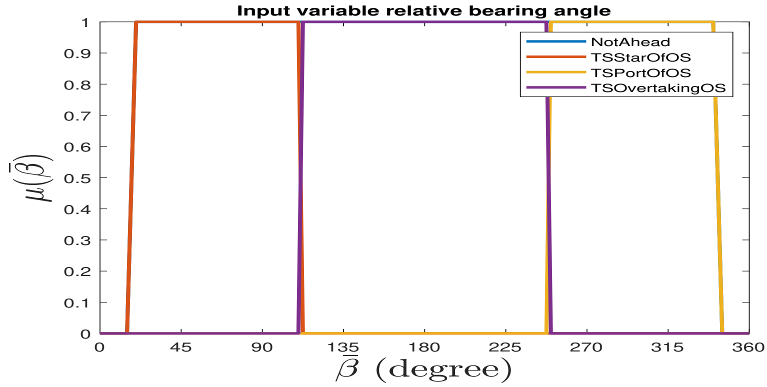


Figure 3.8: FMFs for relative bearing angle

The output variables for the three subsystems (R13, R14 and R15), see Figure 3.1, are utilizing the FMFs given in Figure 3.9. The Defuzzified output values are calculated as given in Section 2.4.4, i.e. using the center of gravity. R14 only utilizes the fuzzy value *GW*, while R13 and R15 utilize both fuzzy values, i.e. *GW* and *SO*. The FMF for the fuzzy value *GW* is defined by the parameters $[0\ 0\ 0.4\ 0.6]$ and *SO* is defined by the parameters $[0.4\ 0.6\ 1\ 1]$, both with trapezoidal functions.

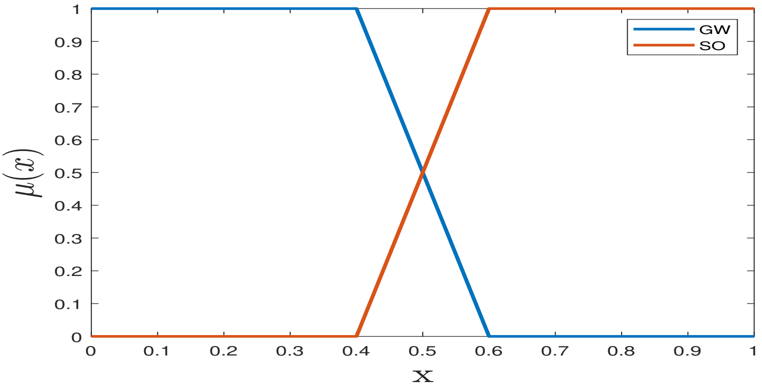


Figure 3.9: Output FMFs

R13, R14 and R15 are connected with an ”OR” logic in a fuzzy logic manner. The ”OR” fuzzy logic system receives six inputs, i.e. the two outputs from R13, two outputs from R14 and two outputs from R15 which determine R_i. For R13 and R15 the output could be a degree of truth to *SO* or *GW* or in-between these fuzzy values. For R14 the only role of vessel i is *GW*. This is only when the if-then fuzzy rule is true. The input FMFs for the fuzzy ”OR” logic system is given in Figure 3.10. The FMF for these inputs are defined differently than the output from R13, R14 and R15, see Figure 3.9 and Figure 3.10. As a consequence of the output from these subsystems are 0.5 when no rules fired, i.e. the output would give a defuzzified value of its mean range, or if two opposite roles hold simultaneously if a situation is exactly between two sectors, where the 0.5 has belongings to the fuzzy values *GW* and *SO* in Figure 3.9. Therefore, the *GW* and *SO* FMF for the fuzzy ”OR” logic system are defined as $[0\ 0\ 0.2508\ 0.5]$ and $[0.5\ 0.7492\ 1\ 1]$ respectively, given in Figure 3.10. These values, 0.2508 and 0.7492, are the maximum values possible to obtain as output (Defuzzifed) from R13 and R15 for *GW* and *SO* role respectively. For R14 the maximum output value is 0.2508 due to it only considers the *GW* fuzzy value.

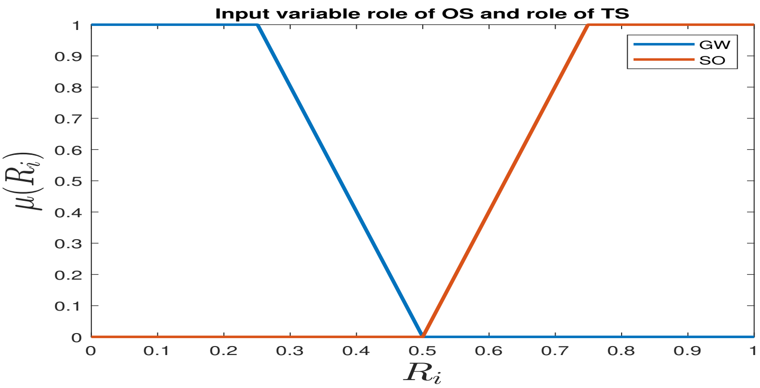


Figure 3.10: Input for fuzzy or logic FMF

The fuzzy output variables of the ”OR” fuzzy logic system are designed using the same FMFs given in Figure 3.9. By this the fuzzy rules are given below:

A_7 : If $R_{i,13}$ is *GW* or $R_{i,14}$ is *GW* or $R_{i,15}$ is *GW* then R_i is *GW*

A_8 : If $R_{i,13}$ is *SO* or $R_{i,14}$ is *SO* or $R_{i,15}$ is *SO* then R_i is *SO*

The time index is removed for simplicity for all variables in system A, but all variables are calculated at the timestamp where the range and TCPA is equal or below a pre-determined value, i.e. to evaluate if the vessels are insight of each other measured by range and TCPA. Range specifies the distance and TCPA specifies how far away the vessel is in time from the CPA. If e.g. the range is 3 nautical miles, but it is a high speed vessel the TCPA becomes lower than it would be for a slow vessel and must therefore be evaluated earlier. The range is set to 5 nautical miles, i.e. range $\leq$ 5 nautical miles, and the TCPA to 1200 seconds, i.e. TCPA $\leq$ 1200 seconds.

3.1.3 System B

The fuzzy input variables to system B are R_i, TCPA(ts_i), $|\Delta\chi_i|$, $|\Delta U_i|$ and $\#SC_i$. The output is the degree of compliance of the GW vessel, i.e. C_{GW}. System B evaluates Rule 8 and Rule 16 which are ”*Action to avoid collision*” and ”*Action by give-way vessel*” (IMO (1972)). Rule 8 b states to avoid small succession of alterations for course and/or speed. Rule 16 states that action to avoid a collision should be early and substantial, these are good examples of vague terms used in COLREGs as it does not state when an early action should be nor how large a substantial action should be. The method to test for succession of small alterations is managed by counting the numbers of continuous heading offsets and propulsion commands, i.e. denoted as #SC$_i$. The magnitude of course and speed change, i.e. denoted as $|\Delta\chi_i|$ and $|\Delta \mathrm{U}_i|$ respectively, are calculated as the largest offset of speed and heading experienced in the continuous heading offsets and propulsion commands values sent to the feedback linearizing controller. These are calculated to verify that the vessel does a large enough alteration. If a vessel does successions of small alterations or even a large alteration, but the complete alteration is inadequate, it might be challenging to interpret what the intention is and even if the vessel is doing an action to avoid a collision. In other words it is harder to interpret a turbulent maneuver than one large maneuver.

The earliness is due to the statement in Rule 16 ”*take early and substantial action*” (IMO (1972)), substantial is evaluated by the $|\Delta\chi_i|$ and $|\Delta \mathrm{U}_i|$ and the earliness is calculated as TCPA at the first time the vessel deviates form original speed or path (ts$_i$), i.e. TCPA(ts$_i$). Here, TCPA(ts$_i$) is given as input to the FMF in Figure 3.11.

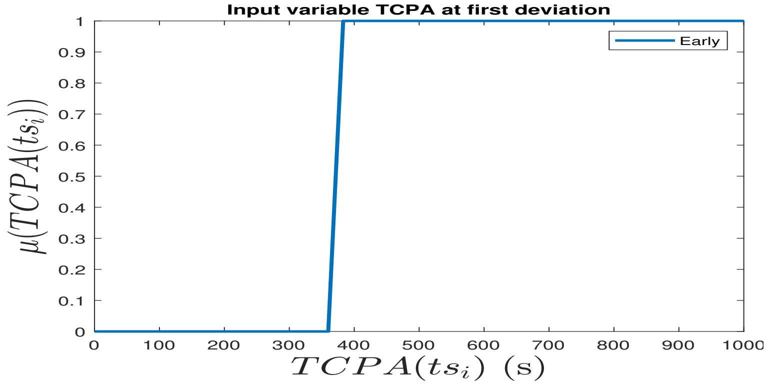


Figure 3.11: FMF to determine the earliness of change for TS

Figure 3.11 illustrates the earliness of R$_i$ actions. The fuzzy variable TCPA(ts$_i$) is in the fuzzy value *Early* in the set [360 383 1000 1000]. The values are inspired by the literature review on CPA, see Section 1.2.5, where Vujičić et al. (2017) determined a DCPA of 1.6-2 nautical miles for a vessel at 15 knots as a safe DCPA. The time it takes to travel 1.6 nautical miles at 15 knots vessel speed is 383 seconds, thereof the FMF [360 383 10000 10000]. This fuzzy value is biased to 15 knots, due to a vessel travelling with a higher speed of 15 knots will have a lower TCPA at DCPA $=$ 1.6 nautical miles, i.e. TCPA(1.6 nautical miles)$<$ 383 seconds, and opposite for a vessel with a speed below 15 knots. More of this will be discussed in Section 5.2.

$|\Delta\chi_i|$ and $|\Delta \mathrm{U}_i|$ are assigned to different FMFs since it is easier to interpret a course change than a speed change for another vessel, and COLREGs Rule 8b states ”*alteration of course alone may be the most effective action*” (IMO (1972)). The fuzzy variable $|\Delta \mathrm{U}_i|$ is given to the fuzzy value *Insufficient* given in Figure 3.12 and the fuzzy variable $|\Delta\chi_i|$ is given to the fuzzy value *Insufficient* given in Figure 3.13.

