Master's thesis

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

Eivind Løvoll

Evaluating Collision Avoidance Algorithms in Urban and Semi-restricted Waters using Fuzzy Logic

Master's thesis in Marine Technology
Supervisor: Øyvind Smogeli
Co-supervisor: Emil Hjelseth Thyri, Dong Trong Nguyen
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Norwegian University of Science and Technology
Department of Marine Technology

MSC THESIS DESCRIPTION SHEET

Name of the candidate: Eivind Løvoll

Field of study: Marine control engineering

Thesis title (Norwegian): Evaluering av Kollisjonsunngåelsesalgoritmer i Urbane og Semi-begrensede Domener ved bruk av Fuzzy Logic

Thesis title (English): Evaluating Collision Avoidance Algorithms in Urban and Semi-restricted Waters using Fuzzy Logic

Background

The development of technology that enables autonomous navigation at sea has surged in recent years. Introducing autonomous surface vessels to a domain governed by rules written for human interpretation poses a challenge that is yet to be solved. This has led to a gap between regulatory verification and validation procedures and the technology being developed, and tightening this gap demands quick action. Being able to robustly assure that the autonomous technology is safe for everyone at sea is of great importance and requires a thorough assessment of regulatory concerns, passenger and personnel safety concerns, and risk.

The regulatory concerns include adherence to the International Regulations for Preventing Collisions at Sea (COLREGs), a set of rules that all vessels at sea must abide by. The COLREGs were written with the intention of needing human interpretation, where linguistic terms need quantification for the automatic evaluation to be efficient.

Encounter safety concerns are expected to differ from COLREGs concerns. The encounter safety has been assessed by many before, however, the challenge of adjusting the risk assessment to a semi-restricted and urban domain is of great interest due to the increasing focus on utilizing the urban water ways in congested cities.

A final concern that has received less attention is the perceived safety of passengers on board an autonomous passenger ferry in an urban domain. When introducing autonomous surface vessels, a vital task is to assure passengers of the safety onboard. However, how to assess the perceived safety is still a young research field.

These three concepts are highly dependent on a human's objective interpretation of the situation, and their evaluation is hence not easily automated. A proposed method to mitigate challenges with complex and non-linear systems is fuzzy logic, a branch within artificial intelligence that aims to imitate the way humans make decisions based on imprecise and non-numerical information.

Work description

The thesis should as a minimum include the following:

1. A motivation for the thesis' work and a summary of related work to provide information and relevant references on:
   - COLREGs
   - Encounter safety and risk
   - Perceived safety
2. A list with abbreviations and definitions of terms, explaining relevant concepts related to the literature study and project assignment.
3. A clarification of the thesis' research question(s) and explicit definition of the thesis' contributions. The thesis' contributions should be along the lines of:
   - A proposal of a method to evaluate the collision avoidance algorithms considering the COLREGs, encounter safety, and perceived safety.

4. Necessary background theory for the understanding of the thesis' methodology and results. The background theory should as a minimum include relevant background on:
   - Collision avoidance algorithm
   - COLREGs
   - Fuzzy logic
5. A description of the thesis' methodology.
6. A presentation of results demonstrating the capabilities of the developed evaluation system and a following discussion where the method's advantages, shortcomings and limitations are highlighted.
7. A conclusion and proposal of further work.

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, summary, preface, 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.

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Supervisor: Øyvind Smogeli
Co-advisor(s): Emil Hjelseth Thyri, Dong Trong Nguyen

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Øyvind Smogeli
Supervisor

Summary

The development of technology that enables autonomous navigation at sea has surged in recent years. Introducing autonomous surface vessels to a domain governed by rules written for human interpretation poses a challenge that is yet to be solved. This has led to a gap between regulatory verification and validation procedures and the technology being developed, and tightening this gap demands quick action. Being able to robustly assure that the autonomous technology is safe for everyone at sea is of great importance and requires a thorough assessment of regulatory concerns, passenger and personnel safety concerns, and risk.

This thesis presents a method for evaluating the maneuvering performance of marine surface vessels, suitable for use in simulation-based evaluation and assurance of autonomous maneuvering and collision avoidance algorithms. We consider three individual evaluation metrics, namely, adherence to International Regulations for Preventing Collisions at Sea (COLREGs), encounter safety and perceived passenger safety.

These concepts are highly dependent on a human's objective interpretation of the situation, and their evaluation is hence not easily automated. We propose to mitigate this using fuzzy logic, a branch within artificial intelligence that aims to imitate the way humans make decisions based on imprecise and non-numerical information. Specifically, COLREGs are addressed by deciding whether a vessel has the role of Give-Way (GW) or Stand-On (SO). Subsequently, the compliance of each vessel is calculated through the designed fuzzy membership functions based on rules 7, 8, 13, 14, 15, 16, and 17 in the COLREGs. Further, we calculate a safety score based on the pose and range at the closest point of approach. The safety score calculation uses dynamic range thresholds based on the maneuverable space in the encounter area. Finally, a score for perceived passenger safety is calculated and addressed using a combination of data from ongoing public projects in Trondheim, Norway, and pose, velocity, and acceleration assessment.

The developed evaluation systems' capabilities are demonstrated through simulations from Sandefjord harbor and Kristiansund harbor. Both ports represent a suitable operational domain for the evaluation system, i.e., semi-restricted domains in urban areas. Using a geographic-specific operational domain we can realistically reproduce the domain geometries in simulation by creating land masks that enable the calculation of the maneuverable space in an encounter. Further, the evaluation system is tested through batch simulations to demonstrate its capability to differentiate between minor changes in vessel behaviors.

The evaluation method proves to efficiently, and presumably correctly, determine COL-

REGs roles of Own Ship (OS) and Target Ship (TS) in vessel-to-vessel encounters. Also, it successfully calculates compliance according to rules 7, 8, 16, and 17. The fuzzy logic approach demonstrates advantages compared to similar evaluation purposes when accounting for conflicting vessel roles by embracing the vagueness of the COLREGs and allowing a vessel to be evaluated as partly SO and partly GW.

The encounter safety evaluation demonstrates the capability of evaluating the safety of an encounter by using evaluation criteria recognized by research, i.e., pose at the closest point of approach and distance at the closest point of approach. The developed method differs from other similar evaluation methods by using dynamic distance thresholds to determine the safe passing distance in an encounter. The dynamic range calculation is based on the available maneuverable space about the TS and proves to be a robust method for evaluating the passing distance.

Finally, the perceived safety from a passenger's point of view is calculated. The evaluation criteria are found by investigating results from a citizen engagement project in conjunction with the ongoing research project "TRUSST – Assuring Trustworthy, Safe and Sustainable Transport for All." Other evaluation criteria are found from comfort studies on comparable means of transport such as metro and bus, where predominantly horizontal acceleration governs the comfort. The evaluation results are promising, but it is emphasized that this is a young research field that needs further investigation.

Sammendrag

Utviklingen av teknologi som muliggjør autonom navigering til havs har skutt til værs de siste årene. Å introdusere autonome overflatefartøy til et domene styrt av regler skrevet med intensjon om menneskelig tolkning utgjør en utfordring som ennå ikke er løst. Dette har ført til et gap mellom regulatoriske verifiserings- og valideringsprosedyrer og teknologien som utvikles. Å minske dette gapet krever rask handling. Det er av stor betydning å kunne sikre at teknologien ombord autonome fartøy er robust og trygg for alle på sjøen, og dette krever en grundig vurdering av regulatoriske krav, passasjer- og personellsikkerhet og risiko.

Denne oppgaven presenterer en metode for å evaluere manøvreringsytelsen til marine overflatefartøyer, egnet for bruk i simuleringsbaserte verifikasjon- og valideringsmetoder. Vi vurderer tre individuelle evalueringskriterier, nemlig overholdelse av International Regulations for Preventing Collisions at Sea (COLREGs), risiko og opplevd passasjersikkerhet.

Disse konseptene er svært avhengige av et menneskes objektive tolkning av situasjonen, noe som gjør det utfordrende å automatisere evalueringsprosessen. Vi foreslår å løse dette ved å bruke fuzzy logic, en gren innen kunstig intelligens som prøver å imitere måten mennesker tar avgjørelser basert på upresis og ikke-numerisk informasjon. Spesifikt adresseres COLREGs ved å bestemme om et fartøy har rollen som Give-Way (GW) eller Stand-On (SO). Deretter beregnes en score for hvert fartøy ved hjelp av fuzzy membership funksjoner som modellerer reglene 7, 8, 13, 14, 15, 16 og 17 i COLREGs. Videre beregner vi en sikkerhetsscore basert på geometrien mellom båtene og distansen mellom de ved nærmeste passeringspunkt. Sikkerhetsscoren for passeringsavstand er funnet ved å bruke en metode som beregner den tillate passeringsavstanden mellom to båter ved hjelp av det manøvrerbare området rundt båten som passeres.

Til slutt beregnes en score for opplevd passasjersikkerhet ved å bruke en kombinasjon av data fra pågående offentlige prosjekter i Trondheim, og vurdering av posisjonsdata, hastighet og akselerasjon.

Evalueringssystemenes evner blir så demonstrert gjennom simuleringer fra Sandefjord havn og Kristiansund havn. Begge havner representerer et passende operasjonsdomene for evalueringssystemet, det vil si semi-begrensede domener i urbane områder. Ved å bruke et geografisk spesifikt operasjonsdomene kan vi realistisk reprodusere domenegeometriene i simulering og lage landmasker som muliggjør beregning av det manøvrerbare rommet i et møte. Videre blir evalueringssystemet testet gjennom batch-simuleringer for

å demonstrere dets evne til å skille mellom mindre endringer i fartøysatferd.

Evalueringsmetoden viser seg å effektivt, og antagelig korrekt, avgjøre COLREGs-rollene til Own Ship og Target Ship. Den utviklede metoden beregner også overholdelse av COLREGs i henhold til regel 7, 8, 16 og 17, og viser seg å være en effektiv metode for å modellere vage definisjoner i COLREGs. Fuzzy logic-tilnærmingen demonstrerer visse fordeler sammenlignet med lignende evalueringsmetoder, spesielt når man tar hensyn til motstridende fartøysroller ved å omfavne vagheten til COLREGs og tillate et fartøy å bli vurdert som delvis Give-Way og delvis Stand-On.

Møtesikkerhetsevalueringen demonstrerer evnen til å evaluere sikkerheten i et møte ved å bruke evalueringskriterier anerkjent av forskning, det vil si fartøyenes geometri ved det nærmeste passeringspunkt og avstand ved det nærmeste passeringspunkt. Den utviklede metoden skiller seg fra andre lignende evalueringsmetoder ved å bruke en dynamisk avstand for å bestemme sikker passeringsavstand i et møte. Dynamisk avstandsberegning er basert på den tilgjengelige manøvrerbare plassen rundt Target Ship og viser seg å være en robust metode for å evaluere risikoen knyttet til avstand mellom to båter ved passering.

Til slutt beregnes den opplevde sikkerheten fra en passasjers synspunkt. Evalueringskriteriene er funnet ved å undersøke resultater fra en innbyggerundersøkelse i forbindelse med det pågående forskningsprosjektet "TRUSST – Assuring Trustworthy, Safe and Sustainable Transport for All." Andre evalueringskriterier er funnet fra komfortstudier på sammenlignbare transportmidler som T-bane og buss, hvor det blant annet blir funnet at horisontal akselerasjon er viktig for å vurdere komfort, og dermed også viktig for den opplevde sikkerheten ombord. Evalueringsresultatene er lovende, men det understrekes at dette er et ungt forskningsfelt som behøver videre forskning.

Preface

The past five months working with the thesis has been highly rewarding. Digging deeper into the field of autonomous surface vessels and addressing the important task of assuring adherence to regulations and safety has been joyous. The guidance received from field experts from NTNU and Zeabuz has been a big motivation and has pushed me to deliver to the best of my abilities.

I would like to acknowledge my supervisor and co-supervisors, Adj.Prof. Øyvind Smogeli (NTNU/Zeabuz), Prof. Dong Trong Nguyen (NTNU) and Dr. Emil Hjelset Thyri (NTNU/Zeabuz) respectively, for the help and guidance that I have received during the period of working with this thesis. They have all been instrumental for giving me direction, providing me with invaluable and continuous feedback, allowing flexibility and always being available. A special thanks to Emil for providing simulation data, and for being a sparring partner whenever needed.

Finally, I would like to thank Ingrid for motivating me and my family for their continuous and unconditional support.

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Acronyms

AI Artificial Intelligence.
AIS Automatic Identification System.
ASV Autonomous Surface Vehicle.

CAS Collision Avoidance System.
COG Course Over Ground.
COLAV Collision Avoidance.
COLREGs International Regulations for Preventing Collisions at Sea.
CPA Closest Point of Approach.
CPD Change Point Detection.

DCPA Distance at Closest Point of Approach.
DoM Degree of Membership.

FL Fuzzy Logic.
FLS Fuzzy Logic System.

GPU Graphics Processing Unit.
GW Give-Way.

LoA Levels of Autonomy.

MF Membership Function.

OS Own Ship.

SO Stand-On.
SSA Shortest Signed Angle.

TCPA Time to Closest Point of Approach.
TRUSST Assuring Trustworthy, Safe and Sustainable Transport for All.
TS Target Ship.

UAS Unmanned Aircraft System.

V&V Validation and Verification.

Chapter 1

Introduction

This section provides some motivation for the work presented in this thesis and presents previous work in the field. The research questions are presented, and an overview of the main contributions is given, along with an outline of the remainder of the thesis.

1.1 Motivation

The efforts to develop autonomous systems have skyrocketed in recent years. However, we are yet to see Autonomous Surface Vehicle (ASV)s in a commercialized application. Increasing Levels of Autonomy (LoA) promises to reduce emissions, cut costs and increase operational safety (Vagale et al., 2021). It has become well known through several studies that ship collisions are more often caused by human errors. The numbers differ slightly, but in a recent survey conducted by the European Maritime Safety Agency (EMSA), it emerges that 54% of the analyzed incidents over the period 2014-2020 are caused by human error (Agency, 2021). Another study indicates that 75%-96% of maritime collisions and causalities were caused by human errors and that 56% of major collisions involve one or several violations of the International Regulations for Preventing Collisions at Sea (COLREGs) (Rothblum, 2002). Reducing these numbers by introducing autonomy is an essential motivating factor for the current developments.

Challenges with verification and validation

Before ASVs can become a reality, several hinders must be surpassed. One such hinder is the lack of sufficient test schemes for Validation and Verification (V&V) of the navigation system to ensure the system's capability of safe, predictable, and reliable maneuvering. One of the main challenges that make conventional testing, verification, and validation insufficient is the non-deterministic nature of autonomous systems capable of learning and adapting continuously (Helle et al., 2016). The consequence of not developing V&V schemes able to tackle this challenge could be unfortunate and, in the worst case, fatal. Another interesting challenge is the general public's underlying skepticism toward autonomous systems. Weiss wrote that: "society holds robots to a higher standard and has a lower tolerance for their errors (Weiss, 2011). A recent survey even indicated that the public perception trust barrier of autonomous ferries depends on operator presence on board (Goerlandt and Pulsifer, 2022). This further motivates the development of robust, secure, and efficient methods for V&V of autonomous systems.

The maritime industry and the automotive industry share many of the same challenges regarding the introduction of autonomous vehicles. However, the automotive industry is advancing quickly and is arguably quite far ahead with developments of V&V methods. The state-of-the-art method to overcome some of the challenges regarding V&V is to utilize the increase in computational power in recent years. The vast advances in Graphics Processing Unit (GPU)s have made it possible to use high-quality simulations efficiently. Simulation-based testing to evaluate autonomous systems is already playing an important role for the V&V in the automotive industry, and all indicators in the maritime sector are pointing in this direction (Brandsæter and Knutsen, 2018). A simulation-based approach aims to identify critical or edge-case scenarios that can be reproduced in both simulation environments and in the test fields (Hejase et al., 2020). Simulations allow for systematically iterating through the input-space, and evaluating the output-space, to gain an understanding of the performance boundaries and behavior modes of the system. Simulations can be used both for determining the safety of the system, by testing for failure, and also as an important tool for improving performance. However, for simulation-based V&V to be feasible, it is important to have an effective way of automatically generating meaningful scenarios, and also an effective way of automatically evaluating the performance of the system, since manual testing is unfeasible for a system of any complexity, due to the many dimensions of the input space (Akkermann and Hjøllo, 2019; Reiher and Hahn, 2021).

It is projected that testing efforts will increase disproportionately when systems become more complex (Tallant et al., 2006). Current test methods will be cost-ineffective and non-sufficient to prove safety for complex autonomous systems. Thompson wrote that: "there is a common misconception in the testing industry that all unmanned autonomous systems can be tested using methodologies developed to test manned systems" (Thompson, 2008).

This emphasizes the importance of developing improved test schemes capable of dealing with the complexity of safety-critical autonomous systems, which will be a prerequisite for enabling the technology. Macias put it this way; ”the evolutionary nature of Unmanned Aircraft System (UAS) [..] must be met with evolutionary test capabilities yet to be discovered and developed” (Macias, 2008), and this can undoubtedly be extended to apply ASVs.

COLREGs

Another challenge related to the introduction of ASVs is the requirement to successfully maneuver in complex situations and interact with other vessels controlled by humans, possibly making non-compliant and unpredictable maneuvers. Due to the interaction with human-controlled vessels, ASVs need to comply with the same rules and regulations as more traditional vessels. One of the fundamental rules all sailing vessels must comply with is the COLREGs. This is a set of rules written with the intention of being vague and needing human interpretation. Determining whether vessels act according to the COLREGs is thus a complex task requiring quantifying linguistic terms and parameters. Quantifying linguistic terms in COLREGs is a recognized field lacking research and Hagen et al. (2021) stated that quantification of COLREGs in terms of angles, velocities, and distances, along with the identification of their dependencies on encounter specific factors still need research and will be important for comparison purposes between autonomous and human collision avoidance behavior.

A proposed approach to deal with the vagueness of the COLREGs is to use Artificial Intelligence (AI) to mimic cognitive functions associated with the human brain. AI methods can capture human-like inference, and potentially be used to quantitatively evaluate an autonomous vessel’s compliance with the COLREGs (Trodahl, 2021). One technique that could be used in this regard is fuzzy logic, a branch within AI that imitates the way humans make decisions based on imprecise and non-numerical information.

Encounter safety

While the COLREGs give guidelines and regulations for how to maneuver when the risk of collision exists, the regulations do not give clear guidelines on how the risk of collision should be evaluated. This is in large left to the interpretation of the skilled operators. Therefore, also these considerations need to be handled by the autonomous system to ensure that the vessel complies with the social conduct. Thus, determining the COLREGs compliance is not a sufficient measure of the risk present in an encounter.

Collision risk has been a heavily investigated research topic, and many different approaches to determine risk have been proposed. However, due to the complexity of vessel encounters with different operational domains, environmental impact, surroundings etc., it is demanding to measure the risk with sufficient robustness by using conventional methods. Fuzzy logic could thus serve as a means to mitigate challenges connected to the large complexity of vessel encounters. By designing membership functions covering the input space of the membership parameter it is possible to capture complex behavior with a simple IF-THEN rule-based system.

Perceived passenger safety

A domain of increased interest in recent years is urban waterways. Utilization of the already existing waterways of cities and urban areas with autonomous water shuttles promises to reduce emissions, remove traffic from congested roads and be more cost-efficient than existing solutions (Reddy et al., 2019; Burmeister et al., 2014). A fundamental challenge is to ensure that passenger feels safe when boarding an autonomous ferry. How passengers assess safety is likely to deviate from how encounter safety is considered. E.g., it is expected that passenger comfort will affect how safety is perceived by a passenger, but comfort does not influence the encounter safety evaluation. The research project Assuring Trustworthy, Safe and Sustainable Transport for All (TRUSST) has tried to gain insight into this field by arranging citizen activities to map and understand the needs and concerns of future passengers of an autonomous ferry (Forskningsrådet, 2020). Also, Lättman et al. (2016) discovered strong connections between perceived service quality (e.g., trip planning, punctuality, and comfort) and perceived travel safety on public ground transportation vehicles. I.e., how safe passengers feel in public transport is instrumental for how the quality of service and accessibility are perceived. This motivates further investigation into the topic, and to the author's knowledge, no previous work has attempted to quantify perceived safety from a passenger's point of view.

1.2 Related work

COLREGs

In recent years research on automatic evaluation of COLREGs compliance of collision avoidance algorithms has emerged with increasing intensity. In 2016 Kyle Woerner published his Ph.D. dissertation on multi-contact protocol-constrained collision avoidance for autonomous marine vehicles, paving the way for several research articles in the years to follow (Woerner, 2016). Also in 2016, Woerner et al. (2016) proposed a road-test framework for autonomous marine vehicles prior to operating outside of a testing environment.

The article aims to make conversations of future literature more exact and create a framework for others, such as certifying bodies so that performance can be reliably demonstrated to a required degree of satisfaction within given categories of COLREGs.

Woerner et al. (2019) also proposed a method with means to quantify and evaluate the subjective COLREGs with a goal of standardizing evaluation and certification of autonomous vessels. Algorithms for the different COLREGs scenarios were presented with entry criteria and included head-on, crossing, give-way, stand-on, and overtake. The goal was to establish a road test of the collision avoidance system, such that it can be tested and verified before being introduced in the real world (Woerner et al., 2019). In the research article, collision avoidance evaluation mainly consisted of risk and protocol compliance. The safety (risk) score was based on range and pose at the Closest Point of Approach (CPA). The COLREGs compliance was measured based on the rule-specific requirements mentioned in the rules. One of the tools for quantifying and evaluating the safety of a collision-avoidance encounter presented in the paper was concentric range rings that represent configurable threshold range values. The rings are defining the ship domain which were divided into r_{pref}, r_{min}, r_{nm}, and r_{col}, where r_{pref} defined the threshold for preferred range at CPA, r_{min} the threshold for acceptable range if precautions are taken, r_{nm} the threshold for encounters considered as unsafe and near miss, and lastly r_{col} is the threshold for where a collision is assumed to occur.

However, Woerner defined the range thresholds as static parameters and emphasized the need for customization of the thresholds based on the operational domain. To evacuate the need for individual assessment for each encounter to determine the appropriate passing distance Thyri and Breivik (2021) proposed a method to dynamically decide this based on the maneuverable space. The maneuverable space is defined as the available sea-room from a Target Ship (TS) to the closest obstacle in the relevant passing area. E.g., the distance from TS to land on the portside of TS. Finding the maneuverable space for each encounter diminishes the need for static range thresholds and individual assessment of the operational domain and current surroundings.

Another article (Porres et al., 2020) assessed COLREGs compliance evaluation by employing a neural network to create scenarios that were likely to challenge the collision avoidance algorithms under test. Although the main proposal of this article is scenario generation, metrics to define and evaluate when risk was present and when the system is non-compliant with respect to COLREGs gave an impression of the performance of the algorithms. The evaluation of compliance with COLREGs is given as the percentage of simulation steps where the system under evaluation did not behave according to COLREGs.

A recent Master's thesis (Trodahl, 2021) investigated the utilization of Fuzzy Logic (FL) in order to assess the COLREGs compliance of a Collision Avoidance System (CAS).

In the thesis a method to evaluate a CAS with regard to COLREGs for both single- and multi-vessel encounters in one score. The method evaluated the score post situation and assumed perfect knowledge of states such as position, velocity, and course for both Own Ship (OS) and TSs. The Fuzzy Logic System (FLS) designed in Trodahl (2021) consisted of four sub-systems. The first system is concerned with deciding what COLREGs situation applied based on the vessels' position and course, i.e., to evaluate whether it is a overtake, head-on, or crossing scenario according to Rule 13, Rule 14 and Rule 15. The output of this sub-system is the role of each vessel relevant for the scenario, more specifically if vessels have a Stand-On (SO) or Give-Way (GW) role. The second sub-module evaluated the compliance of the GW vessels with regard to COLREGs Rule 8 and Rule 16. The output of sub-system two is a compliance score of the GW vessel. The third evaluation sub-system evaluated the actions made by the SO vessels according to Rule 8 and Rule 17 and returned the compliance score. Finally, the three sub-systems were combined to calculate an encounter score.

One of the latest research articles with basis on the aforementioned articles (Woerner et al., 2019, 2016) aimed to provide a system for evaluation of vessel behavior with regards to compliance with COLREGs Rule 8a, 8b and 13-17 is Hagen et al. (2021). The paper included several improvements to the evaluation algorithm and a more detailed description of the complete evaluation process. The total score is calculated from penalties based on behavior with regard to COLREGs. Detection of COLREGs situation is based on entry criteria as outlined in Woerner et al. (2019). The proposed method is capable of evaluating multi-vessel encounters, which is being evaluated by giving each vessel in the encounter an independent score, i.e., calculating the score sequentially for each vessel. The only consideration made for multi-vessel encounters is a give-way compensation given if a vessel has contradicting responsibilities. It is also emphasized that the framework should be combined with a framework capable of assuring sufficient coverage of the test space. Finally, it is mentioned that quantification of COLREGs in terms of entry criteria such as angles, velocities, and distances and their dependencies on encounter-specific factors should be investigated further.

Such quantification is a challenge due to the differences in how the COLREGs are interpreted. Stankiewicz et al. (2020) stated that it is typical for mariners to have predefined distances internally at which they begin to consider making a maneuver. In GW situations taking early action is preferred and it is not uncommon to make the maneuver when the TS is reliably detected on radar or Automatic Identification System (AIS). It is further emphasized that the dimensions of exactly when a ship begins to maneuver vary with the preference of the mariner. Thus, the COLREGs operates in an environment of mutual comprehension, understanding, and coordination (Belcher, 2002), which naturally makes it challenging for ASVs that are reliant on extrapolating future positions and to some extent foresee other vessels' maneuvers. Also Stankiewicz et al. (2020) indicated that there is a dearth of literature on methods to determine such terms and parameters.

Encounter safety

Risk is a term mentioned briefly in COLREGs, e.g. in Rule 7, but a definition of how to measure or quantify risk is lacking. The quantification of risk is thus also an interesting aspect when evaluating a CAS and has been a heavily investigated research field, e.g. Tam and Bucknall (2010a), Katrakazas et al. (2019), Woerner et al. (2016) and Ozturk and Cicek (2019), where the latter summarizes the existing literature on collision risk assessment. It is found that the most frequently used parameters for assessing collision risk are Time to Closest Point of Approach (TCPA), Distance at Closest Point of Approach (DCPA), and relative bearing.

