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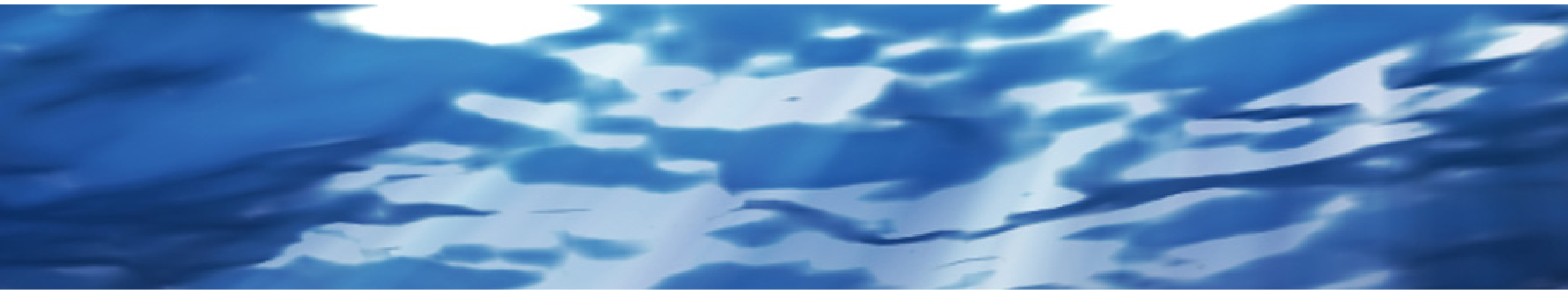

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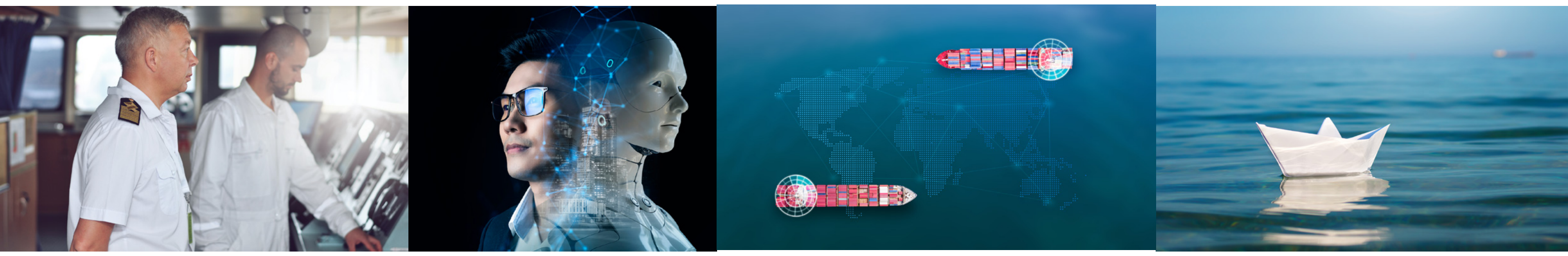
COLREG 2 - Potential consequences of varying algorithms in traffic situations



En forskningsprojekt utfört inom Trafikverkets branschprogram Hållbar sjöfart som drivs av Lighthouse. Publicerad mars 2023

TRAFIKVERKET

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HÅLLBAR
SJÖFART

COLREG 2 - Potential consequences of varying algorithms in traffic situations

Authors

Reto Weber, Chalmers

Luis Sanchez-Heres, RISE

Ted Sjöblom, RISE

With in-kind support from

Wärtsilä

SEAMADE

A research project carried out within the Swedish Transport Administration's industry program Sustainable Shipping, operated by Lighthouse

Summary

Many academic papers suggest different solutions how the COLREGs may be implemented in algorithms but the parameters controlling how close quarters situations are avoided may potentially differ depending on the type of used algorithm and its settings. When tuning a collision avoidance algorithm for a specific ship and voyage, the effects and potential consequences are basically unknown without an in-depth understanding and testing of the algorithm. This report highlights the potential effect of a limited number of input parameters of an algorithm and simulations indicate that the variances in parameters and their values result in different actions taken and that the predictability of autonomous ships in a traffic situation may be poor.

As it is initially expected that autonomous ships will need to follow the existing COLREGs due to the mixed environment of both manned and un-manned ships, it becomes imperative for there to be clear and universally accepted requirements and standards for autonomous ships. These standards need to ensure that all autonomous ships not only follow a common set of rules and algorithms in traffic situations, but also that such set of algorithms reflects how professional mariners would handle the situation.