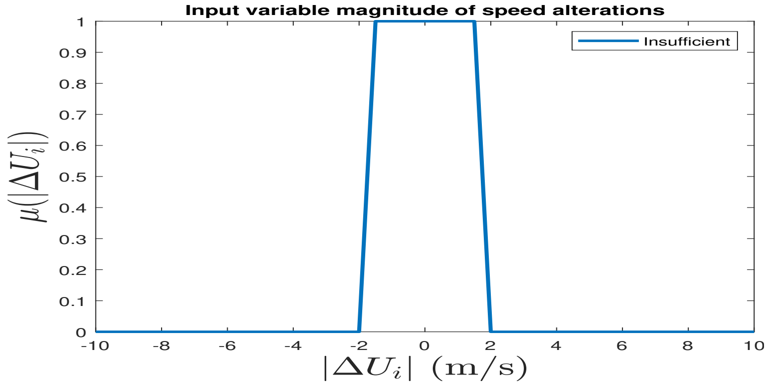


Figure 3.12: The magnitude of velocity FMF

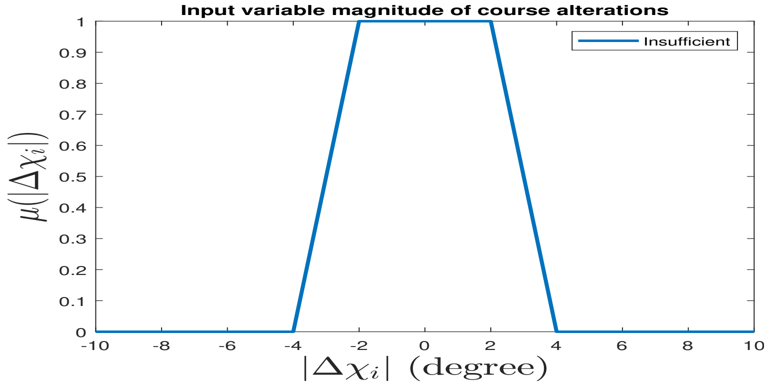


Figure 3.13: The magnitude of course FMF

Since the sufficient action can be in either direction, i.e. negative or positive values, the fuzzy subset of sufficient alteration is divided into two subsets, which results in extra FMFs and extra rules to cover all possibilities. To avoid this, only *Insufficient* subset is defined and the *Sufficient* subset is establish by $\mu_{Sufficient}(x)$=$\mu_{NOT Insufficient}(x)$=$1-\mu_{Insufficient}(x)$.

The input variables R_i are designed as fuzzy variables with the FMFs shown in Figure 3.9. The largest part of the universe of discourse is mapped to full and zero membership which correspond to clearly-classified situations.

The $\#\mathrm{SC}_i$ for speed and course is stated as the numbers of deviation from original speed and path, which is given to the FMF given in Figure 3.14.

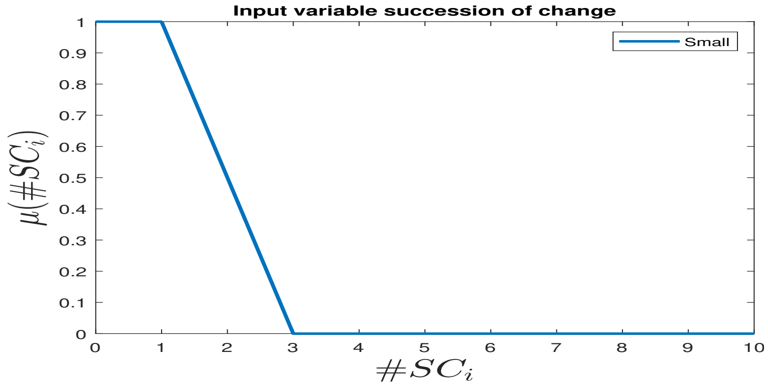


Figure 3.14: FMF to assess successive deviation changes for TS

The fuzzy variable, $\#\mathrm{SC}_i$, is picking the maximum of speed or course deviations from original path, i.e. $\#\mathrm{SC}_i = \max(\#\mathrm{SC}_{i,\Delta\chi_i}, \#\mathrm{SC}_{i,\Delta U_i})$.

A MATLAB script is developed to determine if OS passes on portside of TS, denoted as ”OSPortOfTS”, and if TS passes on portside of OS, denoted as ”TSPortOfOS”. This used for evaluating Rule 14 Head situation, where Rule 14 states that both vessels should GW by ”*each shall alter her course to starboard so that each shall pass on the portside of the other*”(IMO (1972)). This must therefore be incorporated into system B to obtain C_{GW} if Rule 14 is applied.

The fuzzy logic rules of system B are given below:

B_1 : If R_{OS} is *GW* and R_{TS} is NOT *GW* and $|\Delta \mathrm{U}_{OS}|$ is NOT *Insufficient* and $\#\mathrm{SC}_{OS}$ is *Small* and TCPA(ts_{OS}) is *Early* then C_{GW} is *Good*

B_2 : If R_{OS} is NOT *GW* and R_{TS} is *GW* and $|\Delta \mathrm{U}_{TS}|$ is NOT *Insufficient* and $\#\mathrm{SC}_{TS}$ is *Small* and TCPA(ts_{TS}) is *Early* then C_{GW} is *Good*

B_3 : If R_{OS} is *GW* and R_{TS} is NOT *GW* and $|\Delta \chi_{OS}|$ is NOT *Insufficient* and $\#\mathrm{SC}_{OS}$ is *Small* and TCPA(ts_{OS}) is *Early* then C_{GW} is *Good*

B_4 : If R_{OS} is NOT *GW* and R_{TS} is *GW* and $|\Delta \chi_{TS}|$ is NOT *Insufficient* and $\#\mathrm{SC}_{TS}$ is *Small* and TCPA(ts_{TS}) is *Early* then C_{GW} is *Good*

B_5 : If R_{OS} is *GW* and R_{TS} is *GW* and OSPortOfTS is *true* and TSPortOfOS is *true* and $|\Delta U_i|$ is NOT *Insufficient* and $\#SC_i$ is *Small* and TCPA(ts_i) is *Early* then C_{GW} *Good*

B_6 : If R_{OS} is *GW* and R_{TS} is *GW* and OSPortOfTS is *true* and TSPortOfOS is *true* and $|\Delta\chi_i|$ is NOT *Insufficient* and $\#SC_i$ is *Small* and TCPA(ts_i) is *Early* then C_{GW} *Good*

B_7 : If R_{OS} is *GW* and R_{TS} is *GW* and OSPortOfTS is *true* and TSPortOfOS is *true* and $|\Delta\chi_{OS}|$ is NOT *Insufficient* and $|\Delta U_{TS}|$ is NOT *Insufficient* and $\#SC_i$ is *Small* and TCPA(ts_i) is *Early* then C_{GW} *Good*

B_8 : If R_{OS} is *GW* and R_{TS} is *GW* and OSPortOfTS is *true* and TSPortOfOS is *true* and $|\Delta\chi_{TS}|$ is NOT *Insufficient* and $|\Delta U_{OS}|$ is NOT *Insufficient* and $\#SC_i$ is *Small* and TCPA(ts_i) is *Early* then C_{GW} *Good*

These parallel rules are connected with an ”OR” logic, where the output from this system is the degree of compliance of the GW vessel as stated. The FMF for the output is the same FMF as the *SO* fuzzy value given in Figure 3.9.

3.1.4 System C

System C evaluates Rules 8 and 17. Where Rule 17 ”*Action by stand vessel*” (IMO (1972)) part (a)ii states that the SO vessel (which should maintain course and speed) may take action to avoid collision if the GW vessel does not take appropriate action, i.e. actions in compliance with the COLREGs. Part b states that when the SO vessel is in a situation where keeping course and speed would lead to a collision ”*she shall take such actions as will best aid to avoid collision*” (IMO (1972)).

The inputs to system C are R_i, C_{GW}, $|\Delta\chi_i|$, $|\Delta U_i|$, $\#SC_i$, ”OSPortOfTS”, ”TSPortOfOS” and ”Crossing”. A MATLAB script is also developed to determine crossing situations, if R_i alters her course to portside, i.e. the fuzzy variable $\Delta\chi_i$ with the fuzzy value *Portside*. There are also designed fuzzy variables to determine if there are any changes due to a WP change, as $|\Delta\chi_i|$ and $|\Delta U_i|$, which are calculated from the offsets values from the CAS, thereof would not provide any correct belongingness to the fuzzy value *Insufficient* for a WP change, i.e. for evaluation if the SO vessel does SO. These fuzzy variables are the $\Delta\chi_i$, once again, and ΔU_i given to the fuzzy value *Insufficient*. The MATLAB script is mainly due to Rule 17 c which states that the vessel which should SO, but had to take GW actions can not alter course to port when another vessel is on her own portside in a crossing situation.

R_i are the fuzzy variables mapped to the fuzzy values given by the FMFs in Figure 3.9 to obtain which role they have. The $|\Delta U_i|$ and $|\Delta\chi_i|$ considers the same fuzzy values as in system B, given in Figure 3.12 and 3.13 respectively. $\#SC_i$ are the fuzzy variables mapped to the fuzzy value *Small*, i.e. the same as system B, see Figure 3.14. The fuzzy value C_{GW} uses the "NOT" *Good* to determine if the SO vessel should do actions to avoid collision.

The fuzzy variable C_{GW} is mapped to the fuzzy value seen in Figure 3.15. The defuzzified output value of system B is y_B=0.5 if no rule is fired, $y_B < 0.705$ for non-compliance and $y_B = 0.7492$ for full compliance. Hence the input FMF of system C for C_{GW} is designed with the parameters $[0.705\ 0.7492\ 1\ 1]$. "Crossing" is also provided to a similar FMF, but with the fuzzy value *True*, where "Crossing" utilizes the fuzzy value *SO* from output R15.

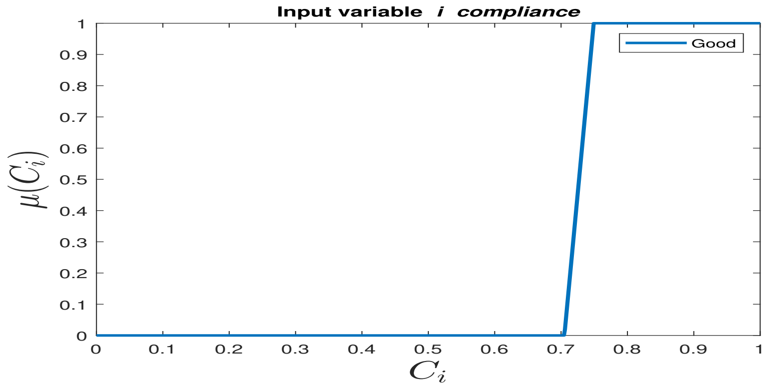


Figure 3.15: GW compliance FMF

By this the fuzzy rules of system C are designed as:

C_1 : If R_{OS} is *GW* and R_{TS} is *SO* and C_{GW} is *Good* and $\Delta\chi_{TS}$ is *Insufficient* and ΔU_{TS} is *Insufficient* then C_{SO} is *Good*

C_2 : If R_{OS} is *SO* and R_{TS} is *GW* and C_{GW} is *Good* and $\Delta\chi_{OS}$ is *Insufficient* and ΔU_{OS} is *Insufficient* then C_{SO} is *Good*

C_3 : If R_{OS} is *GW* and R_{TS} is *SO* and C_{GW} is NOT *Good* and $|\Delta U_{TS}|$ is NOT *Insufficient* and $\#SC_{TS}$ is *Small* and Crossing is *true* and OSPortOfTS is *true* and $\Delta\chi_{TS}$ is NOT *Portside* then C_{SO} is *Good*