In Campbell et al. (2014) the DCPA is used as an assessment of risk in a collision situation. Here the risk is assumed to exist when the DCPA magnitude falls below a given threshold. In Kuwata et al. (2013) both DCPA and TCPA are used to assess whether a risk is present or not and if a COLREGs maneuver is necessary by checking whether $0 \leq TCPA \leq t_{max}$ and $DCPA \leq d_{min}$. In Woerner et al. (2019) the contact angle, defined in Section 2.3, at Closest Point of Approach (CPA) was also used to assess the risk involved in a collision situation. In this article, it was also proposed to use safety functions to calculate a safety score based on contact angle at CPA and DCPA. Lastly, Vestre et al. (2021) usde DCPA, however with a t_{max} value of three times the sim of the vessel lengths, i.e. $DCPA \leq 3 \times (L_i + L_j)$ where L_i and L_j are the vessel lengths of two considered vessels.

Perceived safety

As mentioned in Section 1.1 very little work related to the quantification of perceived safety on autonomous passenger ferries has been found. However, the increasing focus on revitalizing urban waterways with the possibility of introducing autonomy has led to an increasing number of surveys focusing on passengers' trust and perceived safety. E.g., Goerlandt and Pulsifer (2022) studied the benefits, concerns, and safety perceptions of autonomous urban vessels through a survey and interview research methodology. An interesting result illustrative of the vast amount of trust in a human operator is seen in figure 1.1, where MASS-1 to MASS-4 are the different Levels of Autonomy (LoA), with MASS-4 the highest LoA. The article also indicates that people have a lot of distrust in autonomous operations. This means that passengers will be very sensitive to unexpected behavior and that every maneuver will be considered with an arguing eye. Thus, identifying and quantifying such behavior is essential to building trust quickly.

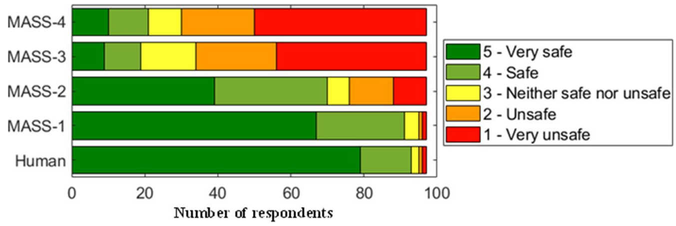

Figure 1.1: Statistics of the perceived safety of different degrees of autonomy of autonomous urban ferries. Source: Goerlandt and Pulsifer (2022)

Hoberock (1976) surveyed available experimental results on passenger comfort to assess the tolerances to longitudinal acceleration on ground transportation vehicles. The literature survey found eleven studies dealing with longitudinal motions connected with passenger comfort. Parameters such as loss of balance and severity of brake application were identified as important for passenger comfort, and also the jerk loads were decisive for the experience of comfort.

1.3 Research question

This paper aims to answer how fuzzy logic can be utilized to quantitatively measure the performance of a collision avoidance algorithm concerning the COLREGs, encounter safety, and perceived safety from a passenger's point of view. Thus, the research questions could be summarized to:

- Can fuzzy logic be utilized to efficiently measure COLREGs compliance in multi-vessel encounters? What are the drawbacks and advantages compared to similar evaluation methods?
- How should COLREGs parameters be designed for constrained operational domains? What domain-specific considerations must be taken?
- Could fuzzy logic also be extended to efficiently measure the risk involved in multi-vessel encounters?
- How can perceived safety from a passenger's point of view be measured and evaluated in a fuzzy logic system?

1.4 Main contributions

The thesis aims to contribute with an increased focus on V&V methods for assuring the safety of autonomous vessels. The thesis also contributes to an increased focus on domain-specific considerations in a domain given little attention - urban waterways. More specifically, the thesis contributes to existing research with the following:

- The thesis contributes to existing research on simulation-based testing for validating collision avoidance algorithms. The thesis presents three individual evaluation aspects that are all important when assessing the performance of a collision avoidance algorithm on a passenger ferry operating in a confined domain. No previous work has combined evaluation of COLREGs compliance, encounter safety, and passenger's perception of safety to the author's knowledge.

- The thesis adds to existing research using fuzzy logic as a means to evaluate collision avoidance algorithms with respect to COLREGs. By further developing the work in Trodahl (2021) a robust method to determine vessels' roles in a COLREGs encounter has been developed, which by utilizing fuzzy logic is able to account for the vague definitions declared by the COLREGs. The developed COLREGs evaluation accounts for rules 7, 8, 13, 14, 15, 16, and 17 and can evaluate both single-vessel encounters and multi-vessel encounters.

- Also, the thesis adds to existing research on encounter safety. Specifically, a fuzzy logic approach to determine the risk related to an encounter has been developed. The thesis is utilizing a dynamic approach to scale the range thresholds about the OS to account for the available maneuverable space. Such a dynamic approach has, to the author's knowledge, never been used for the evaluation of risk compliance.

- Lastly, an evaluation of perceived passenger safety is developed by using fuzzy logic. There is no previous work on quantifying perceived passenger safety on an autonomous passenger ferry to the author's knowledge.

1.5 Thesis outline

The remainder of this paper is structured as follows: Chapter 2 presents some relevant background theory for the work in this thesis. Chapter 3 presents the evaluation method. In Chapter 4, results are displayed, while we in Chapter 5 discusses the results, and point out the challenges and limitations of the proposed method. Finally, Chapter 6 concludes the work.

1.6 A short notice

In connection to the thesis, an article submitted to the 14th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles has been written, submitted, and approved for publishing. The submission deadline was prior to the completion of this thesis. Text and results from the article are re-used in the thesis and vice versa. Also, a project thesis with a similar topic as this thesis was completed last semester. Parts of the literature review from the project thesis are included in this thesis.

Chapter 2

Background theory

This chapter presents theory that is considered to be a prerequisite to grasp the essentials of the thesis' method, results, discussion and conclusion. First, some general collision avoidance theory is presented. This is followed by a brief description of the trajectory planner used in OS's guidance and navigation system. Then, important parameters are defined and described along with an explanation of fuzzy logic. Further, the most relevant COLREGs rules are summarized followed by a description of the maneuver detection method. Finally, the method for determining the maneuverable space is described.

2.1 General theory

Vessel notation

The Own Ship (OS) and Target Ship (TS) is the general notation used to label vessels in an encounter. OS is the vessel being controlled and the main vessel under investigation for evaluating purposes in this thesis. TSs are other vessels involved in the encounter posing a potential collision threat to OS. Definition of reference frame, position, velocity and heading for OS and TS are visualized in Figure 2.1.

Closest point of approach

An important concept in maritime navigation is CPA. This is used e.g. for assessing whether there is risk present in an encounter between vessels. The CPA is the point in

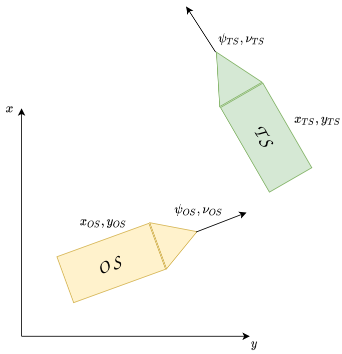

Figure 2.1: Definition of OS and TS position, velocity and heading

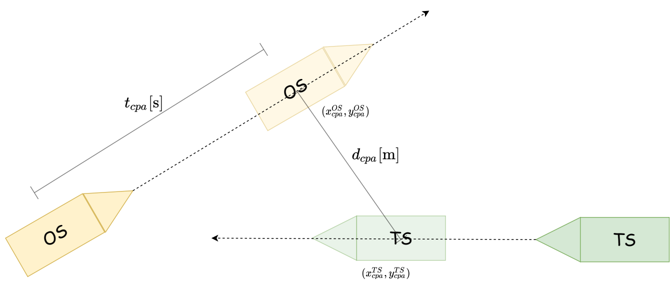

Figure 2.2: Illustration of DCPA and TCPA

space where two vessels have the shortest distance between them in an encounter, and from this both the DCPA and TCPA can be calculated. DCPA is the estimated distance between OS and TS at the estimated CPA, and TCPA is the estimated time until OS and TS are at the point of CPA. The CPA is estimated based on position and velocity of the OS and TS. In the CPA calculation, it is assumed that both vessels will keep a constant speed. Calculation of DCPA and TCPA is done by following the procedure described in Kufoalor et al. (2018). DCPA and TCPA are illustrated in Figure 2.2.

TCPA is calculated as

$$t_{cpa} = \begin{cases} 0 & \text{if } ||\boldsymbol{v}_{ts} - \boldsymbol{v}_{os}||_2 \leq \epsilon. \\ \frac{(\boldsymbol{p}_{ts} - \boldsymbol{p}_{os})(\boldsymbol{v}_{ts} - \boldsymbol{v}_{os})}{||\boldsymbol{v}_{ts} - \boldsymbol{v}_{os}||_2^2} & \text{otherwise.} \end{cases} \tag{2.1}$$

where $\boldsymbol{p}$ is the position, $\boldsymbol{v}$ is the velocity, and ϵ is a threshold in order to avoid division by zero in the case where the relative velocity between the OS and TS is zero. The DCPA is calculated as

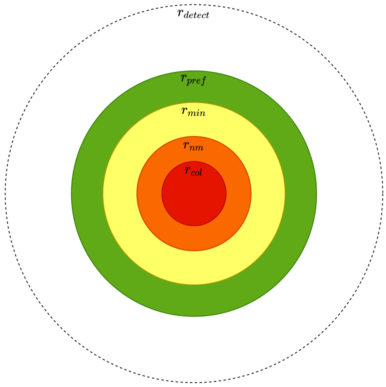

Figure 2.3: Concentric range rings. Source: Woerner et al. (2019)

$$d_{cpa} = ||(\boldsymbol{p}_{os} + t_{cpa}\boldsymbol{v}_{os}) - (\boldsymbol{p}_{ts} + t_{cpa}\boldsymbol{v}_{ts})||_2 \tag{2.2}$$

where t_{cpa} is found from (2.1).

Ranges

The distance between two vessels is an essential metric in the evaluation system. The range between an OS and TS is found as

$$r_{os}^{ts} = \sqrt{(x_{os} - y_{os})^2 + (x_{ts} - y_{ts})^2} \tag{2.3}$$

Woerner et al. (2019) defined configurable range thresholds that could be used as guidelines for the assessment of range related metrics in such evaluation systems. The concentric range rings, shown in Figure 2.3, defines four primary threshold ranges for the DCPA in an encounter between two vessels:

- r_{pref} is the threshold for the preferred DCPA
- r_{min} defines the maximum DCPA which could be considered as accepted
- r_{nm} defines the range that should be considered as unsafe and indicates an encounter with high risk of collision
- r_{col} or smaller DCPA is considered to result in a physical collision

A final range threshold that is important to define is the detection range, i.e. the range that defines the start of a collision avoidance encounter between two vessels. The r_{detect}

threshold is constitutive for a COLREGs encounter. The encounter geometry is considered first when the range between the vessels falls below the r_{detect} threshold. The COLREGs roles are calculated for this moment in time and are valid throughout the encounter.

2.2 Collision avoidance algorithm

The evaluation method developed in this thesis is independent of the collision avoidance algorithm used in the simulations. The required inputs to the developed system is only the vessels' position measurements and its corresponding timestamps. However, for reference, the trajectory planning method used to control the OS in the simulation results used in the thesis will be presented in some detail.

The trajectory planning method is presented in Thyri and Breivik (2022) and is designed to be compliant with Rule 8 and rules 13-17 from COLREGs. The method is designed for vessels operating in restricted waters, similar to the evaluation method's design domain. The trajectory planner is capable of handle both dynamic and static obstacles and is using a dynamic approach to determine the safe distance to other vessels. The trajectory planner is formulated as a finite horizon nonlinear model predictive controller aiming to minimize the deviation from a reference trajectory and the acceleration. Dealing with static objects, the planner constructs convex free sets and dealing with other traffic the planner assigns domains to each vessel in the encounter.

The diagram in Figure 2.4 shows how the modules of the trajectory planner interact. The TS trajectories are used to classify the encounter and a assigned to a priority list based on the CPA and criticality estimates. Further, dynamic constraints are assigned and maneuvering cost reduction windows are identified. The static obstacles are found through map data, and convex free sets for selected steps of the control horizon are constructed. This information is used to formulate an optimal control problem.

2.3 Relative bearing and contact angle

The relative bearing β is defined as the bearing of an obstacle relative to OS's bow. The contact angle α is the relative bearing of OS relative to a TS's bow. I.e., relative bearing from OS as seen from TS's perspective is denoted as the contact angle. Relative bearing is normally defined as inside the interval $\beta \in [0°, 360°)$ measured clockwise. The relative contact angle is normally wrapped inside the interval $\alpha \in (-180°, 180°]$, i.e., the Shortest Signed Angle (SSA). Angles measured at the CPA are noted with a subscript, e.g. β_{cpa}, as illustrated in Figure 2.5a.

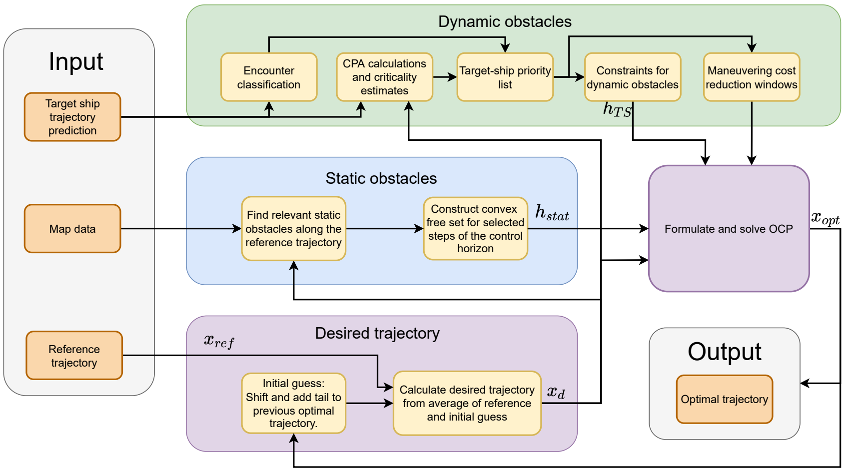

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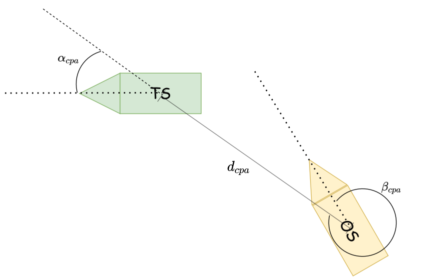
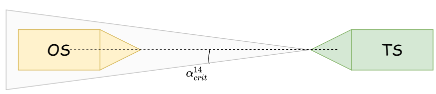
Figure 2.4: Overview of the trajectory planner module. Source: Thyri and Breivik (2022)



(a) Relative bearing β and relative contact angle α at CPA



(b) Illustration of critical contact angle α^{14}_{crit}

Figure 2.5: Relative bearing, contact angle and critical contact angle

It is sometimes useful to express relative bearing angles in the interval $\beta \in (-180°, 180°]$. To easily separate the different notations, a superscript will define the interval of both relative bearing and contact angle, e.g. $\beta^{360°}$ and $\alpha^{180°}$. It is useful to talk about angles for a specific rule in some cases. In such cases, a superscript will be used with similar notation as above, e.g. α^{14}_{crit} which is the critical angle, illustrated in Figure 2.5b, in a head-on situation as described in Rule 14. If a specification of interval and rule is necessary, the notation $\alpha^{14,180°}$ will be used.

Relative bearing and contact angle are calculated based on the same procedure as in Woerner (2016). $\beta^{360°}$ is calculated as

$$\beta^{360^\circ} = \begin{cases} 360^\circ - |\phi_{os} - \psi_{os}|, & \text{if } \phi_{os} - \psi_{os} < 0^\circ \\ \phi_{os} - \psi_{os} - 360^\circ, & \text{if } \phi_{os} - \psi_{os} \geq 360^\circ \\ \phi_{os} - \psi_{os}, & \text{otherwise} \end{cases} \tag{2.4}$$

where $\psi_{os} \in (-180, 180]$ is the heading of OS with clockwise direction as the positive direction. OS with a heading towards north is defined to give $\psi_{os} = 0^\circ$. The bearing ϕ_{os}, i.e., the absolute bearing angle, is found as

$$\phi_{os} = \text{atan2}(y_{ts} - y_{os}, x_{ts} - x_{os}) \tag{2.5}$$

where *atan2(...)* gives an angle in the interval $(-180^\circ, 180^\circ]$.

The contact angle is found as

$$\alpha^{180^\circ} = \begin{cases} 360^\circ - |\phi_{ts} - \psi_{ts}|, & \text{if } \phi_{ts} - \psi_{ts} < 180^\circ \\ 360^\circ - (\phi_{ts} - \psi_{ts}), & \text{if } \phi_{ts} - \psi_{ts} \geq 180^\circ \\ \phi_{ts} - \psi_{ts}, & \text{otherwise} \end{cases} \tag{2.6}$$

where ϕ_{ts} is found as

$$\phi_{ts} = \text{atan2}(y_{os} - y_{ts}, x_{os} - x_{ts}) \tag{2.7}$$

2.4 Fuzzy logic

Fuzzy logic is a term introduced in 1965 by the Azerbaijani scientist Lofti Zadeh. A FLS consists of three main blocks as illustrated in Figure 2.6: a fuzzifier, rules and inference logic, and a defuzzifier.

Mamadani inference system

A Mamadani fuzzy inference system is the most widely adopted method for modeling advanced systems and control purposes. The technique was first presented in Mamdani and Assilian (1975) as an attempt to control a steam engine and boiler combination by using a set of linguistic rules. The work was highly influenced by the publication of Zadeh (1965) (Iancu, 2012).

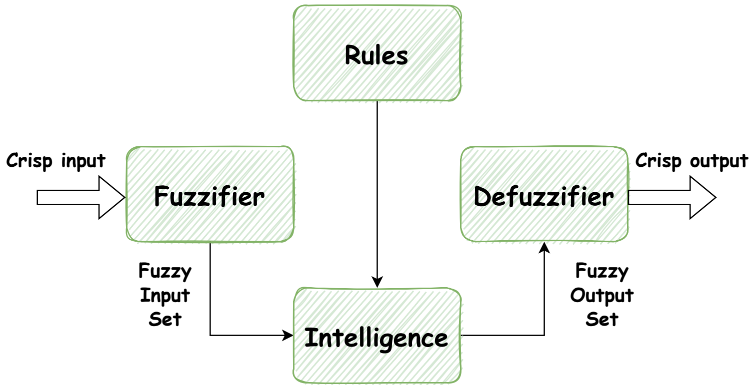


Figure 2.6: Illustration of modules in a Fuzzy logic system

Fuzzy set

To define a fuzzy set we look to the source, Zadeh (1965). He stated that a fuzzy set (class) $\mathcal{A}$ in $\mathcal{X}$ is characterized by a MF $\mu_A(x)$ which associates with each point in $\mathcal{X}$ a real number in the interval [0,1] with the value of $\mu_A(x)$ at x representing the "grade of membership" of $x \in \mathcal{A}$.

Thus a fuzzy set $\mathcal{A}$ can formally be defined as:

$$\mathcal{A} = x, \mu_{\mathcal{A}}(x)|x \in \mathcal{X} \tag{2.8}$$

where $\mathcal{A}$ is the fuzzy set, x is the an element (i.e. the crisp value), $\mu_{\mathcal{A}}(x)$ is the MF that maps the crisp value x in the universe of discourse $\mathcal{X}$ to a membership value, as defined in (2.12). A crisp value is in opposition of a fuzzy value, i.e a value that is well defined and has a precise value. The universe of discourse is defined as the set $\mathcal{X}$ of possible values that can take the variable x.

A fuzzy set has notions such as inclusion, union, intersection, complement, relation and convexity that are very useful when working with FLS. The most important notions are:

Complement:

$$\mu'_{\mathcal{A}}(x) = 1 - \mu_{\mathcal{A}}(x) \tag{2.9}$$

i.e. $\mu'_{good}(x) = 1 - \mu_{good}(x)$. This attribute is useful when using the 'NOT' statement in the rule making. The 'NOT' statement can also be indicated by using a the notation '$\sim$' in front of a membership parameter.

Union: $\mathcal{C} = \mathcal{A} \cup \mathcal{B}$

$$\mu_{\mathcal{C}}(x) = max[\mu_{\mathcal{A}}(x), \mu_{\mathcal{B}}(x)], \quad x \in \mathcal{X} \tag{2.10}$$

which is useful when using the 'OR' statement in rules.

Union: $\mathcal{C} = \mathcal{A} \cap \mathcal{B}$

$$\mu_{\mathcal{C}}(x) = min[\mu_{\mathcal{A}}(x), \mu_{\mathcal{B}}(x)], \quad x \in \mathcal{X} \tag{2.11}$$

which is useful when using the 'AND' statement in rules.

Antecedent and consequent

The terms 'antecedent' and 'consequent' will be used throughout the thesis and is important terms in a FLS. The terms will mainly be used in combination with a MF, as a MF must either be antecedent or consequent. An antecedent is the first half of a hypothetical proposition (Wikipedia, 2022). I.e., it constructs the IF-clause in the IF-THEN proposition. A consequent is the second half of a hypothetical proposition (Wikipedia, 2021). I.e., it constructs the THEN-clause in the IF-THEN proposition. This means that an antecedent MF will be used to construct the fist half of the hypothetical proposition, and the consequent MF will be used to construct the second half of the theoretical proposition. In the hypothetical proposition below, the P is the antecedent and Q is the consequent.

- IF P, THEN Q

Fuzzifier

The first block in Figure 2.6 is a fuzzifier block. This block is responsible for taking in crisp inputs and calculating a fuzzy set based on the crisp input. To transform the crisp input, there exist one or several MFs. A MF is a quantification of a parameter, e.g. a linguistic term such as 'apparent', in the form of a graph.

A membership function for a fuzzy set $\mathcal{A}$ on the universe of discourse $\mathcal{X}$ is defined as:

$$\mu_{\mathcal{A}}(x) : \mathcal{X} \longrightarrow [0, 1] \tag{2.12}$$

where each element of $\mathcal{X}$ is mapped to a value between 0 and 1, the *degree of truth* or Degree of Membership (DoM).

Fuzzy intelligence and fuzzy rules

Inference is the combination of the blocks *Intelligence and Rules* shown in Figure 2.6. Inference is the process where one tries to reason, moving from premises to logical consequences. A Mamdani FLS has an $IF < Antecedent > THEN < Consequent >$

Table 2.1: Rule table

Rule	**IF (AND logic)**				**THEN**
#		ant_1	ant_2	ant_3	con_1
R_1		A	A	A	-
	OR	A	B	B	C
R_2		B	A	A	-
	OR	B	B	A	-
	OR	B	A	B	D

rule-based system (Perera et al., 2010). The IF-THEN rules are developed based on the system under investigation. Common for all IF-THEN rules are that one tries to capture all available knowledge about the system in simple statements. Knowledge about the system can originate from several sources, e.g. from observed behavior of a system, from a set of linguistic and vaguely written rules, or from measured behavior of a system. A common approach is to use expert knowledge gathered from interviews of competent and experienced people within the field.

The IF-THEN rules will be presented in tables similar to Table 2.1. This is a quick and effective way to summarize the rules that are constructed in the thesis. ant_i are the antecedents, i.e. a parameter used in the evaluation, and con_1 is the consequent, i.e. the output parameter of the FLS. 'A' and 'B' are input membership functions connected with the antecedents. 'C' and 'D' are output membership functions connected with the consequent. The tables should be read as:

R_1: IF (ant_1 is 'A' AND ant_2 is 'A' AND ant_3 is 'A') OR (ant_1 is 'A' AND ant_2 is 'B' AND ant_3 is 'B') THEN con_1 is 'C'

R_2: IF (ant_1 is 'B' AND ant_2 is 'A' AND ant_3 is 'A') OR (ant_1 is 'B' AND ant_2 is 'B' AND ant_3 is 'A') OR (ant_1 is 'B' AND ant_2 is 'A' AND ant_3 is 'B') THEN con_1 is 'D'

Defuzzifier

In this last module of the FLS the fuzzy decisions are defuzzified by the output MFs. An output MF is similar to an input MF. The purpose of the defuzzification is to convert the fuzzy sets back into a crisp value.

A defuzzifier can be based on different methods, however, the two most used are the *center of gravity* and the *mean of maxima* methods. With the center of gravity method, the crisp output is the abscissa of the center of gravity of the surface described by the fuzzy output function (Van Broekhoven and De Baets, 2006).

The crisp output is formally defined by

$$y_{COG} = \frac{\sum_{i=1}^{N} A_i * x_i}{\sum_{i=1}^{N} A_i} \quad (2.13)$$

Membership functions

Membership functions are essential in a FLS. MFs are designed to describe the antecedent with linguistic terms that can be modified based on some sort of knowledge. Figure 2.7 shows an example of how MFs are designed to interpret the antecedent 'ActionOS'. The antecedent has three MFs that together cover the input space of 'ActionOS'. The MFs are designed with trapezoidal shapes. A trapezoidal MF is computed using the following function:

$$f(x; a, b, c, d) = \max(\min(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}), 0) \quad (2.14)$$

However, a common way of referencing a trapezoidal function is to use a vector notation on the form $[a, b, c, d]$ where $[a, b]$ defines the linear interval where the function value (y-axis) increases from 0 to 1 and $[c, d]$ defines the linear interval where the function value decreases from 1 to 0.

In Figure 2.7 the MF 'Early' define the values that are regarded as maneuvers taken in ample time in an encounter. The function's vector notation is $[0.6, 0.7, 1, 1]$. Similarly the MFs 'QuiteEarly' and 'Late' are noted as $[0.4, 0.5, 0.6, 0.7]$ and $[0, 0, 0.4, 0.5]$ respectively.