The comparison of track patterns of autonomous ships and human operated ships in the simulations performed is a convincing argument that traffic scenarios handled by autonomous ships must be benchmarked against human operated ships, and that even simulations with combinations of manned and unmanned ships should be performed. The "orderly" track patterns of manned ships may also be regarded as a testimony of the strength and elegance of the COLREGs as a legal document, as it effectively balances the need for a set of clear, concise and universally understood regulations for preventing collisions at sea, with the flexibility to accommodate the unique circumstances of different types of ships and changing maritime conditions. To include all factors influencing human decision making in traffic situations and to potentially incorporate seafarer experience, flexibility and seamanship into artificial intelligence will require machine learning, more advanced neural networks, and a massive amount of data.

Sammanfattning

Många akademiska artiklar föreslår olika lösningar på hur COLREGs kan implementeras i algoritmer, men parametrarna för att undvika närsituationer kan potentiellt skilja sig beroende på den använda algoritmen och dess inställningar. Effekterna och de potentiella konsekvenserna av en COLREG-algoritm i trafiksituationer för ett specifikt fartyg och resa är i stort sett okända utan en djup förståelse och testning av algoritmen. Denna rapport belyser den potentiella effekten av ett begränsat antal parametrar i en algoritm. Simuleringar indikerar att varianser i parametrarna och deras värden resulterar i olika åtgärder och att förutsägbarheten av autonoma fartyg i en trafiksituation kan vara dålig.

Eftersom det förväntas att autonoma fartyg behöver följa de befintliga COLREGs på grund av den blandade miljön med både bemannade och obemannade fartyg blir det avgörande att det finns tydliga och allmänt accepterade krav och standarder för autonoma fartyg. Dessa standarder behöver säkerställa att alla autonoma fartyg inte bara följer en gemensam uppsättning regler och algoritmer i trafiksituationer men också att sådana algoritmer speglar hur yrkesbefäl skulle hantera situationen.

Jämförelsen av spårmönster för autonoma respektive bemannade fartyg i de utförda simuleringarna är ett övertygande argument för benchmarking av trafikscenarier hanterade av autonoma fartyg med bemannade fartyg, där även simuleringar med kombinationer av bemannade och obemannade fartyg bör utföras. De "ordentliga" spårmönstren av bemannade fartyg kan också betraktas som ett vittnesbörd om styrkan och elegansen i COLREGs som rättsligt dokument, eftersom det effektivt balanserar behovet av en uppsättning tydliga, koncisa och universellt förstådda regler för att undvika kollisioner till sjöss, med flexibiliteten att ta hänsyn till de unika omständigheterna för olika typer av fartyg och förändrade förhållanden. Att inkludera alla faktorer som påverkar mänskligt beslutsfattande i trafiksituationer och att potentiellt införliva erfarenhet, flexibilitet och sjömanskap i artificiell intelligens kommer att kräva maskininlärning, mer avancerade neurala nätverk och en enorm mängd data.

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List of abbreviations

AIM	Advanced Intelligent Manoeuvring
AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
CATZOC	Categories of Zone of Confidence depicting the accuracy of data in an ENC
COLREG	International Regulations for Preventing Collisions at Sea, 1972
CPA	Closest Point of Approach
COG	Course over Ground
DIS	Distributed Interactive Simulations
ECDIS	Electronic Chart Display and Information System
ENC	Electronic Navigational Chart
FMBS	Full Mission Bridge Simulator
HDG	Heading
NM	Nautical Miles
NTPro	Wärtsilä's bridge simulator software Navi Trainer
OS	Own ship
OOW	Officer of the Watch
SA	Situation Awareness
SOG	Speed over Ground
STW	Speed through Water
TCPA	Time to Closest Point of Approach
TG	Target ship
UKC	Under Keel Clearance
VHF	Very High Frequency radio communication
WS	Workstation
XTD	Cross Track Distance

1 Introduction

Smart vessels and automated systems will require a reliance upon algorithm-based solutions that infer interpretations of the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs). Many academic papers suggest different solutions how the rules may be implemented in algorithms, but the parameters controlling how close quarters situations are avoided may potentially differ depending on the type of used algorithm and its settings. When tuning a collision avoidance algorithm for a specific ship and voyage, the effects and potential consequences are basically unknown without an in-depth understanding and testing of the algorithm.