C_4 : If R_{OS} is *GW* and R_{TS} is *SO* and C_{GW} is NOT *Good* and $|\Delta\chi_{TS}|$ is NOT *Insufficient* and $\#SC_{TS}$ is *Small* and Crossing is *true* and OSPortOfTS is *true* and $\Delta\chi_{TS}$ is NOT *Portside* then C_{SO} is *Good*

C_5 : If R_{OS} is *SO* and R_{TS} is *GW* and C_{GW} is NOT *Good* and $|\Delta\chi_{OS}|$ is NOT *Insufficient* and $\#SC_{OS}$ is *Small* and Crossing is *true* and TSPortOfOS is *true* and $\Delta\chi_{OS}$ is NOT *Portside* then C_{SO} is *Good*

C_6 : If R_{OS} is *SO* and R_{TS} is *GW* and C_{GW} is NOT *Good* and $|\Delta U_{OS}|$ is NOT *Insufficient* and $\#SC_{OS}$ is *Small* and Crossing is *true* and TSPortOfOS is *true* and $\Delta\chi_{OS}$ is NOT *Portside* then C_{SO} is *Good*

C_7 : If R_{OS} is *GW* and R_{TS} is *SO* and C_{GW} is NOT *Good* and $|\Delta U_{TS}|$ is NOT *Insufficient* and $\#SC_{TS}$ is *Small* and Crossing is NOT *true* then C_{SO} is *Good*

C_8 : If R_{OS} is *GW* and R_{TS} is *SO* and C_{GW} is NOT *Good* and $|\Delta\chi_{TS}|$ is NOT *Insufficient* and $\#SC_{TS}$ is *Small* and Crossing is NOT *true* then C_{SO} is *Good*

C_9 : If R_{OS} is *SO* and R_{TS} is *GW* and C_{GW} is NOT *Good* and $|\Delta\chi_{OS}|$ is NOT *Insufficient* and $\#SC_{OS}$ is *Small* and Crossing is NOT *true* then C_{SO} is *Good*

C_{10} : If R_{OS} is *SO* and R_{TS} is *GW* and C_{GW} is NOT *Good* and $|\Delta U_{OS}|$ is NOT *Insufficient* and $\#SC_{OS}$ is *Small* and Crossing is NOT *true* then C_{SO} is *Good*

The output of this system is the fuzzy variable C_{SO} which has the same FMF output (fuzzy value) as system B for the C_{GW}, i.e. $[0.4\ 0.6\ 1\ 1]$. A note for system B and C is that the rules do not contain the non-compliance cases, the number of rules has to be doubled to obtain non-compliance cases. Hence, system B and C will produce a value 0.5, i.e. no rules fired, in the case of the compliance case rules are not applicable.

3.1.5 Overall Compliance

The final ”overall” degree of compliance depends on the output of system B and system C, i.e. C_{GW} and C_{SO} respectively. Equation 3.4 provides how the C_i corresponds to the degree of compliance, e.g. C_{GW}=0.705, see equation 3.4a, corresponds to 0 degree of compliance, see equation 3.4c. This corresponds to the fuzzification of the defuzzified value, i.e. $\mu(C_i)$ of C_i.

$$0.705 < C_{GW} \leq 0.7492 \tag{3.4a}$$

$$0.705 < C_{SO} \leq 0.7492 \tag{3.4b}$$

$$0 < degree\ of\ compliance \leq 1 \tag{3.4c}$$

Hence, C$_{GW}$ and C$_{SO}$ variables are connected to a ”OR” fuzzy logic system through two fuzzy variables designed with the fuzzy value similar to the fuzzy value *Good* in Figure 3.15. By this the fuzzy rule is developed as:

OA$_1$: If C$_{GW}$ is *Good* or C$_{SO}$ is *Good* then C$_{Overall}$ is *Good*

This is the same as C$_{Overall}$=max($\mu(C_{GW})$,$\mu(C_{SO})$). The overall compliance is taken as the degree of membership to *Good* compliance without the defuzzification phase.

3.2 OS compliance evaluation

As stated an evaluation of OSs control system is also developed, i.e. obj. 2, where this evaluation system is similar to and based on the design of the evaluation system given in the previous (obj. 1). Thereof, the methodology of obj. 2 design is less detailed.

System A will remain the exact same, with the same ”OR” fuzzy logic. System B has some modifications, where B$_5-$B$_8$ are deleted due to it verifies that both vessels GW according to COLREGs Rule 14. There are two rules added instead of these, which are:

B$_5^{OS}$: If R$_{OS}$ is *GW* and R$_{TS}$ is *GW* and TSPortOfOS is *true* and $|\Delta\chi_{OS}|$ is NOT *Insufficient* and $\#$SC$_{OS}$ is *Small* and TCPA(ts$_{OS}$) then C$_{GW}$ is *Good*

B$_6^{OS}$: If R$_{OS}$ is *GW* and R$_{TS}$ is *GW* and TSPortOfOS is *true* and $|\Delta$U$_{OS}|$ is NOT *Insufficient* and $\#$SC$_{OS}$ is *Small* and TCPA(ts$_{OS}$) *Early* then C$_{GW}$ is *Good*

By this B$_5^{OS}$ and B$_6^{OS}$ only focuses on OSs compliance in a head situation, i.e. Rule 14 from COLREGs, but B$_2$ and B$_4$ provides the C$_{GW}$ for the TS as this is to verify if the GW vessel did GW in system C.

For system C the only rules utilized are C$_1$, C$_5$, C$_6$, C$_9$ and C$_{10}$. The other rules evaluates if the TS acts accordingly to Rule 8 and 17 in COLREGs, which are not relevant for OSs evaluation.

The overall compliance evaluation system utilizes the same rule with scaling the defuzzified output value. Since OA$_1$ could provide an overall compliance from the C$_{GW}$ by the TS, there is designed an additional MATLAB script to choose the overall compliance by the OS, i.e. overall compliance is C_{GW} when the OS was the GW vessel or the overall compliance is the C_{SO} when the OS was the SO vessel. This could also be changed in the final ”OR” logic rule, but this MATLAB script provides the same results. Also the overall compliance for the obj. 2 is denoted C_{OS} in the following.

3.3 Evaluation system for multiple vessel encounter

The multiple vessel encounter evaluation system, i.e. obj. 3, is developed based on obj. 1 and 2. The extension is the final ”AND” logic to combine the levels of compliance resulting from evaluation of multiple pairs of OS and TSs, see Figure 3.16 for obj. 1 and 3. Moreover, continuing the focus on obj. 1 and 3. If one vessel, say OS, is engaged in multiple situations that involve a risk of collision with multiple TSs, say TS_i and TS_j, each situation, i.e. a pair of vessels involving OS is evaluated independently using one to one vessel evaluation system, finally the overall compliance of the multi-ship scenario is calculated through a combination of the individual evaluations, because COLREGs are designed for pairwise cases.

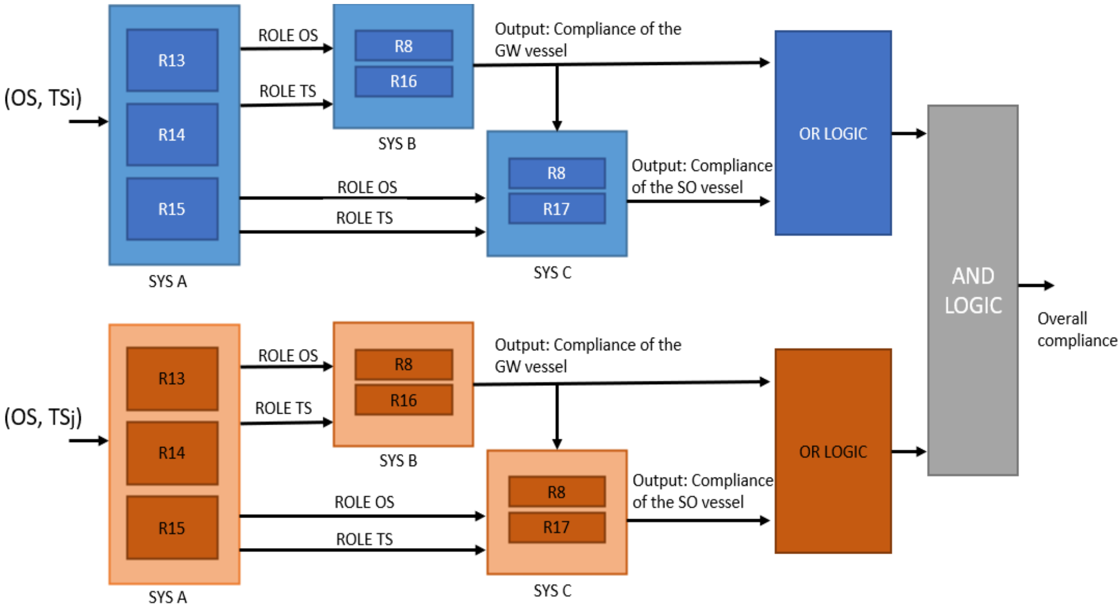


Figure 3.16: Extension to compliance evaluation in multi vessel scenarios

The inputs for the system are the same variables as in obj. 1, but for different TSs. From now on the notation for the blue system is denoted $sys1$ and the orange is denoted $sys2$, given in the figure above. The multiple vessel encounter system could have as many systems as desired, i.e. evaluation of e.g. one OS and four TSs this would make 4 systems.

The inputs for the ”AND” fuzzy logic system are the overall compliance from the pairwise evaluation of obj. 1, i.e. $\mu(\text{C}_{Overall}(\text{OS,TS}_i)$. The overall compliance for a multiple vessel encounter is calculated as scenario compliance=min$\{\mu(\text{C}_{Overall}(\text{OS,TS}_i))\}$, i=1,..,N where N$>$ 1. As seen the final score is not defuzzified and would produce a more intuitive value in the range $0 - 1$ instead of the defuzzified value, which would use the center of gravity method, i.e. the same as the ”OR” fuzzy logic system output for the pairwise encounter, see equation 3.4.

Obj. 3 for obj. 2, i.e. multi vessel encounter for OS compliance evaluation, is designed similarly, but with an extension of obj. 2. In the following, obj. 1_3 and obj. 2_3 refer respectively to the combination of obj. 1 with obj. 3 and the combination of obj. 2 with obj. 3; they respectively evaluate compliance in multi encounter cases for scenario execution and for OS maneuvers only.

3.4 Comments on the developed system

This section will validate/verify the presented design by comparing one fuzzy rule in obj .1 with its equivalent original COLREGs Rule.

Looking at Rule 17 part c, i.e. ”*A power-driven vessel which takes action in a crossing situation. In accordance with subparagraph (a)(ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side*” (IMO (1972)). This is satisfied by the rules listed in Section 3.1.4.