An important notice when assessing the results from a FLS is that even though the value for 'ActionOS' in Figure 2.7 is 1, the crisp output value calculated by the defuzzifying center of gravity method will only be 0.824. The crisp output will be similar for all 'ActionOS' values that result in a full DoM in the MF 'Early', i.e., all values from 0.7 to 1. Intuitively, this feels a bit odd. One might think that this reduces the nuances; going from 'ActionOS', a measure of the earliness of a maneuver from 0 to 1, and reducing it to something that evaluates the scores between 0.7 and 1 equally. However, when reflecting on it, this is more similar to how humans assess a decision parameter. The human brain is not able to exploit fine-grained parameters such as 'ActionOS', thus breaking this down to a more coarse-grained set and using it in combination with other coarse-grained parameters in the decision-making process is more similar to the way humans make decisions.

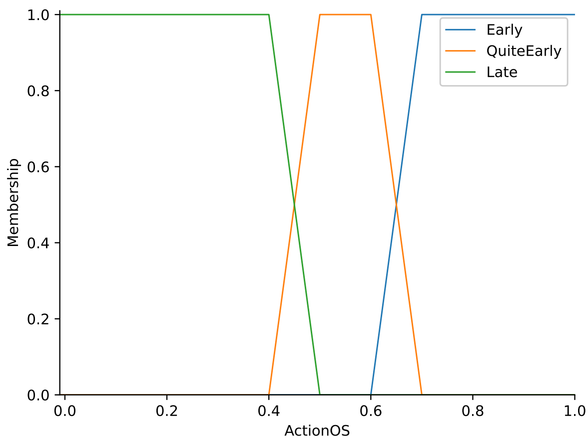


Figure 2.7: Membership functions to determine the antecedent 'ActionOS'

2.5 COLREGs

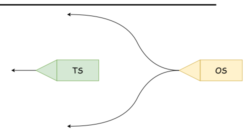
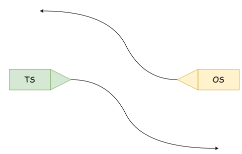
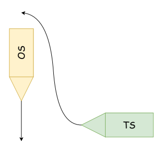
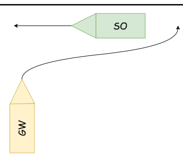
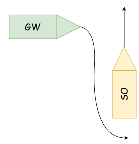
With the introduction of steamships in the early 18th century, new collision risks emerged when they encountered traditional sailing vessels. Collision avoidance rules were formulated in the 1840s to coordinate collision avoidance actions of steamships and sailing vessels to deal with this emerging risk. In the middle of the 19th century, the COLREGs had codified all major actions required to avoid collisions, and many of the principles are still recognizable today. However, various alterations to the COLREGs have been agreed upon in the later years, reflecting the increase of traffic and technological advances. The latest major rewriting of the COLREGs was in 1972 and remains in force today (Belcher, 2002). The most important rules for this paper are summarized in Table 2.2 (Cockcroft and Lameijer, 2012)

Rule 7: Risk of collision

Rule 7 introduces the risk term and give some context to how risk should be considered for a COLREGs encounter. The most important points are:

- Rule 7 (a) states that every vessel should use available means to determine if risk of collision exists, and if there is any doubt such risk should be deemed to exist.
- Rule 7 (d)(i) states that risk shall be deemed to exist if the compass bearing of an approaching vessel does not appreciably change.

Table 2.2: Maneuvers in various obstacle avoidance situations

Rule #	**Situation**	**Keywords**	**Schematics**
Rule 7	Risk of collision	Available means to determine risk, if doubt risk shall be deemed to exist	
Rule 8	Action to avoid collision	Ample time, good seamanship, course and/or speed alteration should be readily apparent, passing at safe distance	
Rule 13	Overtaking	Keep out of the way	
Rule 14	Head-on	Reciprocal or near-reciprocal courses, alter course to starboard, pass on port side	
Rule 15	Crossing	Vessel which has other on starboard side shall keep out of way, avoid crossing ahead	
Rule 16	Action by give-way	Early and substantial to keep out of the way	
Rule 17	Action by stand-on	Keep course and speed	

- Rule 7 (d)(ii) states that risk could still exist even when an appreciable bearing change is evident.

Rule 8: Action to avoid collision

Rule 8 in COLREGs defines how actions should be taken to avoid collision. The most relevant points in Rule 8 are:

- Rule 8 (a) states that any action to avoid collision shall be made in ample time and with due regard to the observance of good seamanship.
- Rule 8 (b) states that any alteration of course and/or speed to avoid collision shall be large enough to be readily apparent to another vessel observing visually or by radar and that successions of small alterations of course and/or speed should be avoided.
- Rule 8 (d) states that action to avoid collision should result in passing at a safe distance.

Rule 13: Overtaking

Rule 13 describes an overtaking situation:

- Rule 13 (a) states that any vessel overtaking any other shall keep out of the way of the vessel being overtaken.
- Rule 13 (b) states that a vessel shall be deemed to be overtaking when coming up another vessel from a direction more than 22.5 degrees abaft her beam. It is emphasized that at night the overtaking vessel should only be able to see the sternlight but neither of the sidelights of the vessel being overtaken.
- Rule 13 (c) states that if if there exists any doubt, an overtaking role should be assumed.
- Rule 13 (d) states that alterations of the bearing subsequent to the detection shall not make the overtaking vessel a crossing vessel. The overtaking vessel shall continue to keep clear of the overtaken vessel until she is past and clear.

Rule 14: Head-on

Rule 14 in the COLREGs is probably the rule that contains the most vague entry-criteria of all.

- Rule 14 (a) states that a head-on encounter exist when two power-driven vessels that are meeting on reciprocal or nearly reciprocal courses, and that both shall alter the course to starboard so that they are passing on port side of the other.
- Rule 14 (c) states that if there is any doubt, a head-on encounter shall be assumed to exist.

Rule 15: Crossing

Rule 15 descirbes a crossing encounter and states that two power driven vessels crossing each other the vessel which has the other on her starboard side shall keep out of way. If the case admit, crossing ahead of the other vessel should be avoided.

Rule 16: Action by give-way vessel

Rule 16 applies to all vessels with a give-way role in an encounter, and the rule states that the vessel is directed to keep out of the way of another vessel and shall so far as possible take early and substantial action to keep well clear.

Rule 17: Action by stand-on vessel

Rule 17 describe the required behavior of a stand-on vessel:

- Rule 17 (a)(i) states that where one of two vessels shall keep out of way the other shall keep speed and course.
- Rule 17 (a)(ii) states that the stand-on vessel may take action to avoid collision as soon as it becomes apparent that the vessel required to keep out of the way is not taking appropriate action in compliance with Rule 16.
- Rule 17 (c) states that an alteration of course towards port by a stand-on vessel for should be avoided for a vessel on her own port side.

Entry criteria

A critical contact angle α_{crit} helps to specify if a vessel should take action as per COLREGs. A critical contact angle can be used to effectively evaluate what COLREGs situation a vessel is in. Using a critical angle allows flexibility to the evaluator, and a designer might tune this angle to best mimic human ship driving practice (Woerner et al. (2019)).

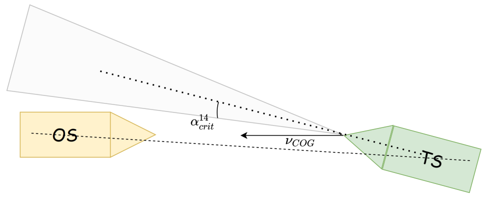


Figure 2.8: Deviation of heading and course

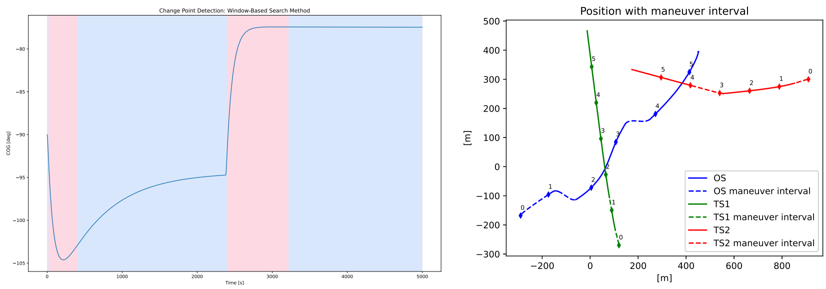
An important aspect that must be considered when using contact angle is that it is based on compass heading which disregards the course of the vessels, which can be quite different from the compass heading. This is illustrated in Figure 2.8 where the TS has a side-slip and/or crab angle. Side-slip is a deviation between heading and Course Over Ground (COG) due to a velocity component in sway during e.g. a sharp turn. Crab angle appears when environmental forces affect the ship causing a deviation between heading and course (Fossen, 2011). This can potentially cause ambiguities for entry criteria in edge-cases. E.g., in Figure 2.8 the entry criteria for Rule 14 – head-on is not fulfilled, and thus the TS would assume that this is a crossing situation and not a head-on situation. However, the velocity vector denoted ν_{COG} reveals that the TS is actually on a direct collision course with OS in a head-on situation. This illustrates why it is important to carefully consider entry criteria within the context of the local environmental conditions. This thesis will assume that heading and course are equal, i.e. no side-slip or crab-angle.

2.6 Maneuver detection

In order to assess whether a maneuver is compliant with respect to COLREGs it is important to know when a maneuver is taken and the magnitude of the maneuver. The importance of determining these parameters become obvious when looking at e.g. Rule 8 in COLREGs, which contains terms like 'readily apparent' and 'ample time' describing how a maneuver should be conducted. In order to evaluate the performance of the OS with respect to these terms, the maneuvers of the vessel must first be reliably detected.

A method for detecting maneuvers from a time-series is Change Point Detection (CPD). This is an algorithm that has the goal of detecting abrupt shifts in time series trends that would usually be easily identified by the human eye, but which can be more challenging to detect with traditional statistical approaches.

One of the most used methods to detect change points is a sliding window method. The idea is to walk through the signal with a fixed size window and through a cost-function calculate a value for the current window. E.g., a cost-function using the standard deviation



(a) Window-based change point detection **(b)** Position plot with maneuver interval

Figure 2.9: Manuever interval from sliding window change point detection

of a signal could be used to identify change points of the mean value in the signal. There exists several packages in different programming languages that are dedicated to change point detection. The *ruptures* package in Python has been utilized in this thesis. The built-in window-based change point detection algorithm uses two windows sliding along the data stream. In each window the signal's statistical properties are calculated and compared to a discrepancy measure d:

$$d(y_{u,v}, yv, w) = c(y_{u,w}) - c(y_{u,v}) - c(v, w) \tag{2.15}$$

where y_t is the input signal and $u < v < w$ are indices. A change point interval is found by calculating the discrepancy curve along the full time-series and identifying the time interval when the curve is above a peak detection threshold (Ruptures, 2022).

The output from the change point detection used on COG measurement is seen in Figure 2.9a.

2.7 Maneuverable space

COLREGs Rule 8 (c) and (d) mention the terms sufficient sea-room, good time and safe distance. These terms are highly relative to the operational domain and the surroundings. E.g., the interpretation of sufficient sea-room would be very different in open water compared to confined water. In open water, a passing distance of several hundred meters is desired because the maneuverable space allows it, however in more confined spaces a passing distance of 30 meters and less could be acceptable. This motivates for a dynamic calculation of range thresholds as defined in 2.1. This dynamic calculation of available maneuverable space should take the surroundings into account, including nearby static and dynamic object in the water, and also map data which indicates land areas. Optimally, information about the bathymetry should be taken into account to calculate the available maneuverable space.

Chapter 3

Method

This section describes the methods developed to evaluate the performance of a vessel in encounters with other vessels with respect to COLREGs, encounter safety, and perceived safety.

3.1 System architecture

The evaluation system is comprised of three independent systems:

- A system for evaluating compliance with the COLREGs.
- A system for evaluating the perceived safety of the vessel.
- A system for evaluating the objective safety in the encounter between two vessels.

The complete system is illustrated in Figure 3.1. The COLREGs compliance evaluation system has four modules, System A, System B, System C and System D. System A is comprised again of four subsystems, all of which are individual FLSs, namely ”R13”, ”R14”, ”R15” and ”ROLE EVAL”. Systems B, C and D are all individual FLSs where the input and output of the systems are indicated in the figure. The perceived safety evaluation is an individual FLS, where the green boxes indicates evaluation parameters that are used to assess the safety. The same applies for the encounter safety evaluation. Further explanations of the modules follow below.

Table 3.1 gives a description of the essential symbols used in the thesis.

Table 3.1: List of symbols

Symbol	Description
α^{180°	Contact angle in interval $[-180^\circ, 180^\circ]$
α^{360°	Contact angle in interval $[0^\circ, 360^\circ]$
β^{180°	Relative bearing angle in interval $[-180^\circ, 180^\circ]$
β^{360°	Relative bearing angle in interval $[0^\circ, 360^\circ]$
w_c	Slack parameter for COLREGs role evaluation
w_r	Slack parameter for range evaluation
α_{13}^{crit}	Critical overtake contact angle.
α_{14}^{crit}	Critial head-on contact angle.
α_{15}^{crit}	Critical crossing contact angle.
R_{min}	Maneuverable space. Minimum distance from TS to static obstacle
r_{detect}	Detection range. Defines start of COLREGs encounter.
r_{pref}	Preferable encounter range.
r_{min}	Minimum acceptable encounter range.
r_{nm}	Near-miss encounter range.
r_{col}	Collision encounter range.
β_{detect}	Relative bearing angle at r_{detect}
α_{detect}	Relative contact angle at r_{detect}
$\triangle d_{cpa}$	Change in estimated d_{cpa} before and after maneuver.
U	Linear velocity.
$U_{docking}$	Docking velocity.
a	Acceleration.
$a_{docking}$	Docking acceleration.
$\triangle\chi$	Course change magnitude.
$\triangle U$	Speed change magnitude.
$\#_{\triangle\chi}$	Number of successive course alterations
$\mathrm{S}_{\triangle U}$	Speed reduction score
θ_{ps}^{bool}	Whether vessels pass on port side or not
CR	Novel collision risk indication based on DCPA
$S_{delay}^{man.}$	Score for earliness of a maneuver

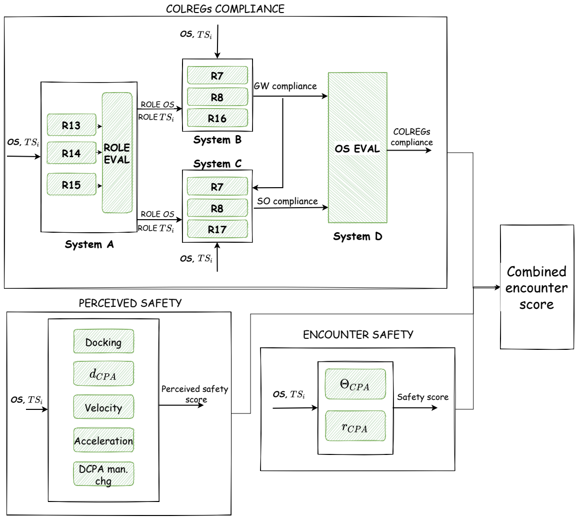


Figure 3.1: Full evaluation system

3.2 COLREGs compliance

As illustrated in Figure 3.1, System A in the COLREGs compliance system is responsible for determining each vessel's role in the encounter, i.e., whether a vessel is GW or SO. This is calculated based on the geometry between the vessels when the distance between them falls below a given threshold. The roles are determined based on a set of entry criteria inspired by Algorithm 5 from Woerner et al. (2016). The entry criteria are used to design MFs, shown in Table 3.3, as antecedents. The consequents are functions that determine the DoM in rules 13, 14 and 15 of OS and TS. System B is responsible for calculating GW compliance based on rules 7, 8 and 16. System C is responsible for calculating the compliance of the SO vessel based on COLREGs rules 7, 8 and 17. The assessment of GW compliance must come before SO compliance assessment due to COLREGs Rule 17 (ii). Rule 17 (ii) grants permission for SO to make a maneuver when the GW vessel is not taking appropriate action to avoid a collision and is thus essential information for SO compliance evaluation.

Tunable parameters

Deciding whether rules 13, 14, or 15 apply to an encounter has been a largely discussed task. Only Rule 13 provides any specific angle measure to assess an overtaking scenario by specifying '... 22.5 degrees abaft her beam'. However, even though a specific angle is stated, confusion arises due to the difficulties of human assessment of angles by eye.

Table 3.2: Tunable parameters for System A and proposed values

Parameter	Proposed value
w_c	2.5°
α_{crit}^{13}	112.5°
α_{crit}^{14}	12.5°
α_{crit}^{15}	10°

Even for an ASV it is not straightforward to assess encounter geometries to decide which COLREGs rule should apply to know whether to SO or GW. The position and heading measurement uncertainties could make the encounter geometry assessment blurry, similar to an assessment by a human operator. And even if one could, hypothetically, know its own and surrounding vessels' position and heading accurately, it would require the assumption that every other vessel in the encounter also knows its own and other vessels' position and heading accurately in order to justify using hard limits to decide and assign roles of SO and GW. This would be a difficult assumption to justify, and thus, using soft limits in the evaluation is preferred to account for such encounter geometry uncertainties. Specifically, this is done by introducing a margin parameter w_c that is used to create overlapping areas between rules 13, 14, and 15. The margin parameter w_c and critical angles are shown in Table 3.2.

The $\alpha_{crit}^{13/14/15}$ parameter defines a hard limit between COLREGs rules 13, 14 and 15, and the parameter w_c is used to 'soften' the limits. The α_{crit} limits are chosen based on previous research, such as Woerner (2016). Specifically, the α_{crit}^{14} and α_{crit}^{15} are similar to the values used in Algorithm 5 in Woerner (2016). However, α_{crit}^{13} is chosen based on a proposed correction of the entry criteria from Algorithm 5 to make it align better with similar entry criteria methods, such as Tam and Bucknall (2010b).

The margin parameter w_c is chosen as 2.5 degrees for all rule assessments in the COLREGs evaluation. This gives an overlapping area of 5 degrees between the vessel domains specified by the COLREGs. However, the value for w_c can easily be changed if the evaluator finds it appropriate.

3.2.1 System A

This section presents the subsystems of System A that is responsible for calculating OS and TS(s) roles in an encounter. This system is interpreting rules 13, 14 and 15 of the COLREGs.

Rule 13

As illustrated in Table 2.2 and described in the COLREGs, 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, and the vessel overtaking shall keep out of the way, i.e., act as the GW vessel. It is also stated that a vessel in doubt as to whether she is overtaking another shall assume this is the case, i.e., assume to be the GW vessel. This highlights that, even though the overtaking angle is defined explicitly, margin must be added to account for the uncertainty in human interpretation of an encounter.

Table 3.3 shows the MFs that have been designed to assess whether a vessel is in an overtaking encounter. The top four rows are the antecedents that have been added for Rule 13. In the Rule column it is seen that two antecedents account for rules 13 and 16, and the two next for rules 13 and 17. This is to distinguish between OS overtaking TS or opposite. In the former, OS has a GW role and TS has a SO role and opposite in the latter. In the interval column, the $w_{COLREGs}$ is added to account for the uncertainty in entry criteria as mentioned above.

Table 3.4 shows the rules that are designed to capture the MF to determine whether OS and TS should be given roles as defined by Rule 13. Rule A_1 defines the scenario where OS is being overtaken by the TS. If the MF 'TSOvertakingOS' has a high DoM in the antecedent β^{360° and 'TSOvertakingOSCrit' has high DoM in the antecedent α^{180° then role of OS, R_{OS}, is SO and role of TS, R_{TS}, is GW. The same logic is used for Rule A_2. The absolute value about e.g. $|\beta^{180^\circ}|$ indicates that the absolute value of the relative bearing is being used when interpreting the DoM.

Rule 14

As summarized in Table 2.2 Rule 14 should be assumed to apply in an encounter where two vessels are meeting on 'reciprocal or nearly reciprocal courses'. The terms reciprocal or nearly reciprocal are highly vague, and contrary to Rule 13 no angle is explicitly mentioned to apply to these encounters. However, from the literature, a relative bearing and contact angle of 10°-13°is a common interpretation of the term 'reciprocal or nearly reciprocal' (Woerner, 2016; Hagen et al., 2021). Similar to Rule 13, it is stated that if any doubt exists, a vessel should assume the encounter to be head-on and act according to a GW role. Thus, the variable w_c is added to the MFs to account for the fuzziness in the rule description. Table 3.5 shows that both β and α must have membership in the FMF 'Head-on' for Rule 14 to be assumed the governing rule. The antecedents used to assess Rule 14 are seen in Table 3.3.

Table 3.3: Antecedent and consequent membership functions for System A

Antecedent MFs

Antecedent	Parameter	MF type	Interval	Rule
$\alpha^{360°}$	OSOvertakingTS	Trapezoidal	[112.5-w_c, 112.5+w_c, 247.5-w_c, 247.5+w_c]	R13/R16
$\beta^{180°}$	OSOvertakingTSCrit	Trapezoidal	[0, 0, α^{13}_{crit}-w_c, α^{13}_{crit}+w_c]	R13/R16
$\beta^{360°}$	TSOvertakingOS	Trapezoidal	[112.5-w_c, 112.5+w_c, 247.5-w_c, 247.5+w_c]	R13/R17
$\alpha^{180°}$	TSOvertakingOSCrit	Trapezoidal	[0, 0, α^{13}_{crit}-w_c, α^{13}_{crit}+w_c]	R13/R17
$\beta^{180°}$	Head-on	Trapezoidal	[0, 0, α^{14}_{crit}-w_c, α^{14}_{crit}+w_c]	R14
$\alpha^{180°}$	Head-on	Trapezoidal	[0, 0, α^{14}_{crit}-w_c, α^{14}_{crit}+w_c]	R14
$\beta^{360°}$	CrossingGW	Trapezoidal	[0, 0, 112.5-w_c, 112.5+w_c]	R15/R16
$\alpha^{180°}$	CrossingGW	Trapezoidal	[-112.5-w_c, -112.5+w_c, 180, 180]	R15/R16
$\beta^{180°}$	CrossingGW	Trapezoidal	[-α^{15}_{crit}-w_c, -α^{15}_{crit}+w_c, 180, 180]	R15/R16
$\alpha^{360°}$	CrossingSO	Trapezoidal	[0, 0, 112.5-w_c, 112.5+w_c]	R15/R17
$\beta^{180°}$	CrossingSO	Trapezoidal	[-112.5-w_c, 112.5+w_c, α^{15}_{crit}-w_c, α^{15}_{crit}+w_c]	R15/R17

Consequent MFs

Consequent	Parameter	MF type	Interval	Rule
RoleOfOS	GW	Trapezoidal	[0, 0, 0.4, 0.6]	-
RoleOfOS	SO	Trapezoidal	[0.4, 0.6, 1, 1]	-
RoleOfTS	GW	Trapezoidal	[0, 0, 0.4, 0.6]	-
RoleOfTS	SO	Trapezoidal	[0.4, 0.6, 1, 1]	-

Table 3.4: Rules for Rule 13

Rule	IF (AND logic)				THEN (AND logic)	
#	$\beta^{360°}$	$\lvert\beta^{180°}\rvert$	$\lvert\alpha^{180°}\rvert$	$\alpha^{360°}$	R_{OS}	R_{TS}
A_1	TSOvertakingOS	-	TSOvertakingOSCrit	-	SO	GW
A_2	-	OSOvertakingTSCrit	-	OSOvertakingTS	GW	SO

Table 3.5: Rules for Rule 14

Rule	IF (AND logic)		THEN (AND logic)	
#	$\lvert\beta^{180°}\rvert$	$\lvert\alpha^{180°}\rvert$	R_{OS}	R_{TS}
A_3	Head-on	Head-on	GW	GW

Rule 15

Rule 15 describes a crossing situation and states that the vessel which has the other on her own starboard side shall keep out of the way and avoid crossing ahead of the other vessel. I.e., a vessel shall assume the role of SO in any case where the other is on her starboard side. A summary and an illustration of this rule are found in Table 2.2. Similar to the above-mentioned rules, the margin is added to account for the challenges regarding the human assessment of an encounter configuration. The antecedents created to account for Rule 15 are seen in Table 3.3. It is seen in the Rule column that there are antecedents to distinguish between a crossing give-way encounter and a crossing stand-on encounter. The rules designed for Rule 15 are shown in Table 3.6.

Table 3.6: Rules for Rule 15

Rule	IF (AND logic)				THEN (AND logic)	
#	$\beta^{360°}$	$\beta^{180°}$	$\alpha^{180°}$	$\alpha^{360°}$	R_{OS}	R_{TS}
A_4	CrossingGW	CrossingGW	CrossingGW	-	GW	SO
A_5	-	CrossingSO	-	CrossingSO	SO	GW

COLREGs roles

This FLS is responsible for calculating the roles of OS and TS(s). The system takes in the result from the previously described subsystems and decides whether OS and TS are SO or GW. The rules in this FLS are shown in Table 3.7.

The rules are designed to account for encounters where the role distribution is not clearly defined, i.e. encounters where the β and α at the entry point could indicate both head-on and a crossing geometry. E.g., Rule A_6 accounts for Rule 14's mention of doubt by stating that if $R14_{os}$ is GW but $R15_{os}$ is SO, i.e. conflicting roles, then a head-on encounter is assumed and thus a GW role. The same reasoning is used for Rule 13 when in conflict with Rule 15, as also seen in Rule A_6. Rules are made for both OS and TS, respectively A_6/A_8 and A_7/A_9.

The MFs for COLREGs roles are shown in Figure 3.2. Because the FLS is using the center of gravity method to defuzzify the fuzzy set, the roles of GW and SO span from 0.246 to 0.764. 0.246 implies full DoM in GW and 0.764 implies a full DoM in SO. A value in between this implies that there is some degree of conflicting roles.

3.2.2 System B

System B is responsible for calculating the COLREGs compliance of GW vessels in the encounter. Input to the system is the output from System A, i.e. the roles of OS and TS in terms of GW or SO. The most important rules to take into account in this evaluation are rules 7, 8 and 16. The parameters that are designed to interpret these rules in the fuzzy logic system are described in further detail in the subsequent subsections. The antecedents, consequents and rules designed for System B are seen in Table 3.8 and Table 3.9. A reminder of that the sign "$\sim$" means 'NOT', i.e., indicates that something should have a low DoM in the antecedent/consequent.