The project "COLREG 2 - potential consequences of varying algorithms in traffic situations" builds on similar traffic situations handled by test persons in Lighthouse project "Operationalizing COLREGs in SMART ship navigation" (Weber, Aylward, MacKinnon, Lundh, & Hägg, 2022) but the situations will be handled purely by autonomous ships with different algorithms developed by Wärtsilä and SEAMADE. While, due to commercial reasons, Wärtsilä's algorithm is not explicitly described and full insight is not possible, the project will have control over the algorithm built by SEAMADE. Although Wärtsilä's algorithm is still under development and only to be used as part of their future decision support system Advanced Intelligent Manoeuvring (AIM) for manned ships, it is the only known system which allows experienced navigators to test and verify the algorithm in a realistic and familiar environment such as a high-fidelity simulator.

2 Background and existing research

During the last decade, there has been substantial research efforts to develop collision avoidance algorithms, motivated by the goal of autonomous or remote-controlled ships (Woerner K. , 2016, Woerner K. , Benjamin, Novitzky, & Leonard, 2016, Perera & Batalden, 2019, Ramos, Thieme, Utne, & Mosleh, 2020). These works (among others) have attempted to quantitatively evaluate and implement the subjective nature of the COLREGs through various approaches including optimization methods, reinforcement learning, fuzzy-logic, neural networks, and Bayesian networks (Woerner, Benjamin et al. 2019, Porres, Azimi et al., 2021).

As machine learning and more advanced neural networks are developed, the potential for collision avoidance systems will be further advanced. However, the application of Artificial Intelligence (AI) for autonomous vessels is still in its earliest stages because of the complexities of traffic situations which may be solved differently even given that the ships involved act according to the steering rules in the COLREGs (MacKinnon, Weber, Olindersson, & Lundh, 2020). A recent review paper for AI in collision avoidance systems identified that only 48% of the studies reviewed complied with the COLREGs, creating a gap between ongoing research and the requirements of regulatory frameworks (Porres, et al., 2021).

As the COLREGs are written primarily for human operators, they are difficult to quantify and open to some interpretation which makes the evaluation of traffic situations challenging (Woerner K. , Benjamin, M, & Leonard, 2019). However, the underlying assumption in most existing research exploring remote and autonomous ships expect that the challenging questions of how to incorporate seafarer experience, and seamanship, into artificial intelligence will be solved eventually (Ramos, Utne, & Mosleh, 2019, Ramos, Thieme, Utne, & Mosleh, 2020). Another complicating factor for developing and evaluating algorithms for COLREGs may be the disconnect between the experienced navigator and the designers of algorithms, who rarely have the experience of numerous traffic situations and how the COLREGs are applied (Woerner K. , 2016) or even lack the understanding of the COLREG term "seamanship" altogether (Wróbel, Gil, Huang, & Wawruch, 2022). As virtually all academic papers are on a higher theoretical level and do not allow experienced mariners to test and verify the proposed algorithms in a realistic and familiar environment such as a high-fidelity simulator, this contributes to the disconnect between developers and practitioners.

Testing methods of algorithms have been proposed by among other Bolbot (Bolbot, Gkerekos, Theotokatos, & Boulougouris, 2022), Pedersen (Pedersen, o.a., 2020) and Minne (Minne, 2017) but are limited by the selection of criteria/rules, the navigational risk metrics and encounter geometries chosen among possible traffic scenarios. Also, they lack a verification on how human operators would solve the situation. Considering that it is initially expected that autonomous ships will need to follow the existing COLREGs due to the mixed environment of both manned and un-manned ships (Perera & Batalden, 2019), solutions derived by algorithms may be different from and possibly conflicting with solutions by human operators.

3 Purpose and research question

Many academic papers suggest different solutions how the rules may be implemented in algorithms, but the parameters controlling how close quarters situations are avoided may potentially differ depending on the type of used algorithm and its settings. As the effect of varying parameters and settings are basically unknown, the purpose of this project aims to provide input for a framework for developing and verifying collision avoidance functionality in autonomous navigation systems, and gives examples of potential consequences in traffic situations involving autonomous ships by:

- Identifying parameters/settings in algorithms for autonomous ships, which will influence the manoeuver of autonomous ships in traffic situations with a risk of collision.

- Illustrating the possible consequences in terms of executed avoiding manoeuvers in traffic situations with autonomous ships having different parameter settings.
- Illustrating, comparing and contrasting traffic situations handled by human operators and algorithms.