C_5 : If R_{OS} is *SO* and R_{TS} is *GW* and C_{GW} is NOT *Good* and $|\Delta\chi_{OS}|$ is NOT *Insufficient* and $\#\text{SC}_{OS}$ and Crossing is *true* and TSPortOfOS is *true* and $\Delta\chi_{OS}$ is NOT *Portside* then C_{SO} is *Good*

The rule above is repeated for simplicity, where this is the COLREGs Rule 17 part c transformed to fuzzy rules, for a TS that does not GW as COLREGs states and there is a crossing situation where TS is on the portside of OS. The COLREGs Rule states that the SO vessel may take actions to avoid collision due to the GW vessel is not taking appropriate action, where the action examined for this particular fuzzy rule is the course alteration of OS, i.e. ”*subparagraph (a)(ii)*” which is verified by examining if the OS course alteration is sufficient by the fuzzy variable $|\Delta\chi_{OS}|$ is ”NOT” *Insufficient*. The COLREGs statement ”*not alter course to port* *for a vessel on her own portside*" (IMO (1972)) is examined if TS is on portside of OS by the fuzzy rule "TSPortOfOS" is *true* and $\Delta\chi_{OS}$ is "NOT" *Portside*. By this Rule 17 part c for a course alteration of OS is transferred to fuzzy rules, the other fuzzy rules for Rule 17 part c considers the other possible situations that would lead to good compliance, e.g. there is not a crossing situation, examining the speed alteration, examining if OS did not obtain GW compliance etc.

The MATLAB scripts developed are binary variables incorporated into fuzzy logic, where true would provide full belongingness to the fuzzy value constructed and opposite for false. One binary variable has been developed for system A, i.e. to determine if the vessels are travelling in same direction (TSD). Two binary variables have been developed for system B, i.e. to determine whether the vessels passes in relation to the other vessel (OSPortOfTS and TSPortOfOS) for Rule 14. Eight Boolean variables have been developed for system C, i.e. if R_i alters course to portside, where the vessel crosses in relation to the other vessel and if there are any alterations due to a WP change. Generally it is stated in the literature that COLREGs are vague, they are not specific enough, but the designed binary variables are specific enough to utilized binary variables and incorporate them into the fuzzy logic evaluation system. This applies for obj. 1 and 2, where obj. 2 does not utilizes all these binary variables, as seen by the fuzzy rules in Section 3.2.

The R_i, $\mathrm{R}_{i,n}$, C_i and $\mathrm{C}_{Overall}$ are parameters developed in the evaluation system, while the other parameters are calculated from the position, heading, speed, WP, offset heading and offset velocity from the simulator, where the author of this thesis had to do some modifications in the simulator to extract the desired variables.

Chapter 4

Results and discussion

This chapter provides results and discussion of the developed evaluation systems. Several one to one vessel encounters and some multiple vessels encounters are presented in the following. The multiple vessel encounter evaluation systems are validated in this section for 2-pairs scenario. The designed method scale easily to N$>$ 2 TSs scenarios, but these scenarios are difficult to simulate and analyse in details.

This work assumes no environmental forces applied to the vessel encounters, therefore the course and heading are equal.

4.1 One to one encounter

This section evaluates the design for the the one to one encounter, i.e. obj. 1 and 2. The testing is divided into three scenarios, i.e. head-on, crossing and overtaking scenarios, due to the focus on Rule 8 and 13-17.

4.1.1 Comments on the evaluations

A note for the following results is when comparing the heading plots with the course/heading change provided in the tables, i.e. $|\Delta\chi_i|$, it seems like this numerical value is smaller than the interpretation of the plots, but this is due to the vessel wants to return to its original path and this course/heading change is not incorporated as a deviation. The heading plots are provided with $\psi_i \in [-180\ 180]$ and the North-East plots are plotted as the North on the vertical axis and East on the horizontal axis, i.e. $\eta_i = [x_i\ y_i\ \psi_i]$ the position of vessel i.

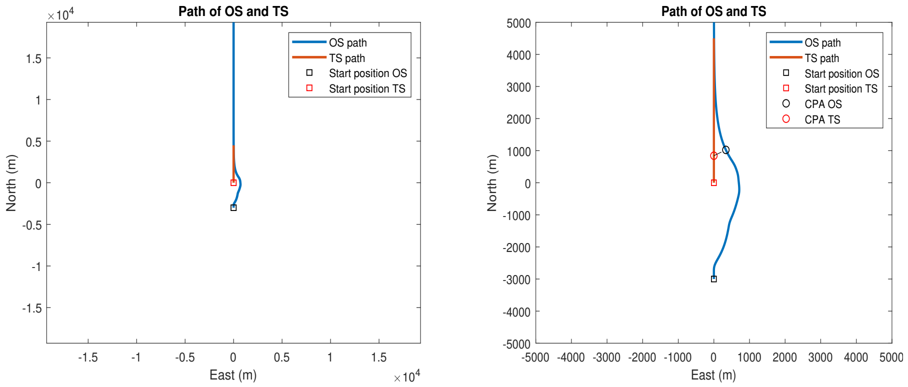
In the following sections all fuzzy variables utilized in the evaluation system will be provided. These variables are similar in obj. 1 and 2, the difference is that obj. 2 does not utilize all variables, e.g. TCPA(ts$_{TS}$) to evaluate earliness in a head-on situation is not important for OSs evaluation.

The MATLAB scripts developed to obtain the binary variables, e.g. TSD, are not provided in the results as these variables are intuitively obtained by the plots.

4.1.2 Overtaking

This section will provide two scenarios where Rule 13 applies, i.e. an overtaking situation.

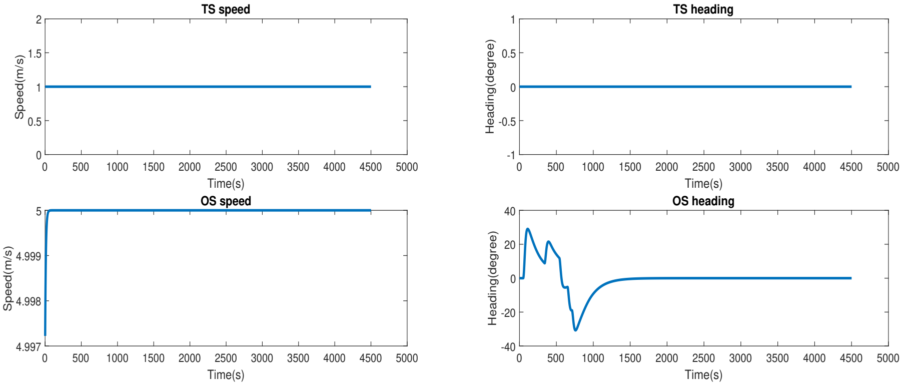
In Figure 4.1 the North-East trajectory of OS and TS is provided for the first overtaking scenario O1. As seen this is an overtaking scenario where OS is the GW vessel and TS is the SO vessel, since OS is coming up towards TS with a direction of more than 22.5 degrees abaft TSs beam, i.e. Rule 13 by COLREGs. See file *OvertakingAnimation_1.mp4* in attachments for animation of the scenario.



(a) Whole path **(b)** Zoomed scaling

Figure 4.1: Path of OS and TS

In Figure 4.2 the speed and heading for OS and TS are provided. As seen TS does not do any alterations and OS changes its heading, i.e. OS does GW and TS does SO. In reality a heading change entitles a speed change, but as seen in the figures, looking at OS heading and OS speed, there is no speed change due to a heading change, more of this is mentioned in Section 2.1.



(a) Speed **(b)** Heading

Figure 4.2: Speed and heading for OS and TS

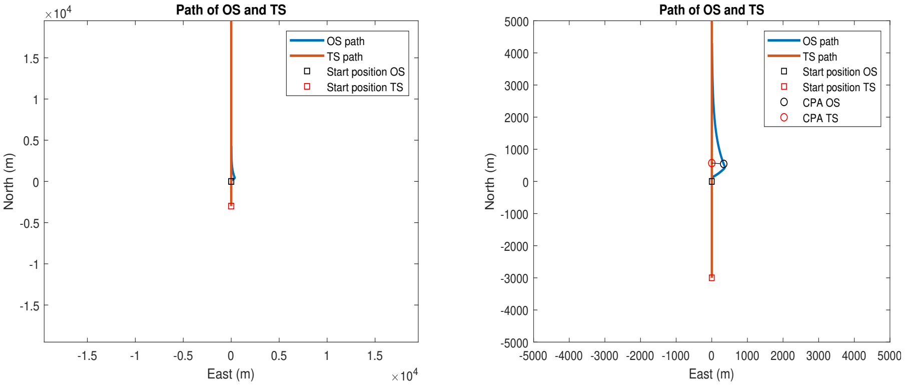
In Table 4.1 the results of both obj. for O1 are provided. As seen $R_{OS,GW} = 1$ and $R_{TS,SO} = 1$, as expected when OS overtakes TS. The OS does GW by $|\Delta\chi_{OS}| = 48.023°$ with one deviation, i.e. $\#SC_{OS} = 1$, and TS does SO by $|\Delta U_{TS}| = 0m/s$ and $|\Delta\chi_{TS}| = 0°$. Therefore, $C_{GW} = 1$ and $C_{SO} = 1$ with obj. 1 evaluation, which results in 100% compliance, i.e. $C_{Overall} = 1$.

Variable	**Value**	**Unit**
R$_{OS,GW}$	1	-
R$_{TS,SO}$	1	-
$\bar{\beta}$	0	degree
$\bar{\alpha}$	180	degree
$\lvert\Delta\chi_{OS}\rvert$	48.023	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	0	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#$SC$_{OS}$	1	-
$\#$SC$_{TS}$	0	-
DCPA	9.3871e-09	m
$\Delta\chi$	360	degree
TCPA(ts$_{OS}$)	699.9101	s
TCPA(ts$_{TS}$)	-	s
C$_{GW}$	1	Pairwise evaluation
C$_{SO}$	1	Pairwise evaluation
C$_{Overall}$	1	Pairwise evaluation
C$_{GW}$	1	OS evaluation
C$_{SO}$	0	OS evaluation
C$_{OS}$	1	OS evaluation

Table 4.1: Overtakes with OS had CAS

For obj. 2, the variables presented in the table above are also utilized as stated in the previous, where $C_{OS} = 1$, i.e. compliance of OS, as expected since the OS does GW and act according to Rule 13 and 16. C$_{SO} = 0$ due to this is the TSs role and thereof not evaluated by obj. 2 system.