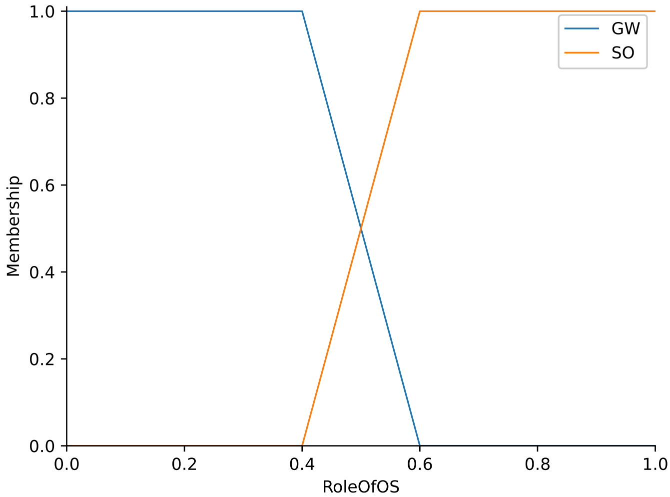


Figure 3.2: Membership functions to determine antecedent 'RoleOfOS'

Table 3.7: COLREGs roles

Rule		**IF (AND logic)**						**THEN (AND logic)**	
#		$R13_{OS}$	$R13_{TS}$	$R14_{OS}$	$R14_{TS}$	$R15_{OS}$	$R15_{TS}$	R_{OS}	R_{TS}
A_6		GW	-	-	-	-	-	-	-
	OR	-	-	GW	-	-	-	-	-
	OR	-	-	-	-	GW	-	-	-
	OR	GW	-	-	-	SO	-	-	-
	OR	-	-	GW	-	SO	-	GW	-
A_7		-	GW	-	-	-	-	-	-
	OR	-	-	-	GW	-	-	-	-
	OR	-	-	-	-	-	GW	-	-
	OR	-	GW	-	-	-	SO	-	-
	OR	-	-	-	GW	-	SO	-	GW
A_8		SO	-	-	-	-	-	-	-
	OR	-	-	SO	-	-	-	-	-
	OR	-	-	-	-	SO	-	-	-
	AND NOT	GW	-	-	-	SO	-	-	-
	OR	-	-	GW	-	SO	-	SO	-
A_9		-	SO	-	-	-	-	-	-
	OR	-	-	-	SO	-	-	-	-
	OR	-	-	-	-	-	SO	-	-
	AND NOT	-	GW	-	-	-	SO	-	-
	OR	-	-	-	GW	-	SO	-	SO

Readily apparent course change

This quality is essential in order to evaluate Rule 8's demands for actions taken to avoid collisions. The course and/or speed change should be large enough to be readily apparent

Table 3.8: Antecedent and consequent membership functions for GW compliance

Antecedent MFs			
Antecedent	**Parameter**	**MF type**	**Interval**
RoleOfOS	GW	Trapezoidal	[0, 0, 0.4, 0.6]
RoleOfOS	SO	Trapezoidal	[0.4, 0.6, 1, 1]
RoleOfTS	GW	Trapezoidal	[0, 0, 0.4, 0.6]
RoleOfTS	SO	Trapezoidal	[0.4, 0.6, 1, 1]
CourseChng	NotApparent	Trapezoidal	[0, 0, 10, 15]
CourseChng	QuiteApparent	Trapezoidal	[15, 20, 30, 35]
CourseChng	ReadilyApparent	Trapezoidal	[30, 35, 90, 90]
SpeedChng	NotApparent	Trapezoidal	[0, 0, 0.3, 0.4]
SpeedChng	QuiteApparent	Trapezoidal	[0.3, 0.4, 0.6, 0.7]
SpeedChng	ReadilyApparent	Trapezoidal	[0.6, 0.7, 1, 1]
RiskCol	Low	Trapezoidal	[r_{min}, r_{pref}, 100, 100]
RiskCol	Medium	Trapezoidal	[r_{nm}, r_{min}, r_{min}, r_{pref}]
RiskCol	High	Trapezoidal	[0, 0, r_{nm}, r_{min}]
Maneuver	Early	Trapezoidal	[0.6, 0.7, 1, 1]
Maneuver	QuiteEarly	Trapezoidal	[0.4, 0.5, 0.6, 0.7]
Maneuver	Late	Trapezoidal	[0, 0, 0.4, 0.5]
Passing	PortSide	Trapezoidal	[0.4, 0.6, 1, 1]
Passing	StarboardSide	Trapezoidal	[0, 0, 0.4, 0.6]
CourseAlterations	Few	Trapezoidal	[0, 0, 1, 4]
Consequent MFs			
Consequent	**Parameter**	**MF type**	**Interval**
ComplianceGW	Good	Trapezoidal	[0.6, 0.8, 1, 1]
ComplianceGW	QuiteGood	Trapezoidal	[0.3, 0.5, 0.6, 0.8]
ComplianceGW	Bad	Trapezoidal	[0.01, 0.01, 0.3, 0.5]
ComplianceGW	NotGW	Trapezoidal	[0, 0, 0.01, 0.01]

to other vessels observing visually or by radar. To obtain the value for course change the maneuver interval must be found, i.e. a start and end time for each maneuver throughout the encounter. This is managed by using the CPD method as described in Section 2.6. The next step is to isolate the maneuvers that have been made after the detection of the TS but before the CPA. This is the interval of interest since we assume that maneuvers made before this point is not made in consideration of the encounter. Maneuvers after CPA are also disregarded because actions to avoid collisions must be made prior to this point to make any sense. Maneuvers by all vessels in the encounter inside the interval $[t_{detect}, t_{cpa}]$ are identified. The crisp value for course change $\triangle\chi$ is found as the maximum deviation between the course at the start of the maneuver and the end of the maneuver seen in (3.1). For a maneuver to be considered readily apparent, this value should be well inside the interval defined by the parameter 'ReadilyApparent' which is a MF in the antecedent

Table 3.9: Rules for GW compliance evaluation

Rule		IF (AND logic)								THEN
#		RoleOS	RoleTS	CourseChng	SpeedChng	RiskCol	Maneuver	Passing	CourseAlterations	ComplianceGW
B_1		GW	-	∼NotApparent	-	∼Low	Early	-	Few	-
	OR	GW	-	-	∼NotApparent	∼Low	Early	-	Few	Good
B_2		GW	-	QuiteApparent	-	∼Low	Early	-	-	-
	OR	GW	-	-	QuiteApparent	∼Low	Early	-	-	-
	OR	GW	-	-	-	∼Low	QuiteEarly	-	-	QuiteGood
B_3		GW	-	NotApparent	NotApparent	∼Low	-	-	∼Few	-
	OR	GW	-	-	-	∼Low	Late	-	∼Few	NotGood
B_4		GW	-	-	-	Low	-	-	-	Good
B_5		SO	-	-	-	-	-	-	-	NotGW
B_6		-	GW	∼NotApparent	-	∼Low	Early	-	Few	-
	OR	-	GW	-	∼NotApparent	∼Low	Early	-	Few	Good
B_7		-	GW	QuiteApparent	-	∼Low	Early	-	-	-
	OR	-	GW	-	QuiteApparent	∼Low	Early	-	-	-
	OR	-	GW	-	-	∼Low	QuiteEarly	-	-	QuiteGood
B_8		-	GW	NotApparent	NotApparent	∼Low	-	-	-	-
	OR	-	GW	-	-	∼Low	Late	-	∼Few	NotGood
B_9		-	GW	-	-	Low	-	-	-	Good
B_{10}		GW	GW	-	-	∼Low	-	StarboardSide	-	NotGood
B_{11}		-	SO	-	-	-	-	-	-	NotGW

labeled as 'CourseChng'. The course change is more specifically found as

$$\triangle\,\chi = \max(|\chi(t_0) - \chi(t_i)|) \tag{3.1}$$

where $\chi(t_0)$ is the course initially in the maneuver and $\chi(t_i)$ is the course at time i after the maneuver start.

The MFs are designed based on existing research, where there is a consensus that any course change of 30 degrees or more is considered to be readily apparent both visually and by radar (Allen, 2004). However, this is not a fixed value and would probably need to be larger in different visual conditions, e.g. in foggy conditions. Thus, the MFs are designed with some flexibility.

Readily apparent speed change

Similar to the course change, a speed change is considered a maneuver that could be used as an action to avoid a collision. Thus speed change $\triangle U_i$ is calculated for the time interval $[t_{detect}, t_{cpa}]$ similar to what was described for a course change. However, because it is more challenging to observe visually or by radar that a vessel changes its speed, a maneuver score for speed change is calculated. The formula used to calculate this reduction score is based on Algorithm 15 in Woerner (2016). The speed reduction score is found as

$$\mathrm{S}_{\triangle U} = 1 - \frac{\delta_v - \triangle v}{\delta_v} \tag{3.2}$$

where δ_v is the apparent speed reduction threshold, i.e. the relative speed reduction that results in a perfect speed reduction score. $\triangle v$ is calculated as

$$\triangle v = \frac{v_0 - v_{min}}{v_0} \tag{3.3}$$

where v_0 is the initial speed at the time of detection and v_{min} is the speed after slowing down.

Succession of small alterations

Rule 8 (b) states that when making a maneuver to avoid a collision, successions of small alterations of course or speed should be avoided. This means that the maneuver should be carried out smoothly. E.g., for a course change, this means that the alteration should happen in one smooth movement from the start of the maneuver until the maneuver ends.

This is thus a quality that is interesting for the assessment of COLREGs evaluation. The antecedent 'ManeuverAlterations' in Table 3.8 is evaluated based on the number of maneuvers made within an interval of a given length (time). The number of alterations within this time interval is found by using a sliding-window method. By using a chosen window size and sliding over the time-series of course and speed of OS and TSs the number of maneuvers inside the window interval is counted. The sliding-window method is illustrated in Figure 3.3 and shows the window which is sliding over the time-series. The number of alterations within this time-window is two, marked with two yellow dots.

If a window size of 20 seconds is chosen, then the total number of maneuver successions is found for this 20-second time interval beginning from the start time t_{detect} of an encounter. After sliding across the time interval $[t_{detect}, t_{cpa}]$ using the 20-second window, the highest number of successions for every vessel is returned and used as input to the FLS. From the MF 'Few' in Table 3.8 it is seen that one succession is regarded as few and the DoM transitions towards zero until reaching four successions. There is only one MF for this antecedent. This is to keep the ruleset as simple as possible.

Delayed Action

Calculation of the delayed action is important due to COLREGs emphasis on the importance of taking early action in an encounter. Also, a delayed action by GW gives the SO vessel permission to make a maneuver to avoid a collision, as stated in Rule 17 (ii). The delayed action should be calculated based on the point of detection, the point of maneuver

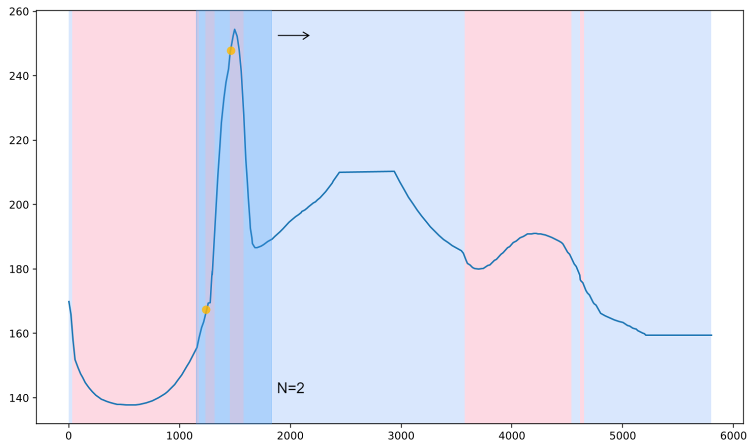


Figure 3.3: Sliding window to count number of alterations within a short amount of time

start, and the DCPA. The delayed action penalty is based on Algorithm 12 in Woerner (2016). The delayed action penalty is calculated as

$$P_{delay} = \frac{r_{detect} - r_{maneuver}}{r_{detect} - r_{cpa}} \tag{3.4}$$

where r_{detect} is the range between the OS and TS at the time of detection, $r_{maneuver}$ is the range to obstacle at the time of the vessels' maneuver and r_{cpa} is the DCPA. The range r_{detect} is found as $1.8 \cdot r_{pref}$. This will result in a penalty between 0 and 1. The developed system uses the score rather than a penalty to determine the earliness of a maneuver. This score is found as

$$S^{man.}_{delay} = 1 - P_{delay} \tag{3.5}$$

This means that a maneuver made at the point of detection will result in a penalty of zero, and a score of one. A maneuver made at the CPA will result in a penalty of one and thus a score of zero.

Portside passing

The antecedent 'Passing' is added to evaluate whether the vessels are passing on the desired side of each other. This is a boolean value, i.e. either 0 or 1. In a head-on encounter, a portside passing is desired, and a starboard passing should thus be penalized in the evaluation. In an overtaking encounter, it is specified that both portside and starboard passings

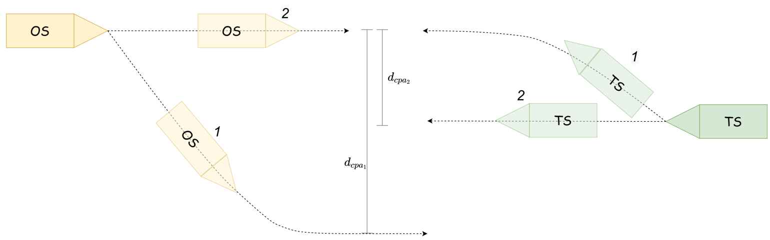


Figure 3.4: Head-on maneuver possibilities

are allowed, and thus the parameter is only relevant for head-on encounters.

Risk of collision

For some encounters where one or both of the vessels have a GW role, it could be a valid choice to not make any maneuver. I.e., in a head-on encounter where the vessels initially have each other on the starboard side, it is often seen that the vessels choose to keep the course and pass on the starboard side. However, this is in conflict with COLREGs Rule 14 which clearly states that in a head-on encounter the vessels should pass on the port side of the other. However, it also states that there has to be a risk of collision involved. To account for this the parameter 'RiskCol' has been added. This allows a GW vessel in a head-on encounter to keep its course if the 'RiskCol' antecedent has large DoM in the MF 'Low'. A simple way of determining the risk of collision for this purpose is to use the DCPA measure. If the DCPA never falls below r_{pref} it is not likely that there will be an encounter with risk of collision. However, if the DCPA falls below r_{nm} or r_{col} at some point it should be assumed that a maneuver to avoid collision is necessary and thus keeping course and speed is not compliant. This is illustrated in Figure 3.4, where OS and TS are meeting in a head-on encounter. Rule 14 states that both should alter course toward starboard and pass so that they have each other on their portside when passing. However, as illustrated, it is possible to keep the course, or even alter course towards the port, and pass on the starboard side. This requires less effort by both vessels, however, it could result in a smaller passing distance. If this passing distance is sufficient, this should be regarded as a viable option.

3.2.3 System C

System C is calculating the compliance of the SO vessel in the encounter. Input to the system is the vessels' roles, and also the compliance of the GW vessel if any. This is because of Rule 17 which permits the SO to take the necessary measures to avoid a collision if the

GW vessel is not acting in compliance with COLREGs Rule 16. There are less antecedents in System C, as seen in Table 3.10. This is due to that the role of SO is very simple. Either it should keep speed and course, given that the GW acts as expected, or it makes an action to avoid a collision. All antecedents apart from 'ComplianceGW' were explained in detail in the previous section and will not be repeated. The antecedent 'ComplianceGW' is the consequent from System B in Section 3.2.2.

In Table 3.11 the rules for SO compliance are shown. Rule C_1 illustrates that if OS is SO and TS is GW, and the compliance of TS from System B is Good, then not making any action in form of course and speed change is evaluated as good SO compliance. However, in the same situation if the TS has a bad GW compliance it is allowed for OS to make a readily apparent maneuver in form of course change or speed change and still receive a good SO compliance.

Table 3.10: Antecedent and consequent membership functions for SO compliance

Antecedent MFs

Antecedent	**Parameter**	**MF type**	**Interval**
RoleOfOS	GW	Trapezoidal	[0, 0, 0.4, 0.6]
RoleOfOS	SO	Trapezoidal	[0.4, 0.6, 1, 1]
RoleOfTS	GW	Trapezoidal	[0, 0, 0.4, 0.6]
RoleOfTS	SO	Trapezoidal	[0.4, 0.6, 1, 1]
ComplianceGW	Good	Trapezoidal	[0.6, 0.8, 1, 1]
ComplianceGW	QuiteGood	Trapezoidal	[0.3, 0.5, 0.6, 0.8]
ComplianceGW	Bad	Trapezoidal	[0.01, 0.01, 0.3, 0.5]
ComplianceGW	NotGW	Trapezoidal	[0, 0, 0.01, 0.01]
CourseChng	NotApparent	Trapezoidal	[0, 0, 10, 15]
CourseChng	QuiteApparent	Trapezoidal	[10, 15, 20, 25]
CourseChng	ReadilyApparent	Trapezoidal	[20, 25, 90, 90]
SpeedChng	NotApparent	Trapezoidal	[0, 0, 0.3, 0.4]
SpeedChng	QuiteApparent	Trapezoidal	[0.3, 0.4, 0.6, 0.7]
SpeedChng	ReadilyApparent	Trapezoidal	[0.6, 0.7, 1, 1]

Consequent MFs

Consequent	**Parameter**	**MF type**	**Interval**
ComplianceSO	Good	Trapezoidal	[0.6, 0.8, 1, 1]
ComplianceSO	QuiteGood	Trapezoidal	[0.3, 0.5, 0.6, 0.8]
ComplianceSO	Bad	Trapezoidal	[0.01, 0.01, 0.3, 0.5]
ComplianceSO	NotSO	Trapezoidal	[0, 0, 0.01, 0.01]

Table 3.11: Rules for SO compliance evaluation

Rule		IF (AND logic)					THEN
#		RoleOS	RoleTS	GWCompliance	CourseChng	SpeedChng	ComplianceSO
C_1		SO	GW	Good	NotApparent	NotApparent	Good
C_2		SO	GW	Bad	ReadilyApparent	-	-
	OR	SO	GW	Bad	-	ReadilyApparent	Good
C_3		SO	GW	Bad	QuiteApparent	-	-
	OR	SO	GW	Bad	-	QuiteApparent	QuiteGood
C_4		SO	GW	QuiteGood	NotApparent	-	-
	OR	SO	GW	QuiteGood	-	NotApparent	QuiteGood
C_5		SO	-	Good	NotApparent	NotApparent	Good
C_6		GW	-	-	-	-	NotSO

3.2.4 System D

System D combines the previously described systems A, B, and C to calculate the compliance of the OS. The inputs to the system are the consequences from these systems, the role of OS, compliance of SO, and compliance of GW respectively. The consequent of System D is the compliance of OS. The antecedents and the consequent are found in Table 3.12 and the rules are seen in Table 3.13.

Table 3.12: Antecedent and consequent membership functions for OS compliance evaluation

Antecedent MFs

Antecedent	Parameter	MF type	Interval
RoleOfOS	GW	Trapezoidal	[0, 0, 0.4, 0.6]
RoleOfOS	SO	Trapezoidal	[0.4, 0.6, 1, 1]
ComplianceGW	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]
ComplianceGW	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
ComplianceGW	Acceptable	Trapezoidal	[0.4, 0.5, 0.6, 0.7]
ComplianceGW	Bad	Trapezoidal	[0, 0, 0.3, 0.5]
ComplianceSO	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]
ComplianceSO	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
ComplianceSO	Acceptable	Trapezoidal	[0.4, 0.5, 0.6, 0.7]
ComplianceSO	Bad	Trapezoidal	[0, 0, 0.3, 0.5]

Consequent MFs

Consequent	Parameter	MF type	Interval
ComplianceOS	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]
ComplianceOS	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
ComplianceOS	Acceptable	Trapezoidal	[0.4, 0.5, 0.6, 0.7]
ComplianceOS	Bad	Trapezoidal	[0, 0, 0.3, 0.5]

Table 3.13: Rules for OS compliance evaluation

Rule		IF (AND logic)			THEN
#		RoleOS	GWCompliance	SOCompliance	ComplianceSO
D_1		GW	VeryGood	-	-
	OR	SO	-	VeryGood	VeryGood
D_2		GW	Good	-	-
	OR	SO	-	Good	Good
D_3		GW	Acceptable	-	-
	OR	SO	-	Acceptable	Acceptable
D_4		GW	Bad	-	-
	OR	SO	-	Bad	Bad

3.3 Encounter safety

The encounter safety score is calculated based on the pose configuration of OS and TS and DCPA as proposed by Woerner (2016). Using the DCPA is the preferred metric for several risk assessment methods. However, Woerner argued that pose at CPA is an important parameter as well. Near-parallel geometries are preferred over near-orthogonal geometries due to several reasons. One is that the possible target area is smaller for slender bodies in near-parallel geometry. Another is that the risk of engine failure in a near-orthogonal geometry could potentially have much more significant consequences than in near-parallel geometries, and also, near-parallel gives more predictability.

Pose configuration

The calculation of the pose score is inspired by the method presented by Hagen et al. (2021), where the calculated values from (3.6) and (3.7) are used as input to the antecedent MF described in Table 3.15.

$$S_{\alpha_{cpa}} = \begin{cases} \frac{1-\cos(\alpha_{cpa})}{1-\cos(\alpha_{cut})}, & |\alpha_{cpa}| < \alpha_{cut} \\ 1, & \text{otherwise} \end{cases} \tag{3.6}$$

$$S_{\beta_{cpa}} = \begin{cases} \frac{1-\cos(\beta_{cpa})}{1-\cos(\beta_{cut}^{min})}, & \beta_{cpa} < \beta_{cut}^{min} \\ \frac{1-\cos(\beta_{cpa})}{1-\cos(\beta_{cut}^{max})}, & \beta_{cpa} > \beta_{cut}^{max} \\ 1-\cos(\beta_{cut}^{min}), & \text{otherwise} \end{cases} \tag{3.7}$$

DCPA

The MF for DCPA is based on the concentric range rings defined in Woerner et al. (2019) where the range values are configurable. The MFs can be seen in Table 3.15.

The antecedent MFs are combined with the rules defined in Table 3.16 and result in a safety score from the consequent MF from Table 3.15. Table 3.14 summarizes how the concentric ranges are calculated, and also the parameter w_r which is used to define the size of the fuzzy area in MFs.

The range limits presented in Section 2.1 are some of the most challenging parameters to decide. These limits will depend on the operational domain and the surroundings. Using fixed limits is thus undesirable. The method presented in Section 2.7 is proposed as a means to overcome this challenge and has been used in this thesis to decide the range limits for safety evaluation. This is done by computing the available maneuverable space around a TS. The obstacles in the simulations relevant for this thesis are mainly TSs. Thus, the positions of the TSs and map data are used to find the shortest distance between TS and land or other static obstacles. This is a measure of the available space that OS has to maneuver in. An important note is that the algorithm is searching for the shortest distance to an obstacle inside a defined search area. The search area is defined based on the relative contact angle at the CPA. This ensures that the maneuverable space is found for the correct area, i.e. the area where OS is passing the TS.

This approach is dependent on land-masking corresponding to the simulation data. The data used in this thesis is simulation data from both Kristiansund harbor and the harbor area in Sandefjord. Thus, land-masking of these areas is needed to get realistic results from the maneuverable space algorithm. After calculating the distance from TS to closest obstacle in the area where OS is passing, the range limits r_{col}, r_{nm}, r_{min} and r_{pref} can be found.

An example of how the map data is created as polygons to form a known area that can be used together with simulation data to find the distance from TS to the closest obstacles is seen in Figure 3.5. The positions of OS and TSs are also shown and will be analyzed in detail in the next chapter.

Figure 3.6 illustrates how the dynamic range rings are formed after finding the maneuverable space associated with the TS. For reference, let us say the TS has 100 meters to the closest arbitrary obstacle. This would result in a preferred passing distance for OS of 60 meters, a minimum acceptable passing distance of 40 meters, a near-miss distance of 25 meters, and a collision distance of 15 meters. In the figure, the relative contact angle α_{cpa} is indicated by the arc going from TS's heading to the line connecting OS and TS. Also, the line from TS to OS constitutes the center of the maneuverable space search area

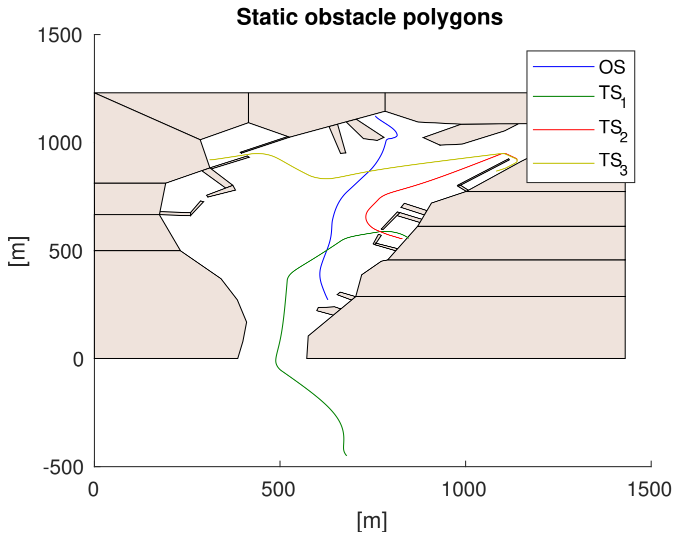


Figure 3.5: Map data and position plot from simulation meant to emulate the port in Sandefjord, Norway.

denoted A_{cpa}. The search area in the Figure is a semicircle, however, the search area can be tailored by specifying a start angle and stop angle defining the area.

Table 3.14: Range limits for the safety evaluation

Parameter	Proposed value [m]
w_r	6
r_{col}	$0.15 \cdot R_{min}$
r_{nm}	$0.25 \cdot R_{min}$
r_{min}	$0.40 \cdot R_{min}$
r_{pref}	$0.60 \cdot R_{min}$

3.4 Perceived safety

Perceived safety is assessed based on some key parameters that have been identified as important for public transport services in previous research and from investigating results from citizen engagement activities through the research project TRUSST. The antecedents, consequents and rules designed to evaluate perceived safety are shown in tables 3.18 and 3.19.