The overall research questions are:

- What are the possible effects of certain settings in a COLREG algorithm used on an autonomous ship?
- What is the combined effect and their potential consequences in traffic situations involving autonomous ships with different COLREG algorithms?
- How can COLREG algorithms be tested?

4 Methodology

To be able to provide an input from a navigator's perspective on some of the required capabilities of a COLREG algorithm for autonomous ships, the methodology was to:

1. Define basic COLREG scenarios to gain an understanding of the algorithms used and the effect of a limited number of settings.
2. Simulate the scenarios as defined in point 1.
3. Review and analyse the result of the basic simulations.
4. Define the scenarios for autonomous ships to be compared with human operators.
5. Simulate the scenarios with different parameters and algorithms (SHIPMAN and AIM).
6. Review and analyse the result of the simulations.
7. Review and summarize major findings.

5 Limitation

Considering that an algorithm for autonomous ships must not exclusively be based on a sophisticated automated sensor system alone but also on a decision and control system (Burmeister H.-C. , Constapel, Ugé, & Jahn, 2020), it is obvious that there are numerous parameters and settings which will have an influence on the manoeuver of autonomous ships involved in traffic situations with a risk of collision. Other parameters such as the number of ships involved, the geographic location, the ship's manoeuvring characteristics, the influence of wind, weather, sea state and visibility etc. add to the potential complexity of traffic situations. Within this project only a limited numbers of sensors/parameters were evaluated, and all simulations were performed with a limited number of ships in calm conditions and good visibility. Investigating the possible effect of all parameters including combinations of parameters and settings is likely extremely laborious and beyond the scope of this research project.

As AIM is the only known system which allows navigators to test and verify their algorithm in a realistic and familiar environment, such as a high-fidelity simulator, most findings are based on simulations using Wärtsilä's algorithm. However, the findings are generally applicable and serve as an input to the required capabilities of algorithms for autonomous ships.

6 Selection of input parameters influencing the executed manoeuvre of an autonomous ship

As stated in the COLREGs, there are numerous factors an Officer on Watch (OOW) needs to consider when ascertaining the risk of collision in a traffic situation. While installed sensors may act as proxies for the human lookout and the OOW (Burmeister H.-C. , Constapel, Ugé, & Jahn, 2020), an autonomous decision system will need to be able to reflect not only the interpretation of the COLREGs themselves but also many other elements which will influence the decision made by a human operator (MacKinnon, Weber, Olindersson, & Lundh, 2020). As navigators often apply their experience when interpreting the Rules, its vagueness is difficult to codify into exact values (Wróbel, Gil, Huang, & Wawruch, 2022) and even using fuzzy-logic to capture and define the vagueness is often highly debatable as it makes verifiability and testability of these systems challenging (Constaple, Koch, & Burmeister, 2022).

For the purpose of this project only a limited number of parameters and settings of an algorithm and their possible effect on a traffic situation were investigated:

1. The triggers for activating the avoiding manoeuver such as detection, distance/Time to Closest Point of Approach (TCPA).
2. The safe distance i.e., the Safety Domain.
3. The potential influence of shallow/non navigational areas and navigational marks.
4. The possible influence of the monitored route on notably path planning algorithms.
5. The mathematical ship model.

6.1 Triggering collision avoidance

6.1.1 Detection, Distance, CPA and TCPA

On manned ships, ascertaining the risk of collision or close quarters situations is mainly achieved by visual bearings, radar/ARPA complemented by AIS information. Simply enough, a steady or nearly steady bearing involves a risk of collision. Using ARPA (and AIS) will give the Officer on Watch (OOW) among others the Closest Point of Approach (CPA) and the Time to CPA (TCPA), which needs to be evaluated as being safe or not safe depending on the specific circumstances and possibly company policies. That assessment can be done at any distance covered by the line of sight or radar/AIS range bearing in mind that the "quality" of the data at long range may be scanty and that the TCPA and CPA values are calculated, based on that the own ship and the target ship both keep their current course and speed. The time the OOW on a give-way vessel acts depends in turn on a number of dynamic factors such as:

- The CPA/TCPA depending on the traffic density, e.g., in dense traffic CPAs may need to be reduced to a still acceptable level, in open ocean passages with few ships, CPAs may be increased as there is no point in passing close to another ship. To safely quantify the terms may even be impossible (Hannaford, Maes, & van Hassel, 2021).
- The environmental conditions: In bad weather and heavy seas, the action may likely be taken much earlier at a far larger distance, basically even beyond the range where the COLREGs are applicable. That range in turn is not clearly defined and depends on the circumstances (Cockcroft & Lameijer, 2011). The visibility in turn is crucial as different steering rules apply, compared with good visibility. In general, weather effects may also degrade sensor performances and decrease the accuracy of the CPA obtained by ARPA and therefore an additional safety margin may be added.
- The monitored route: examples of how the monitored route may influence the decision taken by the OOW are shown in section 8.4.
- If and/or by how much a deviation from the route is safe with regard to the proximity of any navigational hazards such as shallow waters.
- The particulars of the other ship, i.e., a different manoeuvre may be made when encountering a fishing boat compared to a large crude oil tanker.

Regardless of the above-mentioned factors, the action of a give-way vessel must, according to COLREG Rule 8, *"be positive, made in ample time and with due regard to the observance of good seamanship"* (IMO, 1972). The challenge is that the COLREGs are not value specific and clearly depend on individual interpretation and the context of the situation (MacKinnon, Weber, Olindersson, & Lundh, 2020).

Considering the actions of a stand-on vessel, such ship is to keep her course and speed but may take action as soon as it becomes apparent that the give-way vessel is not taking appropriate actions. It is not unless the situation cannot be solved by the action of the give-way vessel alone that the stand-on vessel is obliged to act (Rule 17).. The difficulty is for the stand-on vessel to determine when it becomes compulsory for her to take action (Cockcroft & Lameijer, 2011). However, it can be assumed that any action taken by a stand-on vessel under Rule 17 will likely be later and at a shorter distance compared to the same ship being in a give-way situation.

6.1.2 Safety Domain

The result of the action taken by ships to avoid a collision shall be such as to pass at a safe distance (Rule 8 d). However, such distance is not defined quantitatively and depends on at least the following factors:

- Type of traffic encounter (i.e., crossing, head-on or overtaking)
- Being stand-on or give-way vessel
- Geographical area including vicinity of land and/or shallow areas
- Traffic density and complexity of the traffic situation
- Environmental conditions (wind, sea state, visibility, etc.) affecting the maneuverability of the own ship
- Type, size and particulars of the ships involved
- The navigational state of the ships involved e.g., restricted in the ability to manoeuver
- Sensor data accuracy and reliability (e.g., radar, AIS)
- The familiarity/experience of the navigator with the area and traffic situation
- Prediction of other ships probable behaviour

The term ship (or safety) domain was used for the first time in the 1970's and defined as the area around the own ship not to be infringed by other ships and/or objects (Hörteborn, Ringsberg, Svanberg, & Holm, 2018). Since then, various attempts were made and are being made to measure and define the size and shape of such domain either by, or a combination of, empirical data from past observations of traffic encounters, expert knowledge judging what is deemed to be safe, or AIS data analysis of present traffic encounters (Fiskin, Nasiboglu, & Yardimci, 2020). The shape and size of these domains and factors considered when determining various safety domain models are described and compared in Fiskin's paper (2020).

The ship domain concept has been used in either performing a maritime risk assessment for e.g., a waterway using AIS data comparing actual distances between encountering ships with an empirical safety domain (Szlapczynski & Szlapczynska, 2021), the logic being that if there are more domain encounters then more collisions must be expected. Examples of AIS data derived safety domains for a number of areas in the Baltic Sea area were presented by Hansen et al. (2013) and Hörteborn et al. (2018). However, there is no universal ship domain that is applicable to all cases and most existing studies are limited to small areas (Rawson & Brito, 2021).

The ship domain model is also frequently used to develop collision avoidance decision support systems (Szlapczcynski & Szlapczynska, 2021) with applications for both give-way vessels and stand-on vessels (Szlapczynski, Przemyslaw, & Szlapczynska, 2018) where in both cases a decentralized elliptical shape is used as the safety domain. Other studies used the safety domain concept to identify collision risk hot spots in a limited and geographically well-defined area (Kezhong, Zhitao, Xuri, Jinfen, & Weiqiang, 2021) which is conceivably not applicable for other areas. However, few studies have been found addressing the implication and effects of encounters between autonomous ships representing "the plethora of proposed domain shapes and sizes" (Rawson & Brito, 2021) and if in these encounters the COLREGs are correctly applied.

6.2 Using AIS data to develop algorithms