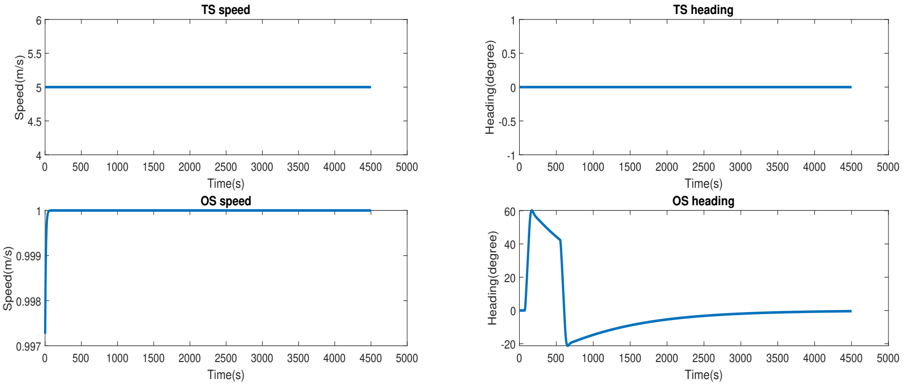
In Figure 4.3 the North-East trajectory of OS and TS is provided for the second overtaking scenario O2, where TS is the GW vessel and OS is the SO vessel, since TS is coming up towards OS with a direction of more than 22.5 degrees abaft OSs beam, i.e. Rule 13. See file *OvertakingAnimation_2.mp4* in attachments for animation of the scenario.



(a) Whole path **(b)** Zoomed scaling

Figure 4.3: Path of OS and TS

In Figure 4.4 the speed and heading for OS and TS are provided. As seen the TS does not alter the course nor the speed and by this violates Rule 16, but OS makes a heading change and act accordingly to Rule 17. As seen in the OS speed and OS heading plots the same as commented above Figure 4.2 applies here too.



(a) Speed **(b)** Heading

Figure 4.4: Speed and heading for OS and TS

In Table 4.2 the results of obj. 1 and 2 for O2 are provided, where OS has a CAS and TS does not have a CAS. As seen the evaluation results provides R$_{OS,SO} = 1$ and R$_{TS,GW} = 1$, i.e. TS is overtaking OS by Rule 13. Obj. 1 resulted in C$_{GW} = 0$ as the TS does not do any action to GW, i.e. $|\Delta\chi_{TS}| = 0°$ and $|\Delta \mathrm{U}_{TS}| = 0m/s$. C$_{SO} = 1$ as the SO vessel, acts according to Rule 17 by making actions when the

GW vessel does not, given by $|\Delta\chi_{OS}| = 60.1406°$. By this $\mathrm{C}_{Overall} = 1$, i.e. full compliance from obj. 1 evaluation.

Variable	**Value**	**Unit**
$\mathrm{R}_{OS,SO}$	1	-
$\mathrm{R}_{TS,GW}$	1	-
$\bar{\beta}$	180	degree
$\bar{\alpha}$	0	degree
$\lvert\Delta\chi_{OS}\rvert$	60.1406	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	0	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#\mathrm{SC}_{OS}$	1	-
$\#\mathrm{SC}_{TS}$	0	-
DCPA	9.3605e-09	m
$\Delta\chi$	360	degree
$\mathrm{TCPA}(\mathrm{ts}_{OS})$	679.8928	s
$\mathrm{TCPA}(\mathrm{ts}_{TS})$	-	s
C_{GW}	0	Pairwise evaluation
C_{SO}	1	Pairwise evaluation
$\mathrm{C}_{Overall}$	1	Pairwise evaluation
C_{GW}	0	OS evaluation
C_{SO}	1	OS evaluation
C_{OS}	1	OS evaluation

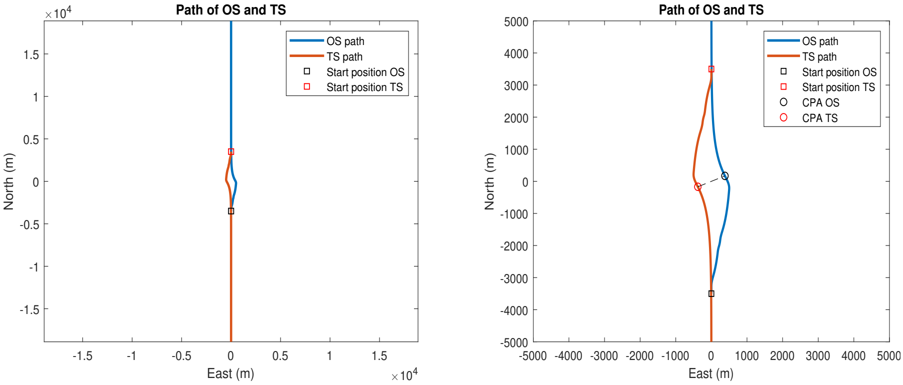
Table 4.2: Overtaking with OS has CAS

Obj. 2 of this overtaking scenario resulted in $\mathrm{C}_{OS} = 1$. This is expected as OS does action to avoid collision due to TS does not GW and act according to Rule 17.

4.1.3 Head-on

This section provides evaluation results for two different head-on scenarios, i.e. Rule 14. The first scenario, i.e. H1, contains a situation where both OS and TS have a CAS and the second scenario, i.e. H2, only the OS has a CAS.

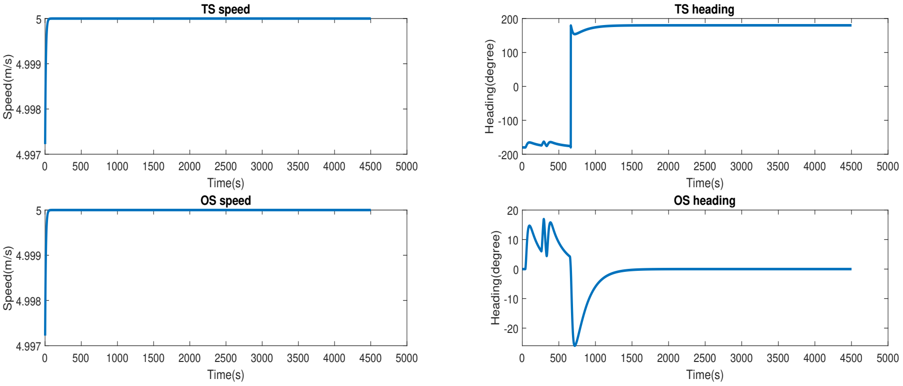
In Figure 4.5 the vessels trajectory in the North-East plan is provided for H1. The vessels alter course to starboard to obtain a portside passing as seen in the figure, thereof act according to Rule 14. See file *HeadOnAnimation_1.mp4* in attachments for animation of the scenario.



(a) Whole path **(b)** Zoomed scaling

Figure 4.5: Path of OS and TS

In Figure 4.6 the speed and heading of OS and TS are provided. As seen both vessels alter their heading to starboard to obtain a portside passing required by Rule 14.



(a) Speed **(b)** Heading

Figure 4.6: Speed and heading for OS and TS

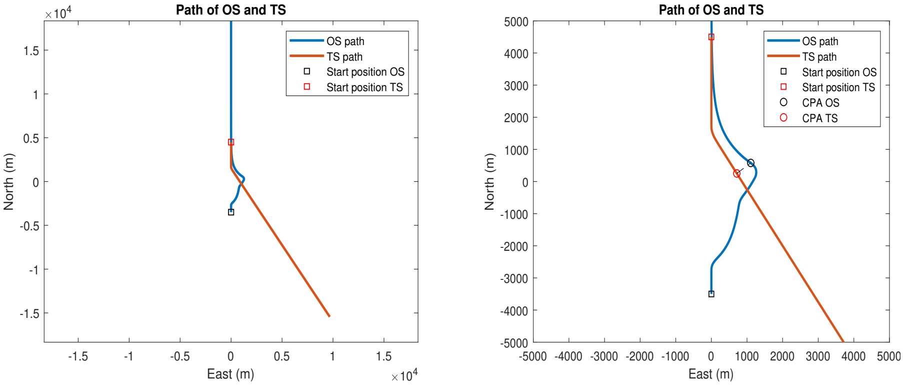
Table 4.3 provides the results of obj. 1 and 2 for H1. As seen from the evaluation results for obj. 1 $C_{GW} = 1$, $C_{SO} = 0$ and $C_{Overall} = 1$ which indicates that in the head-on situation both vessels does GW by altering course to starboard to obtain a portside passing, i.e. Rule 14, where both vessels did a substantial and early action, i.e. Rule 16, given by TCPA(ts_i) and $|\Delta\chi_i|$. In a head-on situation it is expected that $C_{SO} = 0$ as Rule 14 states that both vessels should GW.

Variable	**Value**	**Unit**
$R_{OS,GW}$	1	-
$R_{TS,GW}$	1	-
$\bar{\beta}$	360	degree
$\bar{\alpha}$	0	degree
$\|\Delta\chi_{OS}\|$	16.9395	degree
$\|\Delta\chi_{TS}\|$	16.9395	degree
$\|\Delta U_{OS}\|$	0	m/s
$\|\Delta U_{TS}\|$	0	m/s
$\#SC_{OS}$	1	-
$\#SC_{TS}$	1	-
DCPA	3.5043e-09	m
$\Delta\chi$	180	degree
TCPA(ts_{OS})	659.912	s
TCPA(ts_{TS})	659.912	s
C_{GW}	1	Pairwise evaluation
C_{SO}	0	Pairwise evaluation
$C_{Overall}$	1	Pairwise evaluation
C_{GW}	1	OS evaluation
C_{SO}	0	OS evaluation
C_{OS}	1	OS evaluation

Table 4.3: Head-on parameters TS and OS have CAS

Obj. 2 resulted in $C_{OS} = 1$ as expected due to the OS does GW according to Rule 14, where the system does not care about the TSs action.

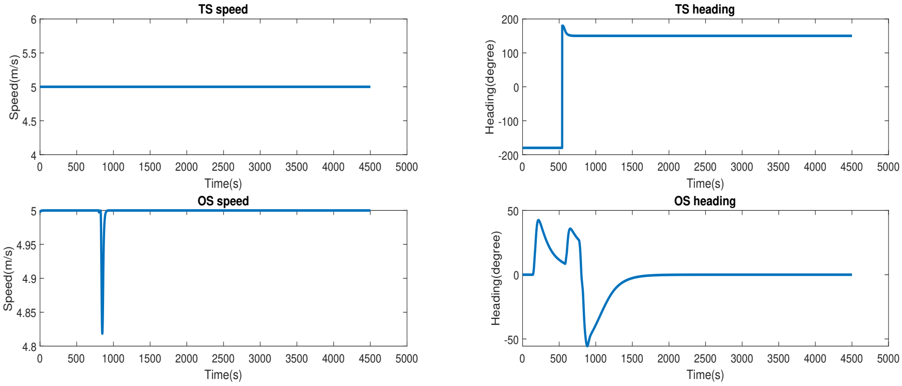
In Figure 4.7 the North-East trajectory of OS and TS is provided for H2. By Rule 14 both vessels should then GW by altering course to starboard, but as seen the TS alters course to portside and by this violates Rule 14. See file *HeadOnAnimation_2.mp4* in attachments for animation of the scenario.