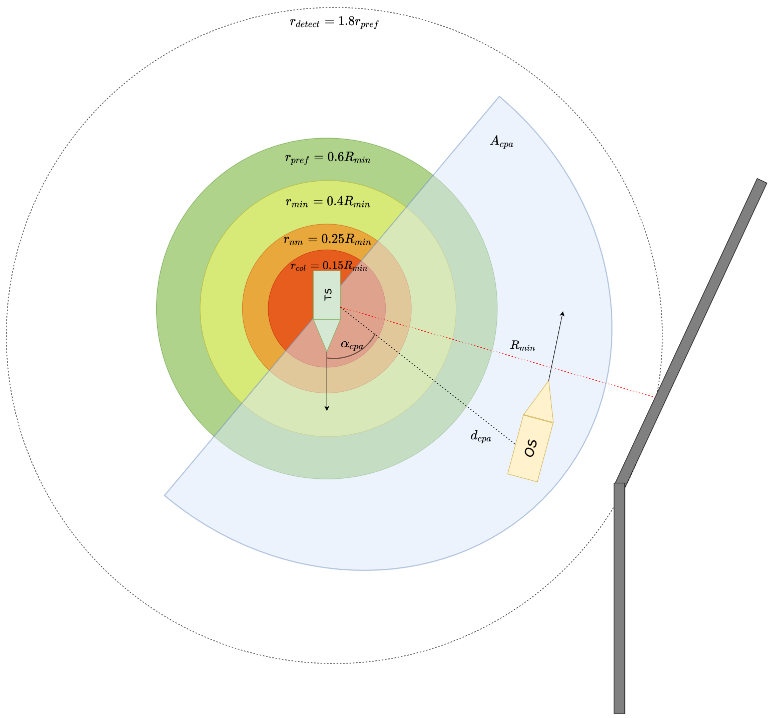


Figure 3.6: Dynamic range rings based on maneuverable space

Table 3.15: Antecedent and consequent membership functions for safety evaluation

Antecedent MFs			
Antecedent	**Parameter**	**MF type**	**Interval**
PoseCPA	Undesired	Trapezoidal	[0, 0, 0.3, 0.4]
PoseCPA	Acceptable	Trapezoidal	[0.3, 0.4, 0.6, 0.7]
PoseCPA	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
PoseCPA	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]
DCPA	Collision	Trapezoidal	[0, 0, r_{col}-w_r, r_{col}+w_r]
DCPA	NearMiss	Trapezoidal	[r_{col}-w_r, r_{col}+w_r, r_{nm}-w_r, r_{nm}+w_r]
DCPA	Minimum	Trapezoidal	[r_{nm}-w_r, r_{nm}+w_r, r_{min}-w_r, r_{min}+w_r]
DCPA	Preferable	Trapezoidal	[r_{min}-w_r, r_{col}+w_r, 1500, 1500]
Consequent MFs			
Consequent	**Parameter**	**MF type**	**Interval**
SafetyScore	NotGood	Trapezoidal	[0, 0, 0.3, 0.4]
SafetyScore	Acceptable	Trapezoidal	[0.3, 0.4, 0.6, 0.7]
SafetyScore	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
SafetyScore	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]

Table 3.16: Rules for safety evaluation

Rule		**IF (AND logic)**		**THEN**
#		PoseCPA	DCPA	SafetyScore
S_1		VeryGood	Preferable	VeryGood
S_2		VeryGood	Minimum	-
	OR	Good	-	-
	OR	Acceptable	Preferable	Good
S_3		Acceptable	Minimum	-
	OR	Good	NearMiss	Acceptable
S_4			Collision	-
	OR	Undesired	-	NotGood

Acceleration comfort

Little research was found describing comfort on small passenger ferries. However, Hoberock (1976) studied the longitudinal acceleration comfort in ground transportation vehicles. Examples of ground transportation vehicles are bus and metro, i.e. means of transport where traveling passengers can choose between sitting and standing. It is assumed that passengers onboard an urban passenger ferry will have the choice to be seated or to stand throughout the voyage. Thus, it could also be assumed that the findings from the above-mentioned study on ground transportation vehicles are applicable also for a small passenger ferry. As stated in the introduction, previous research has shown connections between comfort and perceived safety. Thus, the acceleration limits are assumed to be applicable for the assessment of perceived safety. The acceleration limits are given in Table 3.17.

Table 3.17: Acceleration comfort for standing passengers. Source: Hoberock (1976)

Parameter	Proposed value [g]
Designed acceleration value	0.138
Upper limit	0.160

Velocity and acceleration

Findings from the TRUSST citizen engagement project show that a combination of high velocity and small passing distance to surrounding objects feel unsafe for passengers. This is reflected in the perceived safety evaluation rules, where rule P_5 in Table 3.18 accounts for the case where the velocity and DCPA are acceptable if considered individually, but in combination results in a bad safety score.

Estimated DCPA before and after maneuver

Another parameter considered to be essential for how safe passengers feel is estimated DCPA before and after a maneuver. A maneuver that leads to a smaller estimated DCPA, i.e. a maneuver that seemingly makes it more likely to result in a close-quarters situation compared to the prior-to-maneuver situation, probably feels counter-intuitive and could make the passengers unsure about the intention of the maneuver. However, if a vessel makes a maneuver that leads to an increase in estimated DCPA, it would most likely feel like an assuring maneuver. The designed MF are given in Table 3.18.

Docking

Another outcome of the TRUSST project was that passengers prefer low speed when docking. Throttling towards the quay at high speed before making an aggressive deceleration is uncomfortable and is experienced as unsafe. The parameters 'DockingVel' and 'DockingAcc' are added to the evaluation to account for this. The docking speed and docking acceleration are calculated by defining the area at the docks and drawing a circle about the docking point. When the OS is inside this area and in a direction approaching the quay it is regarded as docking. When inside this area the requirements for acceleration and velocity are more strict.

Table 3.18: Antecedent and consequent membership functions for perceived safety evaluation

Antecedent MFs

Antecedent	Parameter	MF type	Interval
LinearAcc	Good	Trapezoidal	[0, 0, 0.138, 0.15]
LinearAcc	Acceptable	Trapezoidal	[0.138, 0.15, 0.16, 0.17]
LinearAcc	Unacceptable	Trapezoidal	[0.16, 0.18, 1, 1]
DockingAcc	Good	Trapezoidal	[0, 0, 0.1, 0.138]
DockingAcc	Acceptable	Trapezoidal	[0.1, 0.138, 0.15, 0.16]
DockingAcc	Unacceptable	Trapezoidal	[0.15, 0.16, 1, 1]
dCPABeforeAfterMan	Good	Trapezoidal	[20, 25, 100, 100]
dCPABeforeAfterMan	Acceptable	Trapezoidal	[0, 5, 20, 25]
dCPABeforeAfterMan	Unacceptable	Trapezoidal	[-100, -100, 0, 10]
DCPA	Good	Trapezoidal	[r_{nm}-w_r, r_{nm}+w_r, 500, 500]
DCPA	Acceptable	Trapezoidal	[r_{col}-w_r, r_{col}+w_r, r_{nm}-w_r, r_{nm}+w_r]
DCPA	Unacceptable	Trapezoidal	[0, 0, r_{col}-w_r, r_{col}+w_r]
LinearVel	Good	Trapezoidal	[0, 0, 4, 4.5]
LinearVel	Acceptable	Trapezoidal	[4, 4.5, 5.5, 6]
LinearVel	Unacceptable	Trapezoidal	[5.5, 6, 10, 10]
DockingVel	Good	Trapezoidal	[0, 0, 2.5, 3.5]
DockingVel	Acceptable	Trapezoidal	[2.5, 3.5, 4.5, 5.5]
DockingVel	Unacceptable	Trapezoidal	[4.5, 5.5, 10, 10]

Consequent MFs

Consequent	Parameter	MF type	Interval
PerceivedSafetyScore	NotGood	Trapezoidal	[0, 0, 0.4, 0.5]
PerceivedSafetyScore	Acceptable	Trapezoidal	[0.4, 0.5, 0.6, 0.7]
PerceivedSafetyScore	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
PerceivedSafetyScore	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]

Table 3.19: Rules for perceived safety evaluation

Rule		IF (AND logic)						THEN
#		LinearAcc	DockingAcc	DCPABeforeAfterMan	LinearVel	DockingVel	DCPA	PerceivedSafetyScore
P_1		Good	Good	Good	Good	Good	Good	VeryGood
P_2		Acceptable	Good	Good	Good	Good	Good	-
	OR	Good	Acceptable	Good	Good	Good	Good	-
	OR	Good	Good	Acceptable	Good	Good	Good	-
	OR	Good	Good	Good	Acceptable	Good	Good	-
	OR	Good	Good	Good	Good	Acceptable	Good	-
	OR	Good	Good	Good	Good	Good	Acceptable	Good
P_3		Acceptable	Acceptable	Good	Good	Good	Good	-
	OR	Good	Acceptable	Acceptable	Good	Good	Good	-
	OR	Good	Good	Acceptable	Acceptable	Good	Good	-
	OR	Good	Good	Good	Acceptable	Acceptable	Good	-
	OR	Good	Good	Good	Good	Acceptable	Acceptable	Acceptable
P_4		Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
P_5		Good	Good	Good	Acceptable	Good	Acceptable	NotGood
P_6		Unacceptable	-	-	-	-	-	-
	OR	-	Unacceptable	-	-	-	-	-
	OR	-	-	Unacceptable	-	-	-	-
	OR	-	-	-	Unacceptable	-	-	-
	OR	-	-	-	-	Unacceptable	-	-
	OR	-	-	-	-	-	Unacceptable	NotGood

Chapter 4

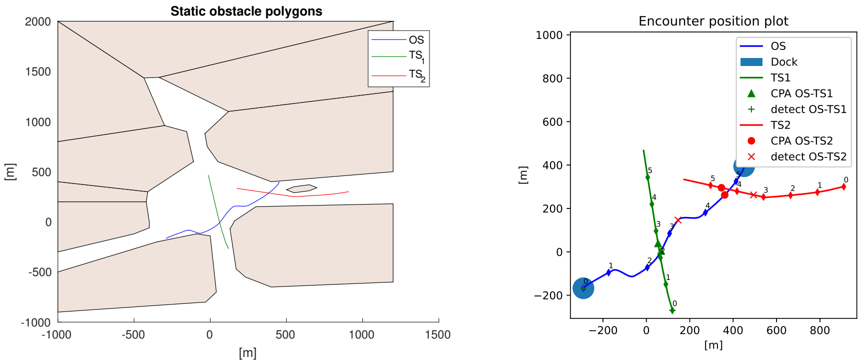
Results

This section presents results from three different simulation scenarios and batch simulations to demonstrate the method's performance. Each simulation will be presented like this: first, a novel interpretation concerning COLREGs will be conducted to form a 'hypothesis' of how the encounter could be assessed with the human eye. Then, the results will be displayed together with the most important parameters influencing the evaluation score. The results will be discussed, and potential deviations from the hypothesis will be explained and discussed. The results are presented in four tables; COLREGs compliance results, encounter safety results, perceived safety results, and the total encounter results respectively.

The results consist of three individual simulations, where two simulations are from Kristiansund harbor, and one is from Sandefjord harbor. Additionally, the systems' capabilities are demonstrated through batch simulations.

4.1 Encounter 1 - Kristiansund harbor

Encounter 1 is a multi-vessel encounter in Kristiansund harbor, where two TSs are interacting with OS. Figure 4.1a shows a representation of Kristiansund harbor. The land masking has been created manually and added as polygons in the plot. Figure 4.1b displays the vessels' paths in closer detail. The dock is marked with a blue circle and indicates the area where OS is recognized to be in docking mode. The paths are annotated with numbers to elucidate the temporal and spacial understanding of the encounter. E.g., the annotation "1" indicates the point in time where $t = 40[s]$, and at this point in time all vessels were



(a) Encounter 1 in Kristiansund harbor with static obstacles

(b) Position plot with essential encounter information

Figure 4.1: Encounter 1: Multi-vessel encounter in Kristiansund harbor

located at the point of the annotation.

- The first encounter is between OS and TS1, where OS has TS1 on its starboard side and makes a course alteration toward its starboard side to pass behind TS1, presumably well in line with a crossing GW role described by Rule 15 and Rule 16 in COLREGs. TS1 keeps course, also well in line with a SO role as defined by Rule 17 in COLREGs.

- The second encounter is between OS and TS2. Similar to the first encounter, the OS has TS2 on its starboard side and makes a course alteration toward its starboard side to pass behind TS2. This is presumably because OS's guidance and navigation system interprets the encounter as a crossing GW encounter and correctly keeps out of the way of TS2. TS2 presumably also acts in accordance with a SO role and keeps course after detection.

COLREGs

Table 4.2 provides all the measurements included in the calculation of COLREGs compliance and the total score for each vessel-to-vessel encounter. It is seen that the encounter with TS1 is classified as a crossing encounter dictated by Rule 15 in COLREGs as expected, where OS has a GW role, and TS1 has a SO role. OS makes a readily apparent course alteration $\triangle_\chi$ of 33.2 degrees. However, the maneuver is penalized because it is delayed from the time of detection so that the safety score $S^{man.}_{delay}$ is only 0.52. This results in a score of 0.55 with TS1, i.e., just inside the 'Acceptable' MF. The encounter with TS2 is evaluated to a score of 0.844, i.e. somewhere between 'Good' and 'VeryGood.' The

Table 4.1: Encounter 1: COLREGs evaluation for multi-vessel encounter in Kristiansund harbour

Vessel	Rule	Role	β^{360}_{detect} [°]	α^{180}_{detect} [°]	$S^{man.}_{delay}$ [-]	$\triangle\chi$ [°]	$\triangle U$ [$\frac{m}{s}$]	d_{cpa} [m]	θ^{bool}_{ps} [-]	CR [m]	$\#_{\triangle\chi}$ [-]	Score [-]
OS	15	0.254	73.9	-	0.52	33.2	0	37.9	0	4.1	1	0.55
TS1	—"—	0.746	-	-71.0	1	9.7	0	—"—	—"—	—"—	-	-
OS	15	0.278	36.8	-	0.89	47.6	0	36.7	0	15.2	1	0.844
TS2	—"—	0.746	-	-30.9	0	0	0	—"—	—"—	—"—	-	-
Total score												**0.697**

Table 4.2: Encounter 1: Safety evaluation for multi-vessel encounter in Kristiansund harbor

Vessel	d_{cpa} [m]	β_{cpa} [°]	α_{cpa} [°]	θ^{score}_{cpa} [-]	R_{min} [m]	r_{pref} [m]	r_{min} [m]	r_{nm} [m]	r_{col} [m]	Score [-]
OS	37.9	310.5	-	0.4	162.7	97.6	65.1	40.7	24.4	0.209
TS1	—"—	-	167.54	—"—	—"—	—"—	—"—	—"—	—"—	-
OS	36.7	291.9	-	0.6	135.9	81.5	54.4	34	20.4	0.5
TS2	—"—	-	-89.51	—"—	—"—	—"—	—"—	—"—	—"—	-
Total score										**0.355**

maneuver is readily apparent with a course alteration of 47.6 degrees, and the maneuver is made a short time after the detection point. Thus the encounter with TS2 is evaluated as compliant with COLREGs. However, the encounter with TS1 reduces the total score because of the delayed maneuver. This gives a total COLREGs compliance score of 0.697, i.e. between 'Acceptable' and 'Good.'

Encounter safety

Table 4.2 provides all the measurements included in the calculation of encounter safety score and the total score for each vessel-to-vessel encounter. The encounter with TS1 is penalized due to a small d_{cpa} value, i.e. smaller than the r_{nm} value. The encounter is also penalized for an undesired pose configuration at the CPA. This results in a score of 0.209 for the encounter with TS1, i.e. well inside 'NotGood.' The encounter with TS2 is evaluated as slightly safer, mostly because the d_{cpa} value is above the r_{nm} value, but also because the pose score θ^{score}_{cpa} is better. The encounter safety with TS2 is evaluated to 0.5, i.e. 'Acceptable.' It is worth mentioning that even though the d_{cpa} value for the encounter with TS2 is smaller than the d_{cpa} value for the encounter with TS1, this is considered a more acceptable distance due to the dynamic range calculation based on the maneuverable space. This is explained by the values for R_{min}, which are 162.7 meters and 135.9 meters for TS1 and TS2, respectively. I.e., in the encounter with TS2, OS has less space available to pass on, and thus a smaller value for d_{cpa} is accepted. The total encounter safety score is calculated to be 0.355, i.e. 'NotGood.'

Table 4.3: Encounter 1: Perceived safety evaluation multi-vessel encounter in Kristiansund harbour

Vessel	$\triangle d_{cpa}$ [m]	d_{cpa} [m]	U [$\frac{m}{s}$]	$U_{docking}$ [$\frac{m}{s}$]	a [g]	$a_{docking}$ [g]	Score [-]
OS	24.1	37.9	0.3	0.3	0	0	0.713
TS1	—”—	—”—	-	-	-	-	-
OS	6.1	36.7	0.3	0.3	0.03	0.03	0.502
TS2	—”—	—”—	-	-	-	-	-
Total score							**0.608**

Perceived safety

Table 4.3 provides all the measurements included in the calculation of the perceived safety score and shows the score for each vessel-to-vessel encounter and the total perceived safety score. The perceived safety score is less reliant on vessel-to-vessel regards compared to the COLREGs compliance score and encounter safety score, as U, $U_{docking}$, a and $a_{docking}$ are all independent of other vessels. However, the $\triangle d_{cpa}$ and d_{cpa} are both calculated based on encounters with a TS involved.

From Table 4.3 it is seen that the total perceived safety score is 0.608, i.e. just above 'Acceptable.' The score of the encounter with TS1 is explained by a value of $\triangle d_{cpa}$ of 24.1 meters, meaning that the course alteration to avoid TS1 increased the estimated DCPA by 24.1 meters. This is regarded as a maneuver that is perceived as satisfying for passengers. However, the d_{cpa} is below the r_{nm} range, something which is considered as bad. The range values for r_{pref}, r_{min}, r_{nm}, and r_{col} are seen in Table 4.2. The velocity and acceleration values are satisfying. Thus, the perceived safety score from the encounter with TS1 is evaluated to 0.704, i.e. 'Good.'

The encounter with TS2 is evaluated to a perceived safety score of 0.502. The $\triangle d_{cpa}$ value is within the MF 'Acceptable' domain of the antecedent 'DCPABeforeAfterMan,' something that reduces the score compared to the encounter with TS1. The d_{cpa} value between OS and TS2 is slightly above the r_{nm} value, however still small enough to be considered too close. This also reduces the score of the encounter.

Total score

The total score of OS for Encounter 1 is calculated to be 0.553, i.e. 'Acceptable.' The evaluation scores from Encounter 1 are given in Table 4.4.

Table 4.4: Encounter 1: Total score

Evaluation	Score
COLREGs	0.697
Encounter safety	0.355
Perceived safety	0.608
Total	**0.553**

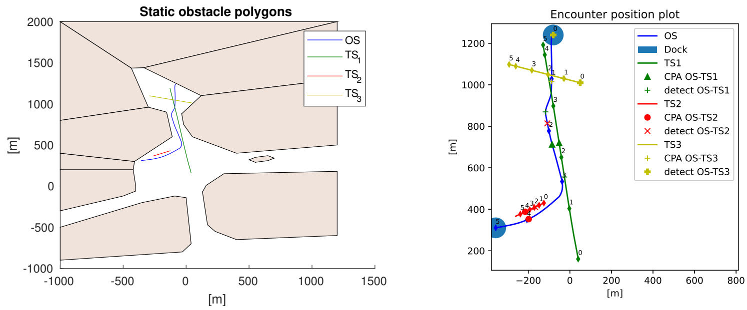
4.2 Encounter 2 - Kristiansund harbor

The second scenario simulation from Kristiansund harbor, seen in Figure 4.2a and 4.2b, consists of three vessel-to-vessel encounters with three different TSs.

- The first encounter is between OS and TS3, where OS initially has TS3 on its port side. This is presumably, a crossing encounter, where OS has a SO role and TS3 has a GW role. TS3 does not make any course or speed alteration, which, depending on the risk of collision present, could be viewed as a non-compliant COLREGs maneuver by TS3. Presumably, OS considers the risk of collision as small and decides to keep the course as the SO role prescribes.
- The second vessel-to-vessel encounter is between OS and TS1. Presumably, they are approaching near reciprocal courses corresponding to a head-on encounter as per Rule 14 in COLREGs. OS avoids collision by making a starboard course alteration. The passing distance is small, but this is explained by the small available space in the passing area, as seen in Figure 4.2a. Presumably, TS1 violates Rule 14 by not making any GW maneuver, making it difficult to achieve a substantial passing distance between the vessels.
- The final encounter is between OS and TS2. OS makes a starboard turn and is coming up with TS2 from behind. Rule 13 states that if OS is coming up with TS2 from more than 22.5 degrees abaft her beam, it should be regarded as an overtaking encounter. It is seen that OS overtakes TS2 and reaches the dock.

COLREGs

In Table 4.5 one can see the results from the COLREGs evaluation. The first encounter with TS3 is classified as a crossing encounter where OS has a role as SO and TS3 has a role as GW. However, from the table, a small maneuver of 4.2 degrees by OS is detected. I.e., OS does not keep its course as the SO role describes. However, TS3 does not GW as one should expect and is thus violating the GW role. Therefore, OS can make any



(a) Encounter 2 in Kristiansund harbor with static obstacles

(b) Position plot with essential encounter information

Figure 4.2: Multi-vessel encounter number two from Kristiansund harbor

maneuver necessary to avoid a collision. The minor course alteration of 4.2 degrees is then considered a compliant behavior and OS receives a score of 0.844, i.e. between 'Good' and 'VeryGood.' The poor maneuver delay score S_{delay}^{man} also reveals that OS is making a late maneuver, indicating that it attempts to SO until it regards the encounter as unsafe and makes an evasive maneuver.

The encounter with TS1 is classified, as expected, as a head-on encounter. Both vessels correctly receive a GW role by the FLS. No maneuver by OS is detected inside the interval $[i_{detect}, i_{cpa}]$, meaning that OS violates its role as GW. However, by closer inspection of the position plot in Figure 4.2b it is seen that OS actually makes a course alteration between timestamps one and two. But because this is prior to the detection point, the evaluation system does not recognize the maneuver as a maneuver made to avoid TS1. r_{detect} is found based on the maneuverable space, and thus the detection range is relatively short for the encounter with TS1. This flaw will be further discussed in the next Chapter. The COLREGs compliance of the encounter with TS1 receives a score of 0.207, i.e. 'NotGood'. The third and final encounter with TS2 is also interpreted as expected by System A in the COLREGs evaluation FLS. The encounter is classified as overtaking where OS has the role of GW and TS2 has the role of SO, i.e., OS is regarded as the overtaking vessel and should keep out of the way of TS2. From Table 4.5 it is seen that a maneuver of 29.2 degrees is detected, which is considered readily apparent. However, the maneuver is delayed compared to the point of detection. This results in a $S_{delay}^{man.}$ score of 0.56, which reduces the COLREGs compliance score of the encounter. The encounter with TS2 is evaluated to a COLREGs compliance score of 0.55, which gives a total COLREGs compliance score of 0.533.

Table 4.5: Encounter 2: COLREGs evaluation for multi-vessel encounter in Kristiansund harbour

Vessel	Rule	Role	β^{360}_{detect} [°]	α^{180}_{detect} [°]	$S^{man.}_{delay}$ [-]	$\triangle\chi$ [°]	$\triangle U$ [$\frac{m}{s}$]	d_{cpa} [m]	θ^{bool}_{ps} [-]	CR [m]	$\#_{\triangle\chi}$ [-]	Score [-]
OS	15	0.746	318.7	-	0.18	4.2	0	57.9	1	39.2	1	0.844
TS3	—"—	0.254	-	46.3	0	0	0	—"—	—"—	—"—	0	-
OS	14	0.278	351.8	-	0	0	0	34.8	1	6.9	1	0.207
TS1	—"—	0.278	-	-10.7	0	0	0	—"—	—"—	—"—	0	-
OS	13	0.254	31.5	-	0.56	29.2	0	39	0	18.6	1	0.55
TS2	—"—	0.746	-	131.5	0	0	0	—"—	—"—	—"—	0	-
Total score												**0.533**

Table 4.6: Encounter 2: Safety evaluation for multi-vessel encounter in Kristiansund harbour

Vessel	d_{cpa} [m]	β_{cpa} [°]	α_{cpa} [°]	θ^{score}_{cpa} [-]	R_{min} [m]	r_{pref} [m]	r_{min} [m]	r_{nm} [m]	r_{col} [m]	Score [-]
OS	57.9	253.3	-	0.1	84.5	50.7	33.8	21.1	12.7	0.177
TS3	—"—	-	-29.9	—"—	—"—	—"—	—"—	—"—	-	
OS	34.8	273.8	-	0.9	75.6	45.4	30.2	18.9	11.3	0.922
TS1	—"—	-	-93.0	—"—	—"—	—"—	—"—	—"—	-	
OS	39	89.7	-	1	107.3	64.4	42.9	26.8	16.1	0.75
TS2	—"—	-	90.3	—"—	—"—	—"—	—"—	—"—	-	
Total score										**0.616**

Encounter safety

Table 4.6 shows the encounter safety evaluation results of Encounter 2 in Kristiansund harbor. The encounter with TS3 evaluates to a safety score of only 0.177. The explanation for this is the low pose configuration score θ^{score}_{cpa} of only 0.1. The generally low pose configuration score received for crossing encounters is also a point of interest and will be discussed further in Chapter 5. The encounter with TS1 receives a very good θ^{score}_{cpa} score of 0.9, but the passing distance d_{cpa} reduces the score slightly. This results in an encounter score of 0.922 with TS1, which is considered 'VeryGood.' The last encounter is between OS and TS2. The pose configuration receives a perfect score of 1. However, the passing distance is below r_{min} and reduces the overall score. Also here the dynamic calculation of maneuverable space shows its importance. The maneuverable space R_{min} of 107.3 meters suggests that the DCPA should be larger than the 39 meters, even though 39 meters for the two previous encounters would be regarded as quite good. This gives a total encounter safety score for Encounter 2 in Kristiansund harbor of 0.616.

Perceived safety

Table 4.7 shows the results from the perceived safety evaluation. It is seen that all encounters receive the same perceived safety score of 0.226. This is because the value for $a_{docking}$ of 0.2 m/s^2 is too big and above the threshold for what is considered a comfortable acceleration defined in Table 3.17. This value is independent of vessel-to-vessel encounters and is thus valid for the entire scenario. Rule P_6 in Table 3.19 states that if the acceleration is 'Unacceptable,' the perceived safety score should be evaluated as 'NotGood.'

Table 4.7: Encounter 2: Perceived safety evaluation for multi-vessel encounter in Kristiansund harbor

Vessel	$\triangle d_{cpa}$ [m]	d_{cpa} [m]	U [$\frac{m}{s}$]	$U_{docking}$ [$\frac{m}{s}$]	a [g]	$a_{docking}$ [g]	Score [-]
OS	-29.7	57.9	0.8	0.8	0.2	0.2	0.226
TS3	—"—	—"—	-	-	-	-	-
OS	0	34.8	0.8	0.8	0.2	0.2	0.226
TS1	—"—	—"—	-	-	-	-	-
OS	2	39	0.8	0.8	0.2	0.2	0.226
TS2	—"—	—"—	-	-	-	-	-
Total score							**0.226**

Table 4.8: Encounter 2: Total score

Evaluation	**Score**
COLREGs	0.533
Encounter safety	0.616
Perceived safery	0.226
Total	**0.458**

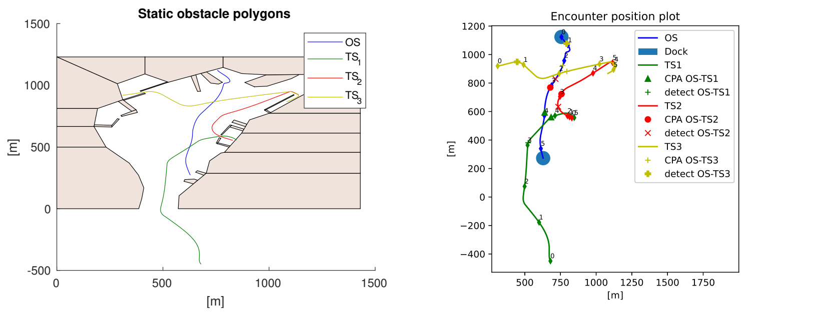
Total score

The total score for Encounter 2 is given in 4.8.

4.3 Encounter 3 - Sandefjord harbor

Encounter 3 is a scenario from the the port in Sandefjord, and is visualised in Figure 4.3a and 4.3b. Also here OS interacts with three TSs. Contrary to the encounter described in Section 4.2 all TSs make maneuvers and have a non-linear path.

- The first encounter is between OS and TS3, where TS3 is coming towards OS on its starboard side. If this is classified as a crossing encounter, then OS is GW and TS3 is SO. TS3 is crossing ahead of OS, which seemingly does not make any course alteration or speed reduction to increase the passing distance.
- The second encounter is between OS and TS2, where TS2 is coming towards OS before making a sharp turn towards starboard, which clearly is due to its future intended path.
- The third encounter is with TS1 which crosses in front of OS. This seems like a head-on encounter and is governed by Rule 14 in COLREGs. This allows TS1 to make a starboard maneuver to pass on the port side of OS, and it is observed that



(a) Encounter in Sandefjord harbor with static obstacles

(b) Position plot with essential encounter information

Figure 4.3: Encounter 3: Multi-vessel encounter from Sandefjord harbor

this is what TS1 does. However, the maneuver is conducted late, resulting in an unnecessary small DCPA. OS does not make any apparent maneuver to avoid TS1 and is presumably a non-compliant behavior. This could be explained by the future intended path of OS and avoiding unnecessarily long routes before going to dock.

CORLEGs

The results from the COLREGs evaluation are shown in Table 4.9. The evaluated roles of OS and TS3 are interesting. The FLS interprets the encounter as partly overtaking and partly crossing. I.e., both Rule 13 and Rule 15 are triggered, where Rule 13 assigns OS with a SO role and TS3 with a GW role. However, Rule 15 assigns OS with a GW role and TS3 with a SO role. This is possible because of the soft and overlapping boundaries between the encounter classifications in COLREGs. The soft boundaries are added with intention, both because COLREGs does not state clearly how to classify encounters, but also due to the challenge for humans and ASVs with assessing vessel-to-vessel configurations precisely at sea. Thus, the soft boundaries are in a way similar to how a human would consider an encounter with no apparent role distribution.

Important notice in COLREGs Rule 13 (c) is that if there exists doubt whether a vessel is overtaking the other, it should be assumed that the vessel is overtaking the other I.e., the vessel overtaking should GW for the other vessel. Using OS and TS3 as an example, Rule 13 obligates TS3 to GW and thus OS to SO. However, Rule 15 obligates the vessels to the opposite, i.e. OS to GW and TS3 to SO. The question then is how to decide which rules should be prioritized to evaluate the encounter correctly according to COLREGs. One issue with Rule 13 (c) is that it only states that the vessel in doubt whether it is overtaking another vessel (TS3) should assume itself to be overtaking, but it does not say anything about the vessel being overtaken (OS) should assume to be overtaken in a situation with conflicting roles. Thus it is assumed that TS3's role according to COLREGs should be GW, but OS's role is still uncertain.

One possible solution would be to assign GW roles to both OS and TS3. In an encounter like this, where uncertainty about whether a vessel should SO or GW exists, GW roles could be regarded as the 'safe' choice. However, this would lead to an encounter not covered by the COLREGs. The only encounter where both OS and TS3 should have a GW role is a head-on encounter as described by Rule 14, and this is clearly not a head-on encounter as defined by COLREGs. Another possibility would be to embrace the encounter uncertainty, allowing the vessels with conflicting roles to act more freely independent of the GW and SO roles, and put more weight on the encounter risk to determine compliance, e.g. DCPA. One final option would be to interpret Rule 13's mention of doubt about the overtaking vessel to also apply to the vessel being overtaken. With this option, TS3 should assume to be overtaking OS, and thus GW, and OS should similarly assume to be overtaken by TS3 and SO.

As seen in Table 3.7, this kind of uncertainty is solved by allowing the vessel in doubt some slack in the evaluation. Using OS and TS3 as examples, this means that TS3 should act according to a GW role because it should assume itself overtaking, but OS will be given some flexibility of whether to GW or SO. The FLS 'COLREGs roles' described in Section 3.2.1 combines rules 13, 14, and 15 to assign COLREGs roles. The output from this FLS indicates that OS has a role corresponding to 0.487, i.e. slightly towards a GW role and that TS3 has a role corresponding to 0.32, i.e. close to a full GW role. This means that OS will not be interpreted as GW or SO solely, but somewhere in between. Thus, the COLREGs compliance is calculated based on GW and SO requirements. The highest calculated score is chosen for the vessel with conflicting roles. This illustrates that the developed system solves the conflicting roles as prescribed and intended.

Further, the COLREGs compliance of OS's encounter with TS3 is evaluated to 0.796. This is a pretty good compliance score, and the parameter values indicate that OS has been evaluated with a GW role. This is explained by a sufficient DCPA, a quite readily apparent and early course maneuver. I.e., if the OS had been evaluated with a SO role, it would receive a worse score.

The score of the encounter with TS2 is 0.844, i.e. a very compliant behavior with respect to COLREGs. OS has a SO role in a crossing encounter, where no maneuvers are detected and with a good passing distance. Thus, OS has kept its course and speed as required by COLREGs. However, the third encounter is evaluated as non-compliant with a score of only 0.207. It is seen that there are conflicting roles for Rule 14 and Rule 15, where Rule 15 obligates OS to SO and TS1 to GW. Rule 14 obligates both vessels to GW in a head-on encounter. However, Rule 14 is prioritized because it states that a head-on encounter

Table 4.9: Encounter 3: COLREGs evaluation from mulit-vessel encounter in Sandefjord harbor

Vessel	Rule	Role	β^{360}_{detect} [°]	α^{180}_{detect} [°]	$S^{man.}_{delay}$ [-]	$\triangle\chi$ [°]	$\triangle U$ [$\frac{m}{s}$]	d_{cpa} [m]	θ^{bool}_{ps} [-]	CR [m]	$\#_{\triangle\chi}$ [-]	Score [-]
OS	13/15	0.712/0.264	110.0	-	0.83	26.3	0	50.5	1	23.1	1	0.796
TS3	—"—	0.288/0.736	-	-22.3	0.75	9.6	0	—"—	—"—	—"—	2	-
OS	15	0.746	322.6	-	0	0	0	91.2	1	7.2	1	0.844
TS2	—"—	0.254	-	15.0	0	0	0	—"—	—"—	—"—	1	-
OS	14/15	0.259/0.746	351.1	-	0.17	7.5	0	56.4	1	19.5	1	0.207
TS1	—"—	0.259/0.254	-	6.2	0.98	28.6	0	—"—	—"—	—"—	2	-
Total score												**0.616**

Table 4.10: Encounter 3: Safety evaluation for multi-vessel encounter in Sandefjord harbor

Vessel	d_{cpa} [m]	β_{cpa} [°]	α_{cpa} [°]	θ^{score}_{cpa} [-]	R_{min} [m]	r_{pref} [m]	r_{min} [m]	r_{nm} [m]	r_{col} [m]	Score [-]
OS	50.5	304.9	-	0.428	137.2	82.3	54.9	34.3	20.6	0.5
TS3	—"—	-	-110.5	—"—	—"—	—"—	—"—	—"—	-	
OS	91.2	270.3	-	0.986	72.3	43.4	28.9	18.1	10.8	0.922
TS2	—"—	-	-89.51	—"—	—"—	—"—	—"—	—"—	-	
OS	56.4	303.8	-	0.443	155.9	93.5	62.4	39	23.4	0.5
TS1	—"—	-	-112.0	—"—	—"—	—"—	—"—	—"—	-	
Total score										**0.640**

should be assumed if any doubt exists. Thus both OS and TS1 are interpreted with a GW role. OS makes a late course alteration of only 7.2 degrees which is not regarded as a readily apparent course alteration and results in a bad score. The maneuver is not taken early or is readily apparent, which is reflected in the compliance score. This gives a mean score of 0.616, which is regarded as an 'Acceptable' COLREGs compliance.

Encounter safety

The encounter safety score is shown in Table 4.10. The encounter with TS3 has a small DCPA of 50.5 meters, which is inside the r_{min} domain, compared to the available space of 137.2 meters. Also, the pose score θ^{score}_{cpa} is not very good. The encounter with TS2 is evaluated as very safe, with a score of 0.922. The DCPA is well outside the r_{pref} domain, and the pose score is good. The final encounter with TS1 receives a safety score of 0.5, similar to the encounter with TS3. The total encounter safety score is 0.640.

Perceived safety

The perceived safety scores for the encounters are shown in Table 4.11. The perceived safety score is quite bad for all three encounters, where the acceleration is too big compared to the acceleration limit. Thus, even though the estimated DCPA increases for maneuvers taken and the actual DCPA is quite good for all encounters, the perceived safety evaluation is unsatisfactory.

Table 4.11: Encounter 3: Perceived safety evaluation for multi-vessel encounter in Sandefjord harbor

Vessel	$\triangle d_{cpa}$ [m]	d_{cpa} [m]	U [$\frac{m}{s}$]	$U_{docking}$ [$\frac{m}{s}$]	a [g]	$a_{docking}$ [g]	Score [-]
OS	11.6	50.5	0.6	0.6	0.3	0.3	0.230
TS3	—"—	—"—	-	-	-	-	-
OS	100	91.2	0.6	0.6	0.3	0.3	0.230
TS2	—"—	—"—	-	-	-	-	-
OS	214.3	56.4	0.6	0.6	0.3	0.3	0.230
TS1	—"—	—"—	-	-	-	-	-
Total score							**0.230**

Table 4.12: Encounter 3: Total score

Evaluation	Score
COLREGs	0.616
Encounter safety	0.640
Perceived safery	0.230
Total	**0.495**

Total score

The total evaluation score for Encounter 3 is seen in Table 4.12.

4.4 Batch simulations

Figure 4.4 shows the results from a batch simulation where the TS start in the same position in each simulation, and the OS start position changes sequentially starting from a relative bearing of -180° with steps of 11.25° until a full round is completed. This is an efficient way of checking whether the developed method for deciding vessel roles, System A, produces expected results. The annotations denote which vessel is OS and TS, and what rule(s) applies to the encounter. An important note is that OS is headed towards the "center," i.e., the annotations are placed at the starting point of each simulation.

The results in Figure 4.4 demonstrate that the developed method for evaluating COLREGs roles can interpret the encounters and assign roles to both OS and TS according to COLREGs rules 13, 14, and 15. OS is assigned a GW role in crossing encounters where it has the TS on the starboard side and in head-on encounters. OS is assigned a SO role when it is overtaken by the TS and crossing encounters where it has the TS on its port side. Interestingly, when Rule 14 and Rule 15 are both triggered and OS has conflicting roles, i.e., Rule 14 commands OS to GW and Rule 15 orders OS to SO, then the OS role is evaluated

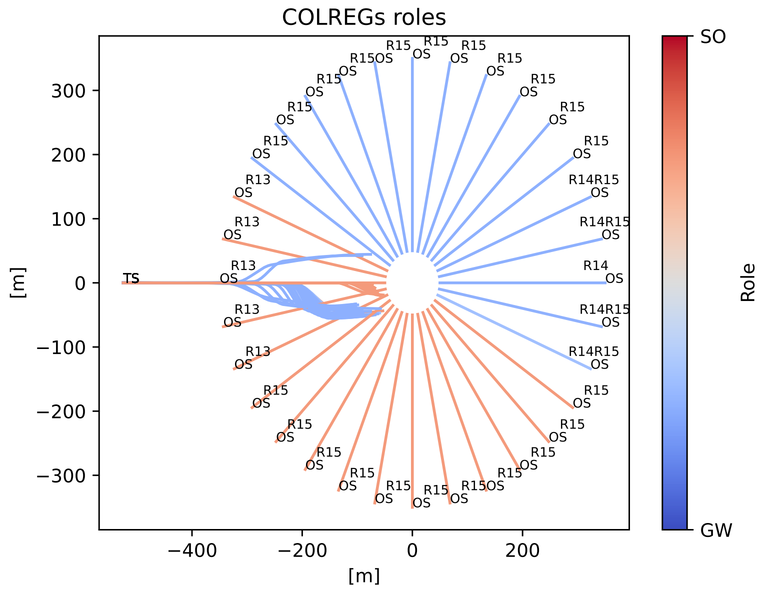
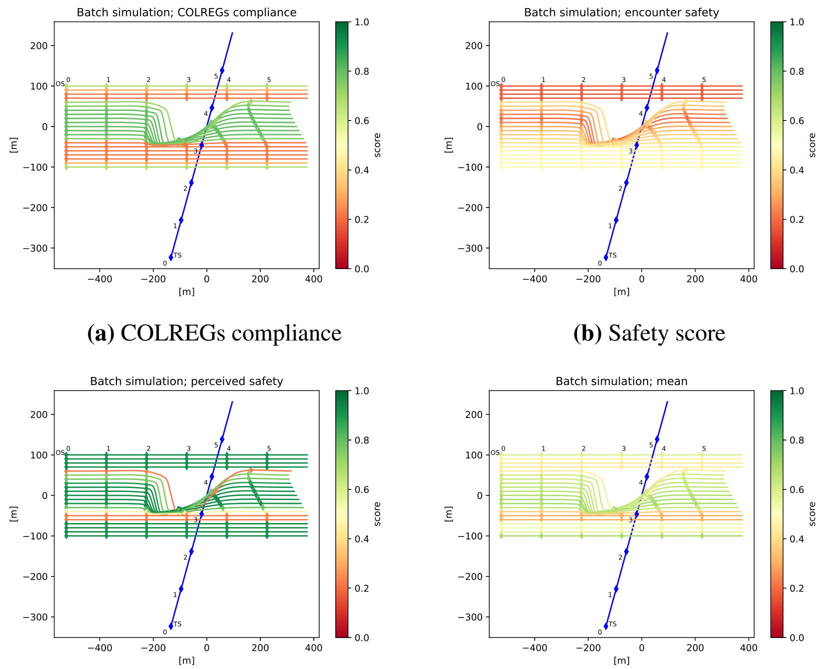


Figure 4.4: Batch simulation of vessel encounter demonstrating the capability of assigning roles according to COLREGs

to GW. Encounters with conflicting roles are handled by the rules A6-A9 shown in Table 3.7. As mentioned previously, Rule 14 states that if any doubt about whether a head-on encounter exists, a head-on encounter should be assumed. Similarly, Rule 13 states that if any doubt about whether overtaking another vessel exists, it should be deemed to be overtaking the other vessel. It is seen that the evaluation system is capable of accounting for this by assigning a GW role in encounters where both Rule 14 and Rule 15 are triggered.

It is also observed that the evaluated roles of TS are reasonable. When TS has a role as GW, it maneuvers to avoid collision with OS. In situations where TS is SO, it keeps course and speed. However, it is seen that TS makes a late maneuver in some simulations even though it has a role as SO. This is assumed in situations where OS does not GW, and TS correctly makes a maneuver according to Rule 17 a.(ii) to avoid a collision.

Figure 4.5 shows the results from the developed evaluation system where Figure 4.5a shows COLREGs compliance score, Figure 4.5b shows the encounter safety score, Figure 4.5c shows the perceived safety score and Figure 4.5d shows the total score combining the above-mentioned evaluation scores. The results are presented as batch simulations, where a score between 0 and 1 is calculated for each simulation. The result from each simulation is represented by a color based on the color bar, spanning from bad (red) to good



(a) COLREGs compliance

(b) Safety score

(c) Perceived safety score

(d) Total score (mean)

Figure 4.5: Results from batch simulation of crossing scenario

(green). The batch simulation in Figure 4.5 shows how the system calculates performance in a crossing encounter where OS has a GW role and where TS has the same path in all simulations. The annotations denote what vessel is OS and TS, in addition to time marks that are helpful for the spatial and temporal understanding of the encounters.

In Figure 4.5 the main results are presented with the calculated OS score for COLREGs compliance, perceived safety, encounter safety, and a total encounter score. In Figure 4.5a it is seen that the COLREGs compliance spans from inadequate and non-compliant to excellent and compliant. In simulations where the OS makes an early and apparent maneuver and crosses behind the TS, the compliance score is very good. However, in simulations where OS is not making any maneuver, presumably because the collision avoidance algorithm classifies the estimated DCPA as safe, the evaluation system punishes the maneuvering because it has a more strict assessment of safe distance. In simulations where OS is furthest away from TS initially, i.e. the upper four simulation paths, it is observed that not making any maneuver is regarded as quite compliant. This is due to the mention of risk in COLREGs, and in these situations it is reckoned that there is little risk of collision, and hence not making a maneuver is assumed to be compliant. I.e., the estimated DCPA never falls below a distance that is considered of any risk of collision, and thus not making any maneuver is regarded as compliant.

Figure 4.5c shows the results from the evaluation of perceived safety. The results demonstrate the capability to distinguish encounters deemed to be safe and those that are not. The most influential parameter for these batch simulations is the DCPA. Both linear acceleration and velocity have full membership in the MF 'Good' for all encounters.

The results from the encounter safety evaluation are displayed in Figure 4.5b. The poor scores are primarily due to the undesired pose at CPA and the strict range thresholds in the evaluation method.

The total results are shown in Figure 4.5d. The best results are achieved when OS makes a readily apparent starboard maneuver to avoid colliding with TS without exceeding the comfortable acceleration and velocity thresholds. This leads to a sufficiently large DCPA.

Chapter 5

Discussion

This section provides a more high-level discussion about the evaluation system. Some challenges with the developed system will be highlighted and reflected upon, and limitations to the method will be further discussed.

5.1 COLREGs compliance evaluation

The developed method to determine the COLREGs compliance by utilizing fuzzy logic proves to have some advantages compared to already proposed methods. One of the main advantages was illustrated in Encounter 2 where the OS and TS had conflicting roles. A proposed way of handling conflicting roles has been to give the vessels with conflicting roles a reduced penalty for their potentially violating behavior, e.g. in Hagen et al. (2021). This implies that the vessel with conflicting roles has been evaluated as either GW or SO, and if its behavior violates the assigned role, it is handed a reduced penalty. This would be a valid method if one could guarantee that the assigned role coincides with the perceived role by the operator (or autonomy system) of the vessel. However, because COLREGs roles are based on vague definitions created to be interpreted by a human operator, there is no right or wrong when deciding roles. This contradicts determining the vessel role as fully GW or SO for every encounter geometries. By imitating how humans infer and make decisions based on the available information, fuzzy logic mitigates this contradiction by allowing a vessel to be interpreted as partly GW and/or partly SO.

Going back to Encounter 2 where the OS had a role corresponding to mostly GW, but it also had some SO obligations. The evaluation system can account for this by using the fraction of GW obligations and SO obligations to assess the COLREGs compliance of the OS. Contrary to the proposed method, e.g. from Hagen et al. (2021), it does not need to decide whether the OS should be evaluated as fully GW or fully SO.

Sensitivity to time of detection

It has become evident after testing with different parameter values that assigning vessel roles is very sensitive to the detection range r_{detect}. The vessels' roles are determined based on the vessel-to-vessel configuration at the time of detection, and nothing after this point can change the vessels' roles. The time of detection is determined based on the maneuverable space range. As stated previously, Woerner (2016) defined the beginning of an encounter to be when the distance between two vessels fell below 1.8 times the preferred passing range at CPA r_{pref}. In this thesis, the maneuverable space has been used to decide r_{pref}. Thus, the point of detection changes from encounter to encounter based on the calculation of the maneuverable space. This method for determining the point of detection has some advantages. One advantage is that different operational domains are likely to require different detection ranges. With a dynamic calculation of detection range, this evaluation system could more easily be extended to operational environments that differ from restricted and urban domains. Also, K. Woerner has already implied that there is a relation between the preferred passing distance between two vessels and the detection range by using r_{pref} as the basis for the calculation of r_{detect}. Since it is assumed that the preferred passing range changes based on the size of the operational domain, it is also fair to assume that the detection distance should do the same. This could also be advantageous in operational domains regarded as similar but differ in size and form.

A drawback with using the maneuverable space as basis for determining the detection range is that areas with very restricted maneuverability results in a late point of detection. I.e., a restricted maneuverable space leads to a small detection range which again could lead to that a maneuver to avoid collision falls outside of the $[i_{detect}, i_{cpa}]$ interval. This might be a bit tricky to follow, but if we look back to Figure 3.6 where R_{min} is a measure of the maneuverable space, it is seen that r_{detect} is scaled with r_{pref} which again is found based on the maneuverable space R_{min}. I.e., a small R_{min} results in small values for $_{pref}$ and r_{detect}. Encounter 1, Figure 4.1, and the encounter between OS and TS1 is illustrative for this drawback. The OS makes an early maneuver, but the detection point is posterior to the maneuver start because the maneuverable space is small. This reduces the compliance score when in reality, the OS made an early and apparent maneuver to avoid collision with TS1. This is an obvious flaw of the evaluation system. This could have been avoided with a static detection range or by increasing the dynamic detection range multiplier. However, this does not necessarily guarantee a more precise evaluation in other scenarios. Restricted operational domains where the vessels are making several maneuvers within a short time pose a general challenge, as it becomes increasingly tricky to find the correct detection point robustly. It is difficult to imagine any detection algorithm capable of solving this issue with great success. By visual inspection of an encounter, it is straightforward to identify what should be the point of detection by assessing the paths of the vessels. However, it appears highly challenging for an algorithm to do the same correctly in every encounter.

As stated, an encounter can be evaluated very differently with different values for r_{detect}. E.g., in Encounter 3, visualized in Figure 4.3, the roles of OS and TS3 change depending on the detection range. If the detection range is big, i.e., the encounter is defined to begin near the initial position, the encounter is interpreted such that TS3 is overtaking OS and has a GW role while OS is being overtaken and has a SO role, as defined by Rule 13. This would require OS to keep speed and course, while TS3 should keep out of the way by making an apparent maneuver. However, it is seen from the subsequent OS path that keeping the course would be inefficient for reaching the desired end-point. Thus, the most appropriate role for OS is to enter a crossing encounter and act according to a GW role. This illustrates that minor changes of the detection point can lead to fundamentally different encounter geometries that will have a large impact on the evaluation.

One possible solution to the issue with detection points of the evaluation method not matching with the 'actual' detection point would be first to detect any maneuver that potentially is made in connection to an encounter and then define the detection point to be somewhere prior to this maneuver. E.g., suppose a maneuver is taken just before the evaluation methods' detection point. In that case, this could be accounted for by adjusting the detection point to be prior to the maneuver instead of before. Doing this one goes the other way when determining the detection point. One assumes that if a maneuver is made within a time range that is considered reasonable, then it is fair to assume that the maneuver is a response to the encounter, and hence the detection point can be adjusted to match it. The window size would still need to be determined, but it could solve the issue of a maneuver happening just before the detection point

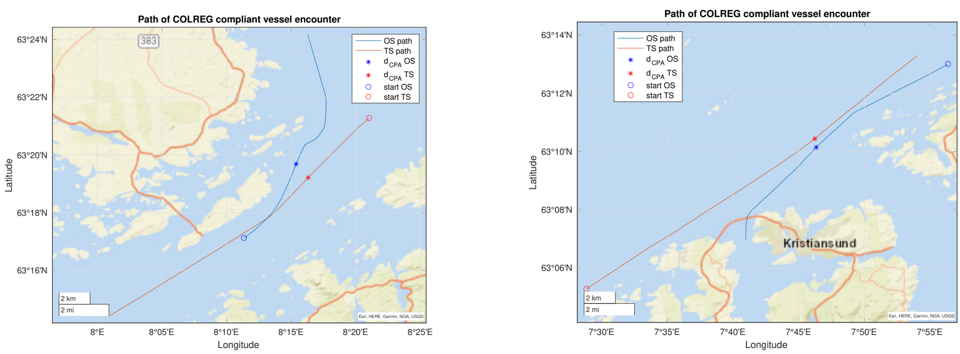
Accounting for vessels intention

A challenge when evaluating COLREGs compliance is that when using only information about the historical position, heading and velocity, it is difficult to know anything about the intention of the vessels. With a vessel's intention it is meant that the planned future path might influence how the vessel acts. To illustrate and prove that this is something that actually happens we have used AIS data from the Trondheimsfjord area. Figure 5.1 shows two different encounters where the OS and TS are meeting in a head-on encounter, but in both encounters OS and TS are passing on the starboard side of each other. In Figure 5.1a the behavior is explained by the ’s future path. In Figure 5.1b the behavior could also be explained by the OS’s future intended path. It is heading towards Kristiansund harbor and thus the shortest path is to pass TS on its starboard side, even though this violates with COLREGs Rule 14.