(a) Whole path **(b)** Zoomed scaling

Figure 4.7: Path of OS and TS

In Figure 4.8 the speed and heading for OS and TS are provided. As seen the OS alters heading to starboard to obtain a portside passing, while TS alters heading to portside due to a WP change (TS does not have a CAS), a violation of Rule 14.



(a) Speed **(b)** Heading

Figure 4.8: Speed and heading for OS and TS

In Table 4.4 the results of both obj. for the H2 are provided. As seen in the table $C_{SO} = 0$ as expected since both vessels should GW in a head-on situation, also proven by $R_{i,GW} = 1$. For obj. 1 $C_{GW} = 0$ and $C_{Overall} = 0$ due to TS does not comply with Rule 14.

Variable	**Value**	**Unit**
$\text{R}_{OS,GW}$	1	-
$\text{R}_{TS,GW}$	1	-
$\bar{\beta}$	360	degree
$\bar{\alpha}$	0	degree
$\lvert\Delta\chi_{OS}\rvert$	52.8105	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	0	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#\text{SC}_{OS}$	1	-
$\#\text{SC}_{TS}$	0	-
DCPA	3.7007e-09	m
$\Delta\chi$	180	degree
$\text{TCPA}(\text{ts}_{OS})$	659.9028	s
$\text{TCPA}(\text{ts}_{TS})$	-	s
C_{GW}	0	Pairwise evaluation
C_{SO}	0	Pairwise evaluation
$\text{C}_{Overall}$	0	Pairwise evaluation
C_{GW}	1	OS evaluation
C_{SO}	0	OS evaluation
C_{OS}	1	OS evaluation

Table 4.4: Head-on only OS has CAS

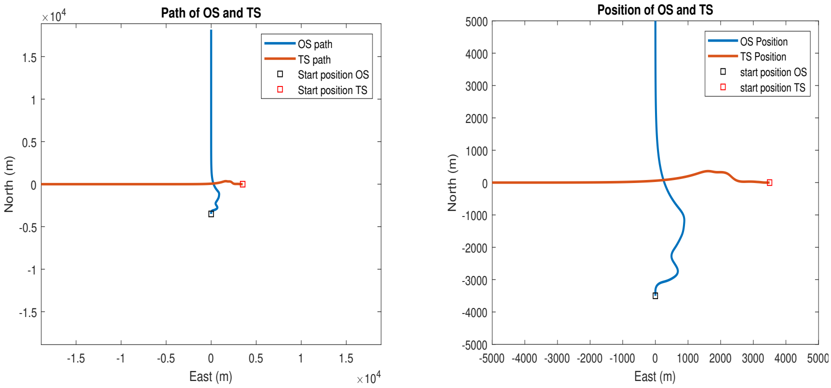
Obj. 2 resulted in $\text{C}_{OS} = 1$, i.e. 100% compliance of OS. This is due to OS does GW and acts according to Rule 14 and 16 by altering course to starboard early and substantially, i.e. $|\Delta\chi_{OS}| = 52.8105°$, $\text{TCPA}(\text{ts}_{OS}) = 659.9028s$ and $\#\text{SC}_{OS} = 1$ respectively, to obtain a portside passing.

4.1.4 Crossing

This section will provide two scenarios with a crossing situation to verify the design for Rule 15. In the first scenario, i.e. C1, both OS and TS have a CAS, while in the second scenario, i.e. C2, only OS has a CAS.

In Figure 4.9 the North-East trajectory of OS and TS is provided for the C1, where

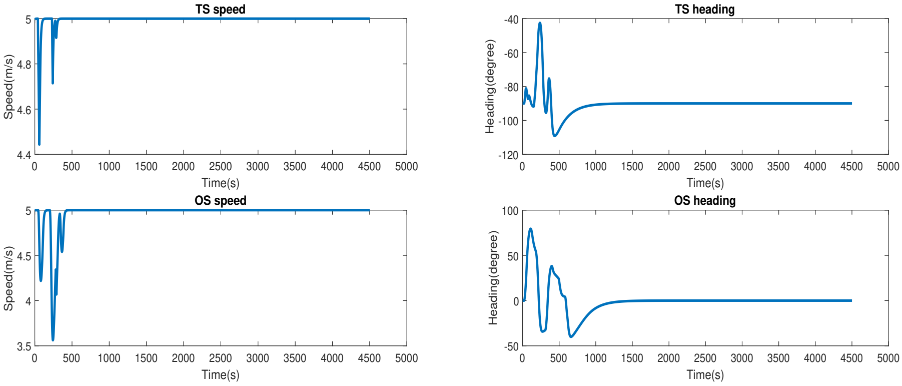
OS has TS on her starboard side and should therefore GW, i.e. Rule 15, and TS should SO. See file *CrossingAnimation_1.mp4* in attachments for animation of the scenario.



(a) Whole path **(b)** Zoomed scaling

Figure 4.9: Path of OS and TS

In Figure 4.10 the speed and heading for OS and TS are provided. As seen both vessels do change the speed and heading to avoid collision, and by this TS violates Rule 15 and 17 as it should SO.



(a) Speed **(b)** Heading

Figure 4.10: Speed and heading for OS and TS

In Table 4.5 the results of obj. 1 and obj. 2 for C1 are provided. As seen $R_{OS,GW} = 1$ and $R_{TS,SO} = 1$, by Rule 15 then OS has TS on her own starboard. For obj. 1 $C_{GW} = 0.90994$ and $C_{SO} = 0$ as seen from the table, OS does GW by $|\Delta\chi_{OS}| =$

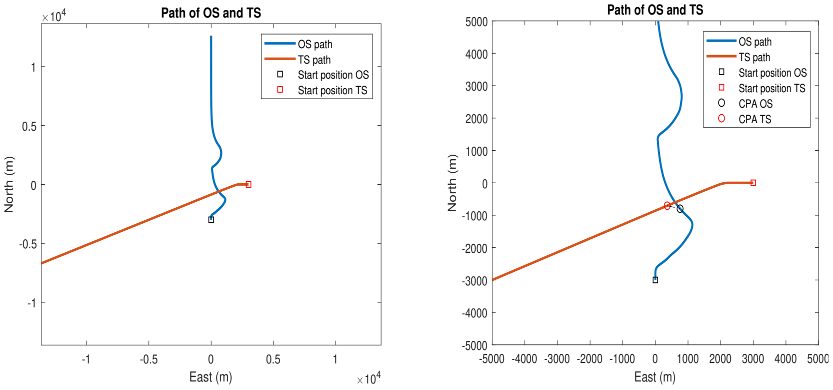
$79.4023°$ and $|\Delta\text{U}_{OS}| = 0.90444°$, where $|\Delta\text{U}_{OS}|$ has zero belongingness to "NOT" *Insufficient* and $|\Delta\chi_{OS}|$ has full belongingness to "NOT" *Insufficient*, see Figure 3.12 and 3.13 respectively. C_{GW} is not 100% due to $\#\text{SC}_{OS} = 2$ which does not provide full belongingness to the fuzzy value *Small*, see Figure 3.14. TS violates Rule 15 by changing heading and speed, but as seen from the evaluation result $\text{C}_{GW} \neq 1$ and by this TS could do actions to avoid a collision. It could, but it is not a must since C_{GW} is provided to system C as a fuzzy variable and $\text{C}_{GW} \neq 1$ provides a belongingness to the fuzzy value *Good* and "NOT" *Good*, see Figure 3.15. From visually analysing the plots it is more or less impossible to state that $\text{C}_{GW} \neq 1$ and by this TS could do actions to avoid a collision. $\text{C}_{SO} = 0$ due to $\#\text{SC}_{TS} = 4$ which does not provide any belongings to the fuzzy value *Small*, see Figure 3.14.

Variable	**Value**	**Unit**
R$_{OS,GW}$	1	-
R$_{TS,SO}$	1	-
$\bar{\beta}$	45	degree
$\bar{\alpha}$	315	degree
$\lvert\Delta\chi_{OS}\rvert$	79.4023	degree
$\lvert\Delta\chi_{TS}\rvert$	37.7386	degree
$\lvert\Delta U_{OS}\rvert$	0.90444	m/s
$\lvert\Delta U_{TS}\rvert$	0.52927	m/s
$\#$SC$_{OS}$	2	-
$\#$SC$_{TS}$	4	-
DCPA	4.9547e-09	m
$\Delta\chi$	270	degree
TCPA(ts$_{OS}$)	679.9554	s
TCPA(ts$_{TS}$)	679.9554	s
C$_{GW}$	0.90994	Pairwise evaluation
C$_{SO}$	0	Pairwise evaluation
C$_{Overall}$	0.90994	Pairwise evaluation
C$_{GW}$	0.90994	OS evaluation
C$_{SO}$	0	OS evaluation
C$_{OS}$	0.90994	OS evaluation

Table 4.5: Crossing with OS and TS have CAS

Obj. 2 resulted in C$_{OS}$ $= 0.90994$ due to $\#$SC$_{OS}$ $= 2$. Also seen obj. 2 gives C$_{SO}$ $= 0$ due to the OS has the role GW, and thereof the SO role is by the TS, which is not concerned in obj. 2, in other words if the TS did comply to Rule 17 such that obj. 1 would have resulted in C$_{Overall}$ $= 1$ obj. 2 would still provide 90.994$\%$ compliance.

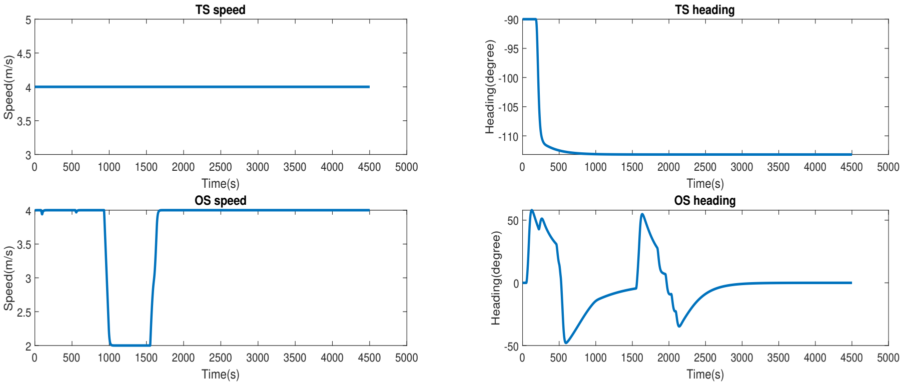
In Figure 4.11 the North-East trajectory for OS and TS is provided for C2. As seen the OS should GW as it has the TS on her own starboard and TS should SO, given by Rule 15. See file *CrossingAnimation_2.mp4* in attachments for animation of the scenario.



(a) Whole path **(b)** Zoomed scaling

Figure 4.11: Path of OS and TS

In Figure 4.12 the speed and heading for OS and TS are provided. As seen TS does not alter the speed, but changes the heading due to a WP change, which violates Rule 15 as the TS should SO. It is a WP change due to the TS does not have a CAS in this scenario. The OS acts according to Rule 16 by altering speed and heading to GW.