A vessel’s intention could, for some encounters, explain non-compliant COLREGs behavior. However, such behavior might be time-saving and more efficient, and the intention might also be communicated over the radio to the counterpart in the vessel-to-vessel encounter. It is not unusual that COLREGs compliance is traded for efficiency, as long as it is communicated clearly to the counterparts. The vessels’ intention has not been accounted for in this thesis but might be worth looking into for further work.

In Figure 5.2 shows another two encounters from the Trondheimsfjord area with non-compliant COLREGs behavior. In these encounters the violation with Rule 14 can not be explained by the vessels’ future path. However, there might be other reasons for the violation with Rule 14, e.g., presence of vessels not tracked by AIS, bathymetric concerns etc.

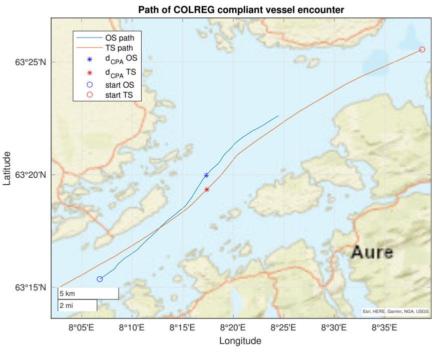
Even though these examples of presumably non-compliant behaviors are from a different operational domain than what has been the focus of the thesis it is illustrative of the general challenge with not knowing the vessels’ intention and the vessels’ surroundings that might affect how it maneuvers.



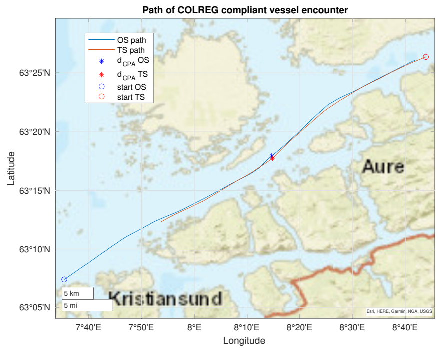
(a) A non-compliant maneuver explained by OS’s future path

(b) A non-compliant maneuver explained by OS’s future path

Figure 5.1: Two non-compliant maneuvers explained by future path



(a) A non-compliant maneuver explained by OS's future path.



(b) A non-compliant maneuver explained by OS's future path.

Figure 5.2: Two non-compliant maneuvers that is more difficult to explain

5.2 Encounter safety evaluation

The encounter safety is measured with evaluation criteria that coincide with previous research's most frequently used parameters, i.e., the DCPA, relative bearing, and contact angle. So this is not unique, and using fuzzy logic to determine the safety has also been done previously. However, using dynamic range thresholds based on the maneuverable space to determine the safety in an encounter has not been seen before. Using the maneuverable space to determine the range thresholds for DCPA is advantageous compared to static thresholds because it accounts for the operational domain and the surroundings of the vessels automatically. With static thresholds, one would have to set this manually based on the operational domain. E.g., in Encounter 2 in Kristiansund harbor, shown in figure 4.2 there is a narrow passage where OS and TS2 pass each other. By using static range thresholds for r_{pref}, r_{min}, r_{nm}, and r_{col}, the requirements for DCPA would be similar if OS and TS2 passed each other in the narrow canal or in the more open space. Possibly also r_{pref} is larger than the total distance across the narrow passage where OS and TS2 are passing each other, making it impossible to achieve a full safety score. This issue is solved by using a dynamic range based on the maneuverable space to scale the range thresholds r_{pref}, r_{min}, r_{nm} and r_{col}.

The pose configuration score used to assess the vessel-to-vessel geometry at the CPA has proven to be reducing the encounter safety score for crossing encounters more than for head-on and overtaking encounters. This seems like a somewhat unfair punishment, as in a crossing encounter it is more common that OS and TS have a pose configuration which is regarded as undesired by the score function proposed by Hagen et al. (2021) shown in (3.6) and (3.7). An example of this is seen in Encounter 2 from Kristiansund harbor and

Table 4.5 where OS receives a score of only 0.1 for the encounter with TS3 and a score of 0.9 and 1 for encounters with TS2 and TS1, respectively. However, little effort was put into investigating this further and is a proposed further work.

An apparent challenge when deciding the range thresholds to determine the safety of the passing distance is that the COLAV system has its own interpretation of what should be considered as a safe passing distance. The COLAV system might not coinciding with the evaluation methods' interpretation, as there are no clear guidelines to decide what should be assumed a safe passing distance. This issue becomes evident in the Results chapter, where the encounter safety score is generally evaluated to not satisfactory. This is simply because the COLAV method's method for determining acceptable DCPA is less "strict" than the evaluation method's acceptable DCPA. This reveals one of the most challenging aspects when designing an evaluation system; to make sure that the parameter choices in the evaluation method are "correct". This is incredibly difficult due to the way COLREGs expect navigators to use their experience and evaluation skills to decide such. Possible ways to determine the parameters are, for example, to involve a large group of experienced sailors and get them to evaluate a bunch of encounters in a survey. From the survey one can extrapolate as much knowledge as possible and replicate such knowledge in the evaluation method. Alternatively, one can use AIS data and based on this find the "common practice" by sailors for specific operational domains. However, in urban areas with small boats and lots of non-tracked traffic, use of AIS data is difficult.

5.3 Perceived safety evaluation

Assessing perceived safety is a challenge due to the lack of research. Thus, finding evaluation parameters and creating MFs for these parameters proved to be challenging. However, the developed evaluation system can determine the perceived safety score based on criteria that are likely to play an essential role in passengers' safety experience, as identified from the citizen engagement project in TRUSST and available research. Some aspects of perceived passenger safety are difficult to capture in simulated data. E.g., the simulation data used in the thesis disregards heave and roll motion, two motions that are likely to be important for comfort assessment. However, even with measurements of heave and roll, no research on what should be regarded as too much heave or roll motion to keep the perceived safety intact has been found.

There are also other aspects of perceived safety that are impossible to measure by using simulated data. An example of this emerged from the TRUSST project. It was found that knowing the ASV's understanding of the surroundings and interpretation of the situation and its navigational intentions is crucial for the perceived passenger safety. This can be compared to how Tesla's situational awareness is displayed to the driver, where all incoming traffic and other obstacles appear. Also, when in self-driving mode, the car will clearly show its future navigational intention. A solution similar to this is expected to become necessary for assuring passengers that the situational awareness algorithms have spotted all nearby obstacles and that the guidance and navigation system has chosen a reasonable path going forward. This is impossible to account for in the kind of perceived safety evaluation performed in this thesis.

Another example of something considered essential for the perceived safety onboard an autonomous ferry is how an emergency is handled when there are no operators present. An emergency could be a fire, a sudden medical health issue, someone falling off the ferry, or other emergencies. These are the situations that an operator would typically handle and the operator is a person the passengers would usually trust when embarking. With no safety operator, demonstrating safety barriers for preventing the occurrences of hazardous events is likely vital for how safe passengers feel when embarking on the ferry. Such aspects are probably as important as how perceived safety is evaluated in this thesis but are challenging to measure using simulated data. This thesis aims to cover important aspects related to the actual crossing and docking and disregard hazardous events such as those mentioned above.

5.4 Increasing number of rules for each parameter

A challenge with any FLS is to design rules to accompany the MFs. The rules should have good coverage, i.e., no input parameter should result in a fuzzy set that falls outside of all rules. An increasing number of parameters makes it increasingly challenging to design efficient rule sets that still cover every potential combination of parameters. Several methods have been proposed to mitigate this problem by automating the process. However, such methods often rely on having data sets representing the behavior of the problems being solved. For the problem being solved in this thesis, it would be challenging to provide such a data set due to the complexity of the problem. Thus, the rules in this thesis had to be made manually, something which proved to be challenging.

It is possible to imagine that if one had access to a data set with a sufficient number of encounters where every evaluation parameter had been labeled with a corresponding MF, and the labeling could be assumed to be 'correct,' and all MFs, antecedents, and consequences had been normalized to a standard format, then this data set could be used to create rules automatically. However, to the author's knowledge, such a data set does not exist. And also, this method assumes that 'correct' labeling of encounters exists, something which is not necessarily fair to assume since the COLREGs are meant to be interpreted based on subjective assessments.

A more simple solution to the challenge of the increasing size of the ruleset would be to reduce the number of MFs. The approach in the thesis has been to use three or more MFs for each antecedent and consequent. This means that the rules must cover all three possible MFs to cover the input space fully. E.g., instead of using three MFs like 'Bad,' 'Acceptable' and 'Good,' one could use only the MF 'Good' and instead make use of the 'NOT' statement to distinguish between 'Good' and 'NOT Good' (Bad). The drawback with this is that the nuances in the evaluation vanish, and the evaluation would struggle with capturing minor changes in encounter configurations. It would be a more simple evaluation system to create and maintain due to fewer rules and a smaller chance of not covering the entire input space, however, it would struggle with capturing nuances.

5.5 Importance of good maneuver detection algorithm

Large parts of the evaluation system depend on maneuvers by OS and TSs. This is essential for evaluating COLREGs, as a maneuver should be made early and be readily apparent to be compliant with a GW role. Also, it is stated that a SO role should keep course and speed. Thus, erroneously registering a maneuver could have consequences for the compliance evaluation. Also for the perceived safety evaluation maneuvers are essential. The measure of whether a course alteration results in a smaller DCPA is used, and thus being able to correctly identify when the maneuver starts, ends, and the magnitude of maneuver is essential. The encounter safety evaluation is only dependent on DCPA and pose at CPA and thus not reliant on the maneuver detection.

This thesis has used a CPD with a sliding-window method to identify maneuvers in the form of course or speed alteration. The technique has been shown to identify maneuvers with acceptable precision overall. However, because the sliding-window method is a comparative method that compares one interval to another, it tends to erroneously detect maneuvers in data with close to constant value throughout the encounter. However, in most encounters, the vessels make maneuvers shown as abrupt changes, e.g., COG. Another challenge with the sliding-window CPD method is that it needs tuning of window size, which could be an error-prone process.

Alternatives to the CPD method were considered. However, maneuver detection was not a targeted scope of this thesis. Thus, the maneuver detection method was deemed satisfactory and suggested for further work.

5.6 Challenges with restricted operational domain

The operational domain in focus in the thesis is arguably the most challenging domain for navigational and evaluation purposes. A more restricted domain from the domain under investigation would be canals, where there are separate rules governing the vessels' behavior which more or less say 'keep right.' In less restricted domains, i.e., fjords and open-sea, vessels keep a more constant speed and course and generally have significant distances between them. In urban and semi-restricted domains, vessels need to interact more, resulting in frequent speed and course alterations. This is challenging because it increases the importance of the point of detection as discussed previously, and also, the maneuver detection algorithm needs to be precise. Another challenge is that the DCPA calculation assumes constant speed and course. This is a fair assumption in less restricted domains due to vessels' generally considerable inertia, resulting in slower dynamics. However, when the vessels are making frequent changes in speed and course, this leads to erroneous estimations of DCPA, which leads to less accurate evaluations.

Chapter 6

Conclusion

This section concludes the thesis with background in the presented results and discussion. Also, a proposal of further works is included and rounds off the thesis.

6.1 Conclusion

The thesis has presented three systems for evaluating different aspects of the maneuvering performance of ASVs in encounters with other vessels. All the proposed systems provide a score between 0 and 1 for their respective evaluation purpose. The systems are all developed by utilizing fuzzy logic to mimic human inference and overcome the challenge of the vaguely written COLREGs, complex operational domains and encounter geometries.

It has been demonstrated that the developed system can interpret an encounter between two vessels as described by the COLREGs and handle the vague definitions by the developed inference system. The method demonstrates the ability to handle encounter geometry uncertainty and conflicting roles efficiently and satisfactorily. However, the method has potential for improved performance in some areas, specially connected to the point of detection and the maneuver detection precision. The developed evaluation system has also demonstrated the ability to quantify the encounter safety using recognized evaluation criteria. The approach differs from similar safety evaluation methods by utilizing dynamic range thresholds, which proves to be efficient for inconstant operational domains. Finally, the developed system has demonstrated the capability of quantifying perceived safety from a passenger's point of view on board an autonomous passenger ferry. Essential safety aspects have been identified by searching existing research on similar transportation means and inspecting the TRUSST project's output.

The method has been demonstrated by using simulations from Kristiansund harbor and Sandefjord harbor, where the geographic-specific simulation environments facilitated the calculation of maneuverable space. The capabilities of separating performance with minor changes in vessel behavior and encounter geometries of the developed system have also been visualized through batch simulations.

6.2 Further work

Maneuver detection

As stated previously, the maneuver detection algorithm is an essential part of the outcome of the evaluation system. The current method utilizes a Python library specifically for detecting abrupt changes in time-series data. This method is performing satisfactorily, however, tuning the algorithm proved difficult and time-consuming. Also, by utilizing such a library, one loses control of the working of the maneuver detection algorithm. Thus, a method to detect changes in time-series data where one have more control over the algorithm could be beneficial.

Pose at CPA

The function to calculate a score for the pose configuration between two vessels in an encounter is based on the approach in Hagen et al. (2021). However, further investigation of how this could be better applied in urban and semi-restricted waters could be beneficial. The experience is that the current method punishes crossing encounters undeservedly harshly.

Parameter design

The evaluation result is dependent on how parameters are designed. Such parameters must be found for different operational domains by using engineering knowledge. This is a perpetual job as there is no right or wrong when choosing thresholds etc. However, a more thorough investigation into how parameters could be designed specifically for an urban and semi-restricted operational domain would be valuable.

Perceived safety evaluation

Further investigation into how perceived safety evaluation could be quantified is suggested. This thesis has identified essential parameters for evaluating perceived safety from a passenger's point of view but should be regarded as an incipient work on the topic. The increased focus on ASVs is likely to lead to more research into passenger safety and comfort studies which could be used as input to evaluation methods similar to the one proposed in this thesis.

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Appendix

Evaluating Collision Avoidance Algorithms in Urban and Semi-restricted Waters Using Fuzzy Logic

Eivind Løvoll * **Dong Trong Nguyen** ** **Øyvind Smogeli** ** **Emil Hjelset Thyri** **

* *Norwegian University of Science and Technology, Trondheim, Norway (e-mail: eivinlov@stud.ntnu.no).*
** *Norwegian University of Science and Technology, Trondheim, Norway (e-mail: dong.t.nguyen@ntnu.no, oyvind.smogeli@ntnu.no, emil.h.thyri@ntnu.no)*

Abstract: This article presents a method for evaluating the maneuvering performance of marine surface vessels, suitable for use in simulation-based evaluation and assurance of autonomous maneuvering and collision avoidance algorithms. We consider three individual evaluation metrics, namely, adherence to International Regulations for Preventing Collisions at Sea (COLREGs), encounter safety, and perceived passenger safety. These concepts are highly dependent on a human's objective interpretation of the situation, and their evaluation is hence not easily automated. We propose to mitigate this using fuzzy logic, a branch within artificial intelligence that tries to imitate the way humans make decisions based on imprecise and non-numerical information. Specifically, COLREGs are addressed by deciding whether a vessel has the role of give-way or stand-on. Subsequently, the compliance of each vessel is calculated through the designed fuzzy membership functions based on rules 8, 13, 14, 15, 16, and 17 in the COLREGs. Further, we calculate a safety score based on the pose and range at the closest point of approach. Finally, a score for perceived passenger safety is calculated and addressed using a combination of data from ongoing public projects in Trondheim, Norway, and pose, velocity, and acceleration assessment.

Keywords: COLREGs, Fuzzy logic, Collision avoidance, Autonomous navigation, Perceived safety, Encounter safety

1. INTRODUCTION

The efforts to develop autonomous systems have sky-rocketed in recent years. However, we are yet to see autonomous surface vessels (ASVs) in a commercialized application. Before ASVs could become a reality, several hinders must be surpassed. One of the challenges is to develop schemes for verification and validation (V&V) of the navigation system to ensure the capability of safe, predictable, and reliable maneuvering. Another challenge that remains to be solved is that ASVs must be able to maneuver in complex situations and interact with other vessels controlled by humans, possibly making non-compliant and unpredictable maneuvers. Due to the interaction with human-controlled vessels, ASVs need to comply with the same rules and regulations as more traditional vessels. One of the fundamental rules all sailing vessels must comply with is the COLREGs. This is a set of rules written with the intention of needing human interpretation. Thus, determining whether vessels act according to these regulations is a complex task requiring quantifying linguistic terms and parameters.

It has become well known through several studies that ship collisions are more often caused by human errors. The numbers differ slightly, but in a recent survey conducted by the European Maritime Safety Agency (EMSA), it emerged that 54% of the analyzed incidents over the period 2014-2020 were caused by human error (Agency, 2021). Another study indicated that 75%-96% of maritime collisions and causalities were caused by human errors and that 56% of major collisions involved one or several violations of the COLREGs (Rothblum, 2002).

Much of the focus in the literature has been on developing collision avoidance algorithms, e.g. Perera et al. (2012); Perera (2018); Kuwata et al. (2013); Campbell et al. (2014); Benjamin and Curcio (2004); Hong et al. (1999). Less attention has been given to developing proper evaluation schemes that can verify that the developed algorithms are capable of maneuvering in compliance with the governing rules and regulations safely and reliably. However, there has been an increasing interest in developing such evaluation schemes in recent times. Previous studies have addressed challenges with quantitatively measuring collision avoidance performance of ASVs, some accounting for COLREGs compliance and some more focused on collision-free and safe behavior, e.g. Woerner et al. (2016, 2019); Hagen et al. (2021); Porres et al. (2020); Stankiewicz et al. (2020); Trodahl (2021).

A proposed approach to deal with the vagueness of the COLREGs has been to use artificial intelligence (AI), which is trying to mimic cognitive functions associated with the human brain. AI methods can capture human-like inference, which could be exploited to determine compliance with COLREGs quantitatively (Trodahl, 2021). One technique that could be used in this regard is fuzzy logic, a branch within AI that tries to imitate the way humans make decisions based on imprecise and non-numerical information.

COLREGs exist to ensure a predictable and reliable scenery in trafficked waters. However, little regard is taken to assess the risk involved in an encounter. This has, however, been addressed in several papers, e.g. Tam and Bucknall (2010), Katrakazas et al. (2019), Woerner et al. (2016) and Ozturk and Cicek (2019), where the latter summarizes the existing literature on collision risk assessment. It is found that the most frequently used parameters for assessing collision risk are time to closest point of approach (TCPA), distance at closest point of approach (DCPA), and relative bearing.

Another challenge and a recognized field of lacking research is how to decide parameters used to measure compliance and safety in different operational domains. E.g., little attention has been given to quantifying what should be considered a safe passing distance between two vessels, which will undoubtedly vary in other operational domains and conditions.

A domain of increased interest in recent years where autonomous vessels seem likely to be introduced within a short time is urban waterways. Utilization of cities' waters with autonomous water shuttles promises to reduce emissions, remove traffic from congested roads and be more cost-efficient than existing solutions. One of the fundamental challenges that still needs research is how to make passengers feel safe when boarding an autonomous ferry. How passengers assess safety is likely to deviate from how encounter safety is considered. E.g., it is expected that passenger comfort will affect how safety is perceived, but comfort does not influence the encounter safety evaluation. Little research has been found on the topic. However, the research project Assuring Trustworthy, Safe and Sustainable Transport for All (TRUSST) has arranged citizen engagement activities to map and understand the needs and concerns of future passengers of an autonomous ferry (Forskningsrådet, 2020). Also, Lättman et al. (2016) discovered strong connections between perceived service quality (e.g., trip planning and comfort) and perceived travel safety on public ground transportation vehicles. I.e., how safe passengers feel in public transport is instrumental for how the quality of service and accessibility are perceived. This motivates further investigation into the topic, and to the author's knowledge, no previous work has attempted to quantify perceived safety from a passenger's point of view.

This paper aims to show how fuzzy logic can be utilized to quantitatively measure the performance of a collision avoidance algorithm concerning the COLREGs, encounter safety, and perceived safety from a passenger's point of view.

The paper is structured as follows: first, the most relevant background theory will be summarized. Then, the evaluation method will be presented, followed by a display of the results in batch simulations. Finally, the results are discussed and the main findings are concluded.

2. BACKGROUND THEORY

2.1 Closest point of approach (CPA)

TCPA is calculated as

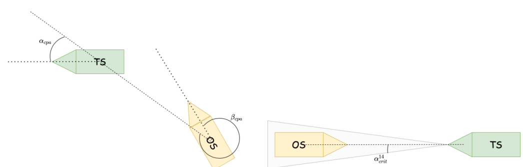
$$t_{cpa} = \begin{cases} 0 & \text{if } ||\boldsymbol{v}_{ts} - \boldsymbol{v}_{os}||_2 \leq \epsilon. \\ \frac{(\boldsymbol{p}_{ts}-\boldsymbol{p}_{os})(\boldsymbol{v}_{ts}-\boldsymbol{v}_{os})}{||\boldsymbol{v}_{ts}-\boldsymbol{v}_{os}||_2^2} & \text{otherwise.} \end{cases} \tag{1}$$

where $\boldsymbol{p}$ is the position, $\boldsymbol{v}$ is the velocity, and ϵ is a threshold in order to avoid division by zero in the case where the relative velocity between the own ship (OS) and obstacle is zero. The DCPA is calculated as

$$d_{cpa} = ||(\boldsymbol{p}_{os} + t_{cpa}\boldsymbol{v}_{os}) - (\boldsymbol{p}_{ts} + t_{cpa}\boldsymbol{v}_{ts})||_2 \tag{2}$$

2.2 Relative bearing and contact angle

Relative bearing is normally defined as inside the interval $\beta \in [0°, 360°)$ measured clockwise. The relative contact angle is normally wrapped inside the interval $\alpha \in (-180°, 180°]$, i.e., the smallest signed angle (SSA). Sometimes it is useful to express relative bearing angles in the interval $\beta \in (-180°, 180°]$. To easily distinct the different notations, a superscript will define the interval of both relative bearing and contact angle, e.g $\beta^{360°}$ and $\alpha^{180°}$. It is useful to talk about angles for a specific rule in some cases. In such cases, a superscript will be used with similar notation as above, e.g. α^{14}_{crit} which is the critical angle, illustrated in fig. 1b, in a head-on situation as described in Rule 14. If a specification of interval and rule is necessary, the notation $\alpha^{14,180°}$ will be used. Angles measured at the CPA are noted with a subscript, e.g. β_{cpa}.



(a) Relative bearing β and relative contact angle α at CPA

(b) Illustration of critical contact angle α^{14}_{crit}

Fig. 1: Relative bearing, contact angle and critical contact angle

Relative bearing and contact angle is calculated based on the same procedure as in Woerner (2016). $\beta^{360°}$ is calculated as

$$\beta^{360°} = \begin{cases} 360° - |bearing - \psi|, & \text{if } bearing - \psi < 0° \\ bearing - \psi - 360°, & \text{if } bearing - \psi \geq 360° \\ bearing - \psi, & \text{otherwise} \end{cases} \tag{3}$$

where $\psi \in (-180, 180]$ is the heading of OS with clockwise direction as the positive direction. OS with a heading towards north is defined to give $\psi = 0°$. The bearing, i.e., the absolute bearing angle, is found as

$$bearing = \text{atan2}(y_{ts} - y_{os}, x_{ts} - x_{os}) \tag{4}$$

where *atan2(...)* gives an angle in the interval $(-180°, 180°]$.

The contact angle is found as

$$\alpha^{180°} = \begin{cases} 360° - |contact - \psi|, & \text{if } contact - \psi < 180° \\ 360° - (contact - \psi), & \text{if } contact - \psi \geq 180° \\ contact - \psi, & \text{otherwise} \end{cases} \tag{5}$$

where *contact* is found as

$$contact = \text{atan2}(y_{os} - y_{ts}, x_{os} - x_{ts}) \tag{6}$$

2.3 Fuzzy logic

Fuzzy logic is a term introduced in 1965 by the Azerbaijani scientist Lofti Zadeh. A fuzzy logic system (FLS) consists of three main blocks as illustrated in fig. 2: a fuzzifier, rules and inference logic, and a defuzzifier.

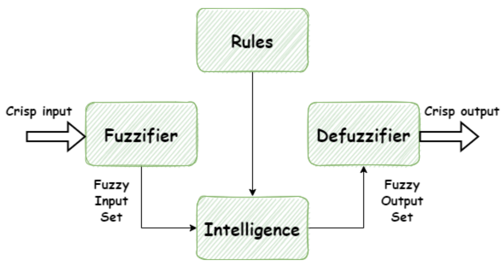


Fig. 2: Illustration of modules in a Fuzzy logic system

Fuzzy set

To define a fuzzy set we look to the source, Zadeh (1996). He stated that a fuzzy set (class) A in X is characterized by a membership function (MF) $\mu_A(x)$ 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.

Thus a fuzzy set A can formally be defined as:

$$A = x, \mu_A(x) | x \in X \tag{7}$$

where A is the fuzzy set, x is the an element (i.e. the crisp value), $\mu_A(x)$ is the membership function that maps the crisp value x in the universe of discourse X to a membership value, as defined in eq. (11). A crisp value is in opposition of a fuzzy value, i.e a value that is well defined and has a precise value. The universe of discourse is defined as the set X of possible values that can take the variable x.

A fuzzy set has notions such as inclusion, union, intersection, complement, relation and convexity that are very useful when working with FLS. The most important notions are:

Complement:

$$\mu'_A(x) = 1 - \mu_A(x) \tag{8}$$

i.e. $\mu'_{good}(x) = 1 - \mu_{good}(x)$. This attribute is useful when using the 'NOT' statement in the rule making.

Union: C = A ∪ B

$$\mu_C(x) = max[\mu_A(x), \mu_B(x)], \quad x \in X \tag{9}$$

which is useful when using the 'OR' statement in rules.

Intersection: C = A ∩ B

$$\mu_C(x) = min[\mu_A(x), \mu_B(x)], \quad x \in X \tag{10}$$

which is useful when using the 'AND' statement in rules.

Fuzzifier

The first block in fig. 2 is a fuzzifier block. This block is responsible for taking in crisp inputs and calculating a fuzzy set based on the crisp input. To transform the crisp input, there exist one or several MFs. A MF is a quantification of a parameter, e.g. a linguistic term such as 'apparent', in the form of a graph.

A membership function for a fuzzy set A on the universe of discourse X is defined as:

$$\mu_A(x) : X \longrightarrow [0, 1] \tag{11}$$

where each element of X is mapped to a value between 0 and 1, the *degree of truth.*

Fuzzy intelligence and fuzzy rules

Inference is the combination of the blocks *Intelligence and Rules* shown in fig. 2. Inference is the process where one tries to reason, moving from premises to logical consequences. A Mamdani FLS has an $IF < Antecedent > THEN < Consequent >$ rule-based system (Perera et al. (2010)). The IF-THEN rules are developed based on the system under investigation. Common for all IF-THEN rules are that one tries to capture all available knowledge about the system in simple statements. Knowledge about the system can originate from several sources, i.e. from observed behavior of a system, from a set of linguistic and vaguely written rules, or from measured behavior of a system. A common approach is to use expert knowledge gathered from interviews of competent and experienced people within the field.

Defuzzifier

In this last module of the FLS the fuzzy decisions are defuzzified by the output MFs. An output MF is similar to an input MF. The purpose of the defuzzification is to convert the fuzzy sets back into a crisp value.

A defuzzifier can be based on different methods, however, the two most used are the *center of gravity* and the *mean of maxima* methods. With the center of gravity method, the crisp output is the abscissa of the center of gravity of the surface described by the fuzzy output function (Van Broekhoven and De Baets, 2006).

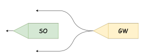
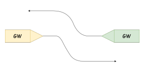
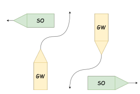
The crisp output is formally defined by

$$y_{COG} = \frac{\sum_{i=1}^{N} A_i * x_i}{\sum_{i=1}^{N} A_i} \quad (12)$$

2.4 COLREGs

With the introduction of steamships in the early 18th century, new collision risks emerged when they encountered traditional sailing vessels. Collision avoidance rules were formulated in the 1840s to coordinate collision avoidance actions of steamships and sailing vessels to deal with this emerging risk. In the middle of the 19th century, the COLREGs had codified all major actions required to avoid collisions, and many of the principles are still recognizable today. However, various alterations to the COLREGs have been agreed upon in the later years, reflecting the increase of traffic and technological advances. The latest major rewriting of the COLREGs was in 1972 and remains in force today (Belcher, 2002). The most important rules for this paper are summarized in table 1.

Table 1: Maneuvers in various obstacle avoidance situations

Rule #	**Situation**	**Description COLREGs**	**Schematics**
Rule 7	Risk of collision	Available means to determine risk, if doubt risk shall be deemed to exist	
Rule 8	Action to avoid collision	Ample time, good seamanship, course and/or speed alteration should be readily apparent, passing at safe distance	
Rule 13	Overtaking	Keep put of the way	
Rule 14	Head-on	Reciprocal or near-reciprocal courses, alter course to starboard, pass on port side	
Rule 15	Crossing	Vessel which has other on starboard side shall keep out of way, avoid crossing ahead	
Rule 16	Action by give-way	Early and substantial to keep out of the way	
Rule 17	Action by stand-on	Keep course and speed	

3. EVALUATION METHOD

The full evaluation system is comprised of three independent systems; COLREGs compliance, perceived safety and encounter safety as illustrated in 3.

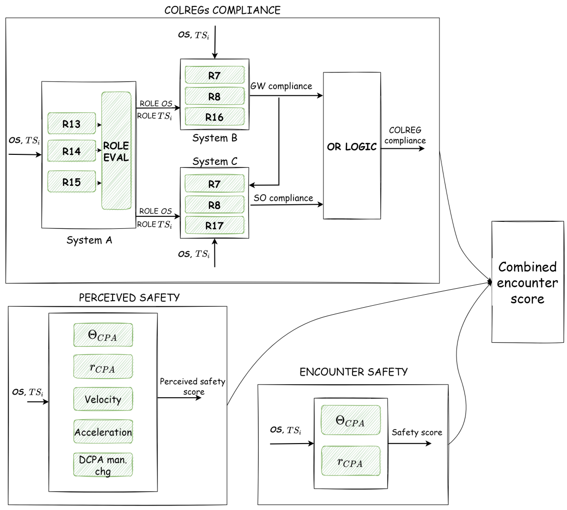


Fig. 3: Full evaluation system

3.1 COLREGs

As illustrated in fig. 3, system A in the COLREGs compliance system is responsible for determining each vessel's role in the encounter, i.e., whether a vessel is give-way (GW) or stand-on (SO). This is calculated based on the geometry between the vessels when the distance falls below a given threshold. The roles are determined based on a set of entry criteria inspired by Woerner et al. (2016). The entry criteria are used to design MFs as summarized in table 3 as antecedents. The consequences are functions that determine the degree of membership (DoM) for roles of OS and target ship (TS). System B is responsible for calculating GW compliance. System C is responsible for calculating the compliance of the SO vessel. The assessment of GW compliance must come before SO compliance assessment due to COLREGs rule 17 (ii). Rule 17 (ii) grants permission for SO to make a maneuver when the GW vessel is not taking appropriate action to avoid a collision, and is thus essential information for SO compliance evaluation.

Deciding whether rule 13, 14, or 15 apply for an encounter has been a largely discussed task. Only rule 13 provides any angle to assess an overtaking scenario, but confusion arises due to the difficulties of human assessment of angles by eye. To account for such difficulties, a margin is added even though the rule specifies '... 22.5 degrees abaft her beam'. Critical angles are given as configurable parameters to account for terms like 'coming up with' and 'reciprocal or near reciprocal.' The margin parameter w and critical angles are shown in table 2.

Rule 13

As illustrated in table 1 and described in the COLREGs, 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, and the vessel overtaking shall keep out of the way, i.e., act as the GW vessel. It is also stated that a vessel in doubt as to whether she

Table 2: Tunable parameters for System A and proposed values

Parameter	**Proposed value**
w	2.5°
α^{13}_{crit}	122.5°
α^{14}_{crit}	22.5°
α^{15}_{crit}	22.5°

is overtaking another shall assume this is the case, i.e., assume to be the GW vessel. This illustrates that, even though the overtaking angle is defined explicitly, margin must be added to account for the uncertainty in human interpretation of an encounter.

Table 3 shows the MFs that have been designed to assess whether a vessel is in an overtaking encounter. In the interval column, the w is added to account for the uncertainty mentioned above. Table 4 shows the rules that are designed to capture the MFs to determine whether OS and TS should be given roles as defined by rule 13.

Table 3: Antecedent and consequent membership functions for system A

Antecedent MFS				
Antecedent	**Parameter**	**MF type**	**Interval**	**Rule**
$\alpha^{360°}$	OSOvertakingTS	Trapezoidal	[112.5-w, 112.5+w, 247.5-w, 247.5+w]	R13/R16
$\beta^{180°}$	OSOvertakingTSCrit	Trapezoidal	[0, 0, α^{13}_{crit}-w, α^{13}_{crit}+w]	R13/R16
$\beta^{360°}$	TSOvertakingOS	Trapezoidal	[112.5-w, 112.5+w, 247.5-w, 247.5+w]	R13/R17
$\alpha^{180°}$	TSOvertakingOSCrit	Trapezoidal	[0, 0, α^{13}_{crit}-w, α^{13}_{crit}+w]	R13/R17
$\beta^{180°}$	Head-on	Trapezoidal	[0, 0, α^{14}_{crit}-w, α^{14}_{crit}+w]	R14
$\alpha^{180°}$	Head-on	Trapezoidal	[0, 0, α^{14}_{crit}-w, α^{14}_{crit}+w]	R14
$\beta^{360°}$	CrossingGW	Trapezoidal	[0, 0, 112.5-w, 112.5+w]	R15/R16
$\alpha^{180°}$	CrossingGW	Trapezoidal	[-112.5-w, -112.5+w, 180, 180]	R15/R16
$\beta^{180°}$	CrossingGW	Trapezoidal	[-α^{15}_{crit}-w, -α^{15}_{crit}+w, 180, 180]	R15/R16
$\alpha^{360°}$	CrossingSO	Trapezoidal	[0, 0, 112.5-w, 112.5+w]	R15/R17
$\beta^{180°}$	CrossingSO	Trapezoidal	[-112.5-w, 112.5+w, α^{15}_{crit}-w, α^{15}_{crit}+w]	R15/R17
Consequent MFS				
Consequent	**Parameter**	**MF type**	**Interval**	**Rule**
RoleOfOS	GW	Trapezoidal	[0, 0, 0.4, 0.6]	-
RoleOfOS	SO	Trapezoidal	[0.4, 0.6, 1, 1]	-
RoleOfTS	GW	Trapezoidal	[0, 0, 0.4, 0.6]	-
RoleOfTS	SO	Trapezoidal	[0.4, 0.6, 1, 1]	-

Table 4: Rules for Rule 13

Rule	**IF (AND logic)**				**THEN (OR logic)**	
#	$\beta^{360°}$	$\lvert\beta^{180°}\rvert$	$\lvert\alpha^{180°}\rvert$	$\alpha^{360°}$	R_{OS}	R_{TS}
A_1	TSOvertakingOS	-	TSOvertakingOSCrit	-	SO	GW
A_2	-	OSOvertakingTSCrit	-	OSOvertakingTS	GW	SO

Rule 14

As summarized in table 1 rule 14 should be assumed to govern in an encounter where two vessels are meeting on 'reciprocal or nearly reciprocal courses'. The terms reciprocal or nearly reciprocal are highly vague, and on the contrary, to rule 13 no angle is explicitly mentioned to apply for these encounters. However, from the literature, a relative bearing and contact angle of 10°-13°is a common interpretation of the term 'reciprocal or nearly reciprocal'. Similar to rule 13, it is also stated that if any doubt exists, a vessel should assume the encounter to be head-on and act according to a GW role. Table 5 shows that both relative bearing and contact angle must have membership in the FMF 'Head-on' for rule 14 to be assumed the governing rule.

Rule 15

Rule 15 describes a crossing situation and states that the vessel which has the other on her own starboard side shall keep out of the way and avoid crossing ahead of the other vessel. I.e., a vessel shall assume the role of GW in any case where the other is on her starboard side. A summary and an illustration of this rule is found in table 1. Similar to the above-mentioned rules, margin is added to account for the challenges regarding the human assessment of an encounter configuration. The rules designed for rule 15 are shown in table 6.

Table 5: Rules for Rule 14

Rule	**IF (AND logic)**		**THEN (OR logic)**	
#	$\lvert\beta^{180°}\rvert$	$\lvert\alpha^{180°}\rvert$	R_{OS}	R_{TS}
A_3	Head-on	Head-on	GW	GW

Table 6: Rules for Rule 15

Rule	**IF (AND logic)**				**THEN (OR logic)**	
#	$\beta^{360°}$	$\beta^{180°}$	$\alpha^{180°}$	$\alpha^{360°}$	R_{OS}	R_{TS}
A_4	CrossingGW	CrossingGW	CrossingGW	-	GW	SO
A_5	-	CrossingSO	-	CrossingSO	SO	GW

COLREGs roles

This FLS is responsible for calculating the roles of OS and TS(s). The system takes in the result from the aforementioned subsystems and decides whether OS and TS are SO or GW.

Table 7: COLREGs roles

Rule			**IF (AND logic)**						**THEN (OR logic)**	
#			$R13_{OS}$	$R13_{TS}$	$R14_{OS}$	$R14_{TS}$	$R15_{OS}$	$R15_{TS}$	R_{OS}	R_{TS}
A_6			GW	-	-	-	-	-	-	-
	OR		-	-	GW	-	-	-	-	-
	OR		-	-	-	-	GW	-	-	-
	OR		GW	-	-	-	SO	-	-	-
		OR	-	-	GW	-	SO	-	GW	-
A_7			-	GW	-	-	-	-	-	-
	OR		-	-	-	GW	-	-	-	-
	OR		-	-	-	-	-	GW	-	-
	OR		-	GW	-	-	-	SO	-	-
		OR	-	-	-	GW	-	SO	-	GW
A_8			SO	-	-	-	-	-	-	-
	OR		-	-	SO	-	-	-	-	-
	OR		-	-	-	-	SO	-	-	-
	AND NOT		GW	-	-	-	SO	-	-	-
		OR	-	-	GW	-	SO	-	SO	-
A_9			-	SO	-	-	-	-	-	-
	OR		-	-	-	SO	-	-	-	-
	OR		-	-	-	-	-	SO	-	-
	AND NOT		-	GW	-	-	-	SO	-	-
		OR	-	-	-	GW	-	SO	-	SO

3.2 Safety

The encounter safety score is calculated based on the pose configuration of OS and TS and DCPA as proposed by Woerner (2016). Using the DCPA is the preferred metric for several risk assessment methods. However, Woerner argued that pose at CPA is an important parameter as well. Near-parallel geometries are preferred over near-orthogonal geometries due to several reasons. One is that the possible target area is smaller for slender bodies in near-parallel geometry. Another is that the risk of engine failure in a near-orthogonal geometry could potentially have much more significant consequences than in near-parallel geometries, and also, near-parallel gives more predictability.

The calculation of pose score is inspired by the method presented by Hagen et al. (2021), where the calculated values from eq. (13) and (14) is used as input to the antecedent MFs described in table 9.

$$S_{\alpha_{cpa}} = \begin{cases} \frac{1-\cos(\alpha_{cpa})}{1-\cos(\alpha_{cut})}, & |\alpha_{cpa}| < \alpha_{cut} \\ 1, & \text{otherwise} \end{cases} \tag{13}$$

$$S_{\beta_{cpa}} = \begin{cases} \frac{1-\cos(\beta_{cpa})}{1-\cos(\beta_{cut}^{min})}, & \beta_{cpa} < \beta_{cut}^{min} \\ \frac{1-\cos(\beta_{cpa})}{1-\cos(\beta_{cut}^{max})}, & \beta_{cpa} > \beta_{cut}^{max} \\ 1-\cos(\beta_{cut}^{min}), & \text{otherwise} \end{cases} \tag{14}$$

The MF for DCPA is based on the concentric range rings defined in Woerner et al. (2019) where the range values are configurable. The MFs can be seen in table 9 and the range limits used for safety evaluation are defined in table 8, where r_{col} defines the above threshold for distance at CPA which is considered a collision, r_{nm} defines near-miss, r_{min} defines the minimum acceptable range and r_{pref} the preferable range. These range limits are essential for the evaluation system. A method for dynamically assessing the maneuverable space, which would be a good measure to use for determining the range limits, is presented by Thyri and Breivik (2021).

The antecedent MFs are combined with the rules defined in table 10 and results in a safety score from the consequent MF from table 9.

Table 8: Range limits safety evaluation

Parameter	**Proposed value [m]**
w	6
r_{col}	10
r_{nm}	25
r_{min}	40
r_{pref}	100

Table 9: Antecedent and consequent membership functions for safety evaluation

Antecedent MFS

Antecedent	**Parameter**	**MF type**	**Interval**
PoseCPA	Undesired	Trapezoidal	[0, 0, 0.3, 0.4]
PoseCPA	Acceptable	Trapezoidal	[0.3, 0.4, 0.6, 0.7]
PoseCPA	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
PoseCPA	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]
DCPA	Collision	Trapezoidal	[0, 0, r_{col}-w, r_{col}+w]
DCPA	NearMiss	Trapezoidal	[r_{col}-w, r_{col}+w, r_{nm}-w, r_{nm}+w]
DCPA	Minimum	Trapezoidal	[r_{nm}-w, r_{nm}+w, r_{min}-w, r_{min}+w]
DCPA	Preferable	Trapezoidal	[r_{min}-w, r_{col}+w, 1500, 1500]

Consequent MFS

Consequent	**Parameter**	**MF type**	**Interval**
SafetyScore	NotGood	Trapezoidal	[0, 0, 0.3, 0.4]
SafetyScore	Acceptable	Trapezoidal	[0.3, 0.4, 0.6, 0.7]
SafetyScore	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
SafetyScore	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]

Table 10: Rules for safety evaluation

Rule			**IF (AND logic)**		**THEN**
#			PoseCPA	DCPA	SafetyScore
S_1			VeryGood	Preferable	VeryGood
S_2			VeryGood	Minimum	-
	OR		Good	-	-
		OR	Acceptable	-	-
		AND	-	Preferable	Good
S_3			Acceptable	Minimum	-
	OR		Good	NearMiss	Acceptable
S_4				Collision	-
	OR		Undesired	-	NotGood

3.3 Perceived safety

Perceived safety is assessed based on some key parameters that have been identified as important for public transport and from investigating results from citizen engagement activities through the research project TRUSST.

Little research has been found describing comfort on small passenger ferries. However, Hoberock (1976) studied the longitudinal acceleration comfort in ground transportation vehicles. Previous research has shown connections between comfort and perceived safety, and it is thus assumed that acceleration limits for comfort also apply to assessing perceived safety on a small passenger ferry. The acceleration limits are shown in table 11.

Table 11: Acceleration comfort for standing passengers

Parameter	**Proposed value [g]**
Designed acceleration value	0.138
Upper limit	0.160

It is also assumed that a high velocity and small DCPA feel unsafe for passengers and should thus be reflected in a perceived safety evaluation. The designed rules for the system are found in table 13.

Another parameter considered essential for how safe passengers feel is estimated DCPA before and after a maneuver. A maneuver that leads to a smaller DCPA is counterintuitive and could make the passengers unsure about the intention of the maneuver. However, if a vessel makes a maneuver that leads to an increase in DCPA, it would most likely feel like a good maneuver. The designed MFs are shown in table 12.

Table 12: Antecedent and consequent membership functions for perceived safety evaluation

Antecedent MFS

Antecedent	**Parameter**	**MF type**	**Interval**
LinearAcc	Good	Trapezoidal	[0, 0, 0.138, 0.15]
LinearAcc	Acceptable	Trapezoidal	[0.138, 0.15, 0.16, 0.17]
LinearAcc	Unacceptable	Trapezoidal	[0.16, 0.18, 1, 1]
dCPABeforeAfterMan	Good	Trapezoidal	[20, 25, 100, 100]
dCPABeforeAfterMan	Acceptable	Trapezoidal	[0, 5, 20, 25]
dCPABeforeAfterMan	Unacceptable	Trapezoidal	[-100, -100, 0, 10]
DCPA	Good	Trapezoidal	[$r_{nm} - w$, r_{nm}+w, 500, 500]
DCPA	Acceptable	Trapezoidal	[$r_{col} - w$, r_{col}+w, $r_{nm} - w$, r_{nm}+w]
DCPA	Unacceptable	Trapezoidal	[0, 0, $r_{col} - w$, r_{col}+w]
LinearVel	Good	Trapezoidal	[0, 0, 4, 4.5]
LinearVel	Acceptable	Trapezoidal	[4, 4.5, 5.5, 6]
LinearVel	Unacceptable	Trapezoidal	[4, 4.5, 10, 10]

Consequent MFS

Consequent	**Parameter**	**MF type**	**Interval**
PerceivedSafetyScore	NotGood	Trapezoidal	[0, 0, 0.4, 0.5]
PerceivedSafetyScore	Acceptable	Trapezoidal	[0.4, 0.5, 0.6, 0.7]
PerceivedSafetyScore	Good	Trapezoidal	[0.6, 0.7, 0.8, 0.9]
PerceivedSafetyScore	VeryGood	Trapezoidal	[0.8, 0.9, 1, 1]

Table 13: Rules for perceived safety evaluation

Rule			**IF (AND logic)**			**THEN**
#		LinearAcc	DCPABeforeAfterMan	LinearVel	DCPA	PerceivedSafetyScore
P_1		Good	Good	Good	Good	VeryGood
P_2		Acceptable	Good	Good	Good	-
	OR	Good	Acceptable	Good	Good	-
	OR	Good	Good	Acceptable	Good	-
	OR	Good	Good	Good	Acceptable	Good
P_3		Acceptable	Acceptable	Good	Good	-
	OR	Good	Acceptable	Acceptable	Good	-
	OR	Good	Good	Acceptable	Acceptable	Acceptable
P_4		Acceptable	Acceptable	Acceptable	Acceptable	Acceptable
P_5		Unacceptable	-	-	-	-
	OR	-	Unacceptable	-	-	-
	OR	-	-	Unacceptable	-	-
	OR	-	-	-	Unacceptable	NotGood

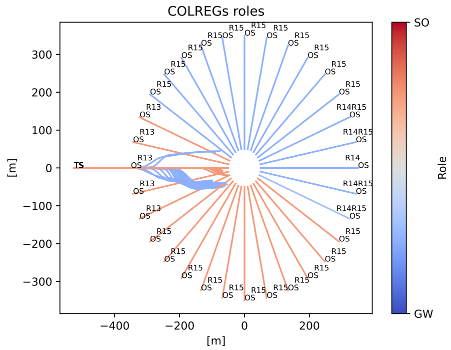


Fig. 4: Batch simulation of vessel encounter demonstrating capability of assigning roles according according to COLREGs

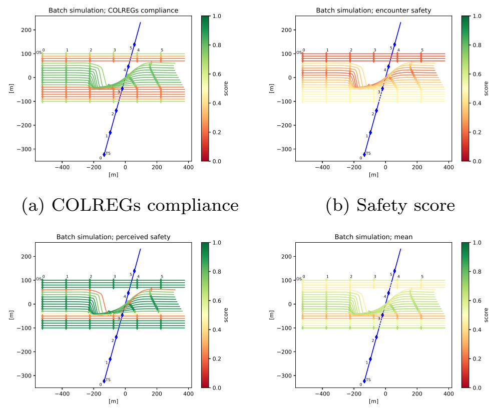
4. RESULTS

Fig. 4 shows the results from a batch simulation where the TS starts in the same position in each simulation and the OS start position changes sequentially starting from a relative bearing of -180° with steps of 11.25° until a full round is completed. This is an efficient way of checking whether the developed method for deciding vessel roles produces expected results. The annotations denote which vessel is OS and TS and which rules apply for the encounter. An important note is that OS is headed towards the "center", i.e., the annotations are placed in the starting point of each simulation.

Fig. 5 show the results from the developed evaluation system where fig. 5a show COLREGs compliance score, fig. 5c shows the perceived safety score, fig. 5b shows the encounter safety score and fig. 5d shows the total score combining the above-mentioned evaluation scores. The results are presented as batch simulations, where a score between 0 and 1 is calculated for each simulation. The result from each simulation is represented by a color based on the color bar. The batch simulation in fig. 5 shows how the system calculates performance in a crossing encounter where OS has a GW role and where TS has the same path in all simulations. The annotations denote what vessel is OS and TS, in addition to time marks that are helpful for the spatial and temporal understanding of the encounters.

5. DISCUSSION

The results in fig. 4 illustrates that the developed method for evaluating COLREGs roles can interpret the encounters and assign roles to both OS and TS according to COLREGs rules 13, 14, and 15. OS is assigned a GW role in crossing encounters with TS on the starboard side and in a head-on encounter. OS is assigned a SO role when it is being overtaken by a TS and in crossing situations where it has TS on its port side. Interestingly, when rules 14 and 15 are triggered and have conflicting roles, i.e., rule 14 commands OS to GW and rule 15 commands OS to SO, the system assigns a GW role. Situations with conflicting



(a) COLREGs compliance (b) Safety score

(c) Perceived safety score (d) Total score (mean)

Fig. 5: Results from batch simulation of crossing scenario

roles are handled by the rules A6-A9 shown in table 7, where a conflict between GW and SO will result in GW.

It is also observed that the evaluated roles of TS are reasonable. When TS has a role as GW, it makes a maneuver to avoid collision with OS. In situations where TS is SO, it keeps course and speed. However, it is seen that TS makes a late maneuver in some simulations even though it has a role as SO. This is assumed to be in situations where OS does not GW, and TS correctly makes a maneuver according to rule 17 a.(ii) to avoid a collision.

In fig. 5 the main results are presented with the calculated OS score for COLREGs compliance, perceived safety, encounter safety, and a total encounter score. In fig. 5a it is seen that the COLREGs compliance spans from bad and non-compliant to good and compliant. In simulations where the OS makes an early and apparent maneuver and crosses behind the TS, the compliance score is very good. However, in simulations where OS is not making any maneuver, presumably because the collision avoidance algorithm classifies the estimated DCPA as safe, the evaluation system punishes the maneuvering because it has a more strict assessment of safe distance. In simulations where OS is furthest away from TS, it is observed that not making any maneuver is assumed to be quite compliant. This is due to the mention of risk in COLREGs, and in these situations, it is reckoned that there is little risk of collision, and hence not making a maneuver is assumed to be compliant.

Fig. 5c show the results from the evaluation of perceived safety. The results display the capability to separate encounters deemed to be safe and those that are not. The most influential parameter for these batch simulations is DCPA. Both linear acceleration and velocity have full membership in the 'Good' MF for all encounters.

The results from the encounter safety evaluation are displayed in fig. 5b. The poor scores are mostly due to the undesired pose at CPA.

The total results are shown in fig. 5d. The best results are achieved when OS makes a readily apparent starboard maneuver to avoid colliding with TS without exceeding the comfortable acceleration and velocity thresholds. This leads to a sufficiently large DCPA.

6. CONCLUSION

The developed evaluation system is comprised of three individual systems, all providing a score between 0 and 1 for their respective evaluation purpose.

It has been shown that the developed system can interpret an encounter between two vessels as described by the COLREGs. Also, the developed system can quantify the degree of compliance based on the most essential rules in COLREGs. Encounter safety has also been quantified through a fuzzy logic system based on the most frequently used parameters for this purpose, i.e., DCPA and pose at CPA. Finally, it has been proved that it is possible to quantify perceived safety from a passenger's point of view by using input from citizen engagement activities and relevant studies on passenger comfort. The results have been visualized through batch simulations showing the system's capabilities of separating performance with minor changes in vessel behavior.

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NTNU

Norwegian University of
Science and Technology