(a) Speed **(b)** Heading

Figure 4.12: Speed and heading for OS and TS

In Table 4.6 the results of both obj. for C2 are provided. As seen $R_{OS,GW} = 1$ and $R_{TS,SO} = 1$, i.e. OS has the TS on her own starboard, i.e. Rule 15, verified by $\bar{\beta} = 45°$ which has full belongingness to the fuzzy value *TSStarOfOS*, see Figure 3.6. The OS does GW by $|\Delta$ U$_{OS}| = 2m/s$ and $|\Delta\chi_{OS}| = 77.4903°$, where both actions provides full belongingness to "NOT" *Insufficient*, see Figure 3.12

and 3.13, respectively. $\mathrm{C}_{GW} \neq 1$ due to $\#\mathrm{SC}_{OS} = 2$ and by this does not provide full belongingness to the fuzzy value *Small*, see Figure 3.14. The TS which is the SO vessel, does not comply to SO, it changes heading due to a WP change. It could change heading or speed due to an action to avoid a collision since $\mathrm{C}_{GW} \neq 1$, but the change was a WP change, therefore $\mathrm{C}_{SO} = 0$ by the evaluation with obj. 1.

Variable	**Value**	**Unit**
$\mathrm{R}_{OS,GW}$	1	-
$\mathrm{R}_{TS,SO}$	1	-
$\bar{\beta}$	45	degree
$\bar{\alpha}$	315	degree
$\lvert\Delta\chi_{OS}\rvert$	77.4903	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	2	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#\mathrm{SC}_{OS}$	2	-
$\#\mathrm{SC}_{TS}$	0	-
DCPA	1.4676	m
$\Delta\chi$	270	degree
TCPA(ts_{OS})	699.905	s
TCPA(ts_{TS})		s
C_{GW}	0.90994	Pairwise evaluation
C_{SO}	0	Pairwise evaluation
$\mathrm{C}_{Overall}$	0.90994	Pairwise evaluation
C_{GW}	0.90994	OS evaluation
C_{SO}	0	OS evaluation
C_{OS}	0.90994	OS evaluation

Table 4.6: Crossing with OS had CAS

Obj. 2 resulted in $\mathrm{C}_{OS} = 0.90994$, i.e. the same compliance as obj. 1 resulted in, as expected due to the OS provides the compliance for obj. 1.

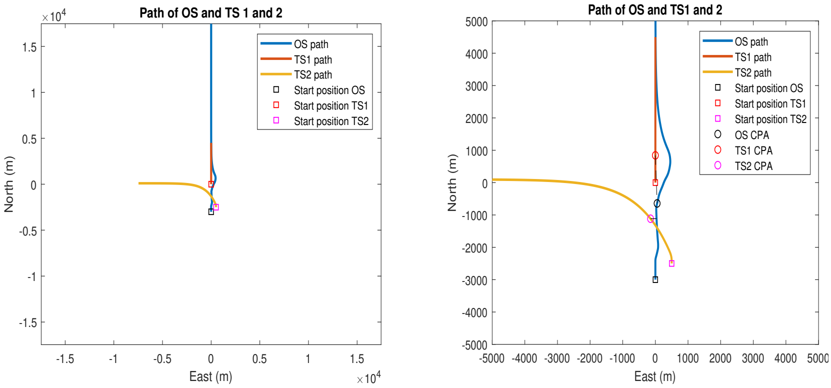
4.2 Multiple encounter scenarios

This section provides the results from evaluation on two different multiple vessel encounters where there are two TSs involved in a risky encounter with OS.

4.2.1 Overtaking

This section provides a scenario where only OS has a CAS.

In Figure 4.13 the North-East trajectory of OS and two TSs is provided. As seen OS is in two overtaking cases, and should therefore SO with respect to TS1 and TS2. TS1 and TS2 should GW in respect to OS. As seen the OS is overtaking both vessels, i.e. OS should SO and TS1 and TS2 should GW according to Rule 13. See file *MultiEncounterAnimation_1.mp4* in attachments for animation of the scenario.

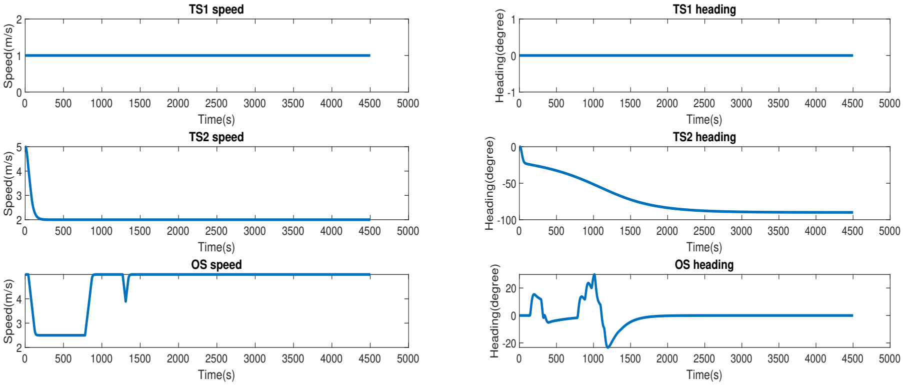


(a) Whole path

(b) Zoomed scaling

Figure 4.13: Path of OS and TS

In Figure 4.14 the speed and heading for OS and two TSs are provided. As seen OS does GW by changing the heading, TS2 does a heading and speed change due to a WP change (TSs does not have a CAS) and TS1 does not change speed nor heading, i.e. SO.



(a) Speed **(b)** Heading

Figure 4.14: Speed and heading for OS and TSs

In Table 4.7 the variables utilized in the evaluation systems are presented. As seen for both pairs $\#\text{SC}_{OS} = 3$ which provides zero belongings to the fuzzy value *Small*, see Figure 3.14. $\text{R}_{OS,GW} = 1$ and does GW by $|\Delta\chi_{OS}| = 38.7029°$ and $|\Delta\text{U}_{OS}| = 2.5m/s$, i.e. for both pairs.

Pair 1

Variable	Value	Unit
R$_{OS,GW}$	1	-
R$_{TS,SO}$	1	-
$\bar{\beta}$	0	degree
$\bar{\alpha}$	180	degree
$\lvert\Delta\chi_{OS}\rvert$	38.7029	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	2.5	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#$SC$_{OS}$	3	-
$\#$SC$_{TS}$	0	-
DCPA	9.3871e-09	m
$\Delta\chi$	360	degree
TCPA(ts$_{OS}$)	709.9157	s
TCPA(ts$_{TS}$)	-	s

Pair 2

Variable	Value	Unit
R$_{OS,GW}$	1	-
R$_{TS,SO}$	1	-
$\bar{\beta}$	45	degree
$\bar{\alpha}$	225	degree
$\lvert\Delta\chi_{OS}\rvert$	38.7029	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	2.5	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#$SC$_{OS}$	3	-
$\#$SC$_{TS}$	0	-
DCPA	1118.0311	m
$\Delta\chi$	0	degree
TCPA(ts$_{OS}$)	513.2531	s
TCPA(ts$_{TS}$)	-	s

Table 4.7: Variables determined by the evaluation systems

In Table 4.8 the compliance scores for each pair for obj. 1 and 2 are provided. As seen the compliance for obj. 2 and 3 are zero for both pairs, i.e. due to $\#$SC$_{OS} = 3$. C$_{OS}$ is calculated from the minimum of C$_{OS.sys1}$ and C$_{OS.sys2}$. For pair 1 in obj. 1 C$_{GW,sys1} = 0$ due to $\#$SC$_{OS} = 3$, therefore TS1 must take actions to avoid collision. From the table above, $|\Delta\chi_{TS,sys1}| = 0°$ and $|$U$_{TS,sys1}| = 0m/s$, i.e. TS1 did not act according to Rule 17. The reason for C$_{overall,sys2} = 0$ is similar, C$_{GW,sys2} = 0$ and the TS2 must take actions to avoid a collision since the GW vessel did not provide any C$_{GW}$, but as seen in the table above, i.e. $|\Delta\chi_{TS,sys2}| = 0°$ and $|$U$_{TS,sys2}| = 0m/s$, TS2 did not act according to Rule 17. By this the overall compliance for obj. 1_3 is also zero, i.e. C$_{Overall} = 0$ which is calculated by the minimum of C$_{Overall,sys1}$ and C$_{Overall,sys2}$.

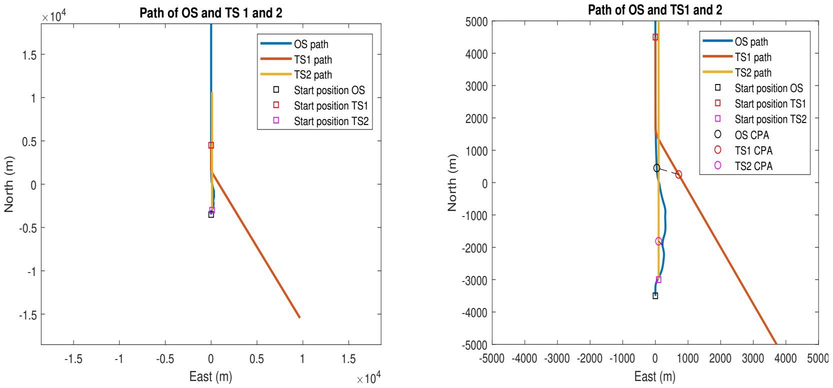
Variable	**Value**	**Evaluation system**
C$_{GW,sys1}$	0	Pairwise evaluation
C$_{SO,sys1}$	0	Pairwise evaluation
C$_{Overall,sys1}$	0	Pairwise evaluation
C$_{GW,sys1}$	0	OS evaluation
C$_{SO,sys1}$	0	OS evaluation
C$_{OS,sys1}$	0	OS evaluation
C$_{GW,sys2}$	0	Pairwise evaluation
C$_{SO,sys2}$	0	Pairwise evaluation
C$_{Overall,sys2}$	0	Pairwise evaluation
C$_{GW,sys2}$	0	OS evaluation
C$_{SO,sys2}$	0	OS evaluation
C$_{OS,sys2}$	0	OS evaluation

Table 4.8: Results of scenario

4.2.2 Head-on and overtaking

This section will provide a scenario where only OS has a CAS.

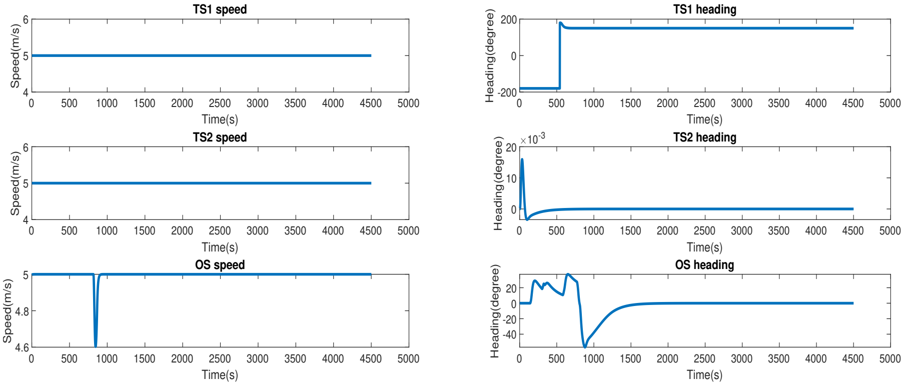
In Figure 4.15 the North-East trajectory for OS and two TSs is provided. As seen OS is in a head-on situation, i.e. Rule 14, with TS1 and in an overtaking situation with TS2, i.e. Rule 13. By these Rules OS should GW in both encounters, TS1 should GW with regard to OS and TS2 should SO with regard to OS. See file *MultiEncounterAnimation_2.mp4* in attachments for animation of the scenario.



(a) Whole path **(b)** Zoomed scaling

Figure 4.15: Path of OS and TS

In Figure 4.16 the speed and heading plots for OS, TS1 and TS2 are provided. As seen TS1 alters heading, but this is due to a WP change, because the TSs do not have a CAS. TS2 did SO, as seen there is given a heading change in the plot, but this is in 10^{-3}. The OS does GW by altering heading and speed.



(a) Speed **(b)** Heading

Figure 4.16: Speed and heading for OS and TSs

In Table 4.9 the variables utilized in the evaluation systems are presented. As seen $R_{OS,GW} = 1$ and does GW by $|\Delta\chi_{OS}| = 31.7844^\circ$ and $|\Delta U_{OS}| = 2.464 m/s$.

Pair 1

Variable	**Value**	**Unit**
$\mathrm{R}_{OS,GW}$	1	-
$\mathrm{R}_{TS,GW}$	1	-
$\bar{\beta}$	349.8914	degree
$\bar{\alpha}$	359.9702	degree
$\lvert\Delta\chi_{OS}\rvert$	31.7844	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	2.4264	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#\mathrm{SC}_{OS}$	5	-
$\#\mathrm{SC}_{TS}$	0	-
CPA	653.7741	m
$\Delta\chi$	169.9212	degree
TCPA(ts_{OS})	759.9065	s
TCPA(ts_{TS})	-	s

Pair 2

Variable	**Value**	**Unit**
$\mathrm{R}_{OS,GW}$	1	-
$\mathrm{R}_{TS,SO}$	1	-
$\bar{\beta}$	11.3099	degree
$\bar{\alpha}$	191.3099	degree
$\lvert\Delta\chi_{OS}\rvert$	31.7844	degree
$\lvert\Delta\chi_{TS}\rvert$	0	degree
$\lvert\Delta U_{OS}\rvert$	2.4264	m/s
$\lvert\Delta U_{TS}\rvert$	0	m/s
$\#\mathrm{SC}_{OS}$	5	-
$\#\mathrm{SC}_{TS}$	0	-
CPA	1004.9843	m
$\Delta\chi$	0	degree
TCPA(ts_{OS})	845.7612	s
TCPA(ts_{TS})	-	s

Table 4.9: Variables determined by the evaluation systems

In Table 4.10 the compliance for obj. 1_3 and 2_3 are provided. As seen these evaluations resulted in zero compliance, due to $\#\mathrm{SC}_{OS} = 5$ for obj. 2_3. For obj. 1_3 $\mathrm{C}_{GW} = 0$ and therefore TS2 must take actions to avoid a collision by Rule 17 and TS1 should already GW as $\mathrm{R}_{TS,GW} = 1$ (pair 1), but as seen in the table above $|\Delta\chi_{TS,sys1}| = 0°$, $|\mathrm{U}_{TS,sys1}| = 0m/s$ $|\Delta\chi_{TS,sys2}| = 0°$ and $|\mathrm{U}_{TS,sys2}| = 0m/s$. Therefore, $\mathrm{C}_{Overall} = 0$.

Variable	**Value**	**Evaluation system**
C$_{GW,sys1}$	0	Pairwise evaluation
C$_{SO,sys1}$	0	Pairwise evaluation
C$_{Overall,sys1}$	0	Pairwise evaluation
C$_{GW,sys1}$	0	OS evaluation
C$_{SO,sys1}$	0	OS evaluation
C$_{OS,sys1}$	0	OS evaluation
C$_{GW,sys2}$	0	Pairwise evaluation
C$_{SO,sys2}$	0	Pairwise evaluation
C$_{Overall,sys2}$	0	Pairwise evaluation
C$_{GW,sys2}$	0	OS evaluation
C$_{SO,sys2}$	0	OS evaluation
C$_{OS,sys2}$	0	OS evaluation

Table 4.10: Results

For obj. 1_3 it might be argued that the relation between TS1 and TS2 also should be assessed.

Chapter 5

Conclusion and further work

This thesis presented a literature review on the relevant topics to provide valuable information and a brief background theory. Moreover, this thesis developed two evaluations systems to provide COLREGs compliance scoring in one metric for both one to one vessel encounter and multiple vessel encounters. The systems were validated in several evaluated scenarios, where the evaluation results are compared by the interpretation of the COLREGs compliance by the plots of the scenario.

5.1 Conclusion

The main motivation behind this thesis was the lack in the literature of evaluating a CAS for a one to one and multi vessel encounters with regard to COLREGs in one metric. As seen in the thesis, COLREGs are expressed vaguely, for human reasoning and might be exploited by human operators, thereof challenging to incorporate into a computer. Chapter 3 provided the method of design to incorporate COLREGs into a computer and evaluate COLREGs compliance; Chapter 4 demonstrated the designed evaluation systems with multiple results.

Examining the evaluation results as a whole, the methodology of utilizing fuzzy logic to incorporate COLREGs into a computer and evaluate COLREGs compliance provide promising results, but there are still demands towards work on the fuzzy logic design, as this could be designed in other methods, and the interpretation of COLREGs, as it could differ a lot as they are written quite vague and are designed for human reasoning.

5.2 Further work

This section provides suggestions to further work on the evaluation systems.

An assumption made in the thesis is that the offset values for speed and heading from the CAS for both OS and TS are available, but this is unlikely in a real collision situation. Therefore, a realistic method to determine path deviation, speed deviation and to count the numbers of deviations can be developed in future works by e.g. using change-point detection to estimate such information

The designed fuzzy variables and values could be investigated with several different geometric and parameters, while this thesis utilized the trapezoidal shape. It could be more focus towards different geometrical shapes and if this could benefit the incorporation of COLREGs into a computer language.

The thesis focused on Rule 8 and 13-17, other rules can be implemented in future works on top of these rules, e.g. Rule 6 safe speed and Rule 19 conduct of vessels in restrict visibility.

The MATLAB fuzzy logic toolbox did not provide any method to construct the fuzzy values with variables, where e.g. determination of risk is dependent on vessel size and speed which could be variables that would design the fuzzy value *Present* for the fuzzy variable DCPA.

The determination of earliness for system B is biased to 15 knots, due to it is calculated based on the safe DCPA and how long time does it takes to travel this distance at 15 knots. TCPA(1.6nm)<383 seconds, where t=DCPA/U=383 seconds.

Look into the different scenarios evaluated, focusing on the start configuration, specially for the multi vessel encounter as this might provide unrealistic scenarios.

Computational time is not focused on in this thesis, and could be good as future work.

Finally, environmental forces can be integrated by using extra inputs and designing their fuzzy variables.

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Appendices

A COLREGs direct citation

In the following a direct citation from IMO (1972) for the rules utilized in this thesis are provided.

Rule 8, Action to avoid collision

(a) Any action to avoid collision shall be taken in accordance with the Rules of this Part and shall, if the circumstances of the case admit, be positive, made in ample time and with due regard to the observance of good seamanship.

(b) Any alteration of course and/or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar; a succession of small alterations of course and/or speed should be avoided.

(c) If there is sufficient sea-room, alteration of course alone may be the most effective action to avoid a close-quarters situation provided that it is made in good times, is substantial and does not result in another close-quarters situation.

(d) Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance. The effectiveness of the action shall be carefully checked until the other vessel is finally past and clear.

(e) If necessary to avoid collision or allow more time to assess the situation, a vessel shall slacken her speed or take all way off by stopping or reversing her means of propulsion.

(i) A vessel which, by any of these Rules, is required not to impede the passage or safe passage of another vessel shall, when required by the circumstances of the case, take early action to allow sufficient sea-room for the safe passage of the other vessel.

(ii) A vessel required not to impede the passage or safe passage of another vessel is not relieved of this obligation if approaching the other vessel so as to involve risk of collision and shall, when taking action, have full regard to the action which may be required by the Rules of this part.

(iii) A vessel the passage of which is not to be impeded remains fully obliged to comply with the Rules of this part when the two vessels are approaching one another so as to involve risk of collision.

Rule 13, Overtaking

(a) Notwithstanding anything contained in the rules of part B, sections I and II, any vessel overtaking any other shall keep out of the way of the vessel being overtaken.

(b) A vessel shall be deemed to be overtaking when coming up with another vessel from a direction more than 22.5 degrees abaft her beam, that is, in such a position with reference to the vessel she is overtaking, that at night she would be able to see only the sternlight of that vessel but neither of her sidelights.

(c) When a vessel is in any doubt as to whether she is overtaking another, she shall assume that this is the case and act accordingly.

(d) Any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of keeping clear of the overtaken vessel until she is finally past and clear.

Rule 14, Head-on situation

(a) When two power-driven vessels are meeting on reciprocal or nearly reciprocal courses so as to involve risk of collision each shall alter her course to starboard so that each shall pass on the port side of the other.

(b) Such a situation shall be deemed to exist when a vessel sees the other ahead or nearly ahead and by night she could see the masthead lights of the other in a line or nearly in a line and/or both sidelights and by day she observes the corresponding aspect of the other vessel.

(c) When a vessel is in any doubt as to whether such a situation exists she shall assume that it does exist and act accordingly.

Rule 15, Crossing situation

When two power-driven vessels are crossing so as to involve risk of collision, the vessel which has the other on her own starboard side shall keep out of the way and shall, if the circumstances of the case admit, avoid crossing ahead of the other vessel.

Rule 16, Action by give-way vessel

Every vessel which is directed to keep out of the way of another vessel shall, so far as possible, take early and substantial action to keep well clear.

Rule 17, Action by stand-on vessel

(a)

(i) Where on of two vessels is to keep out of the way the other shall keep her course and speed-

(ii) The latter vessel may however take action to avoid collision by her manoeuvre alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules.

(b) When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision.

(c) A power-driven vessel which takes action in a crossing situation in accordance with subparagraph (a)(ii) of this Rule to avoid collision with another power-driven vessel shall, if the circumstances of the case admit, not alter course to port for a vessel on her own port side.

(d) This rule does not relieve the give-way vessel of her obligation to keep out of the way.

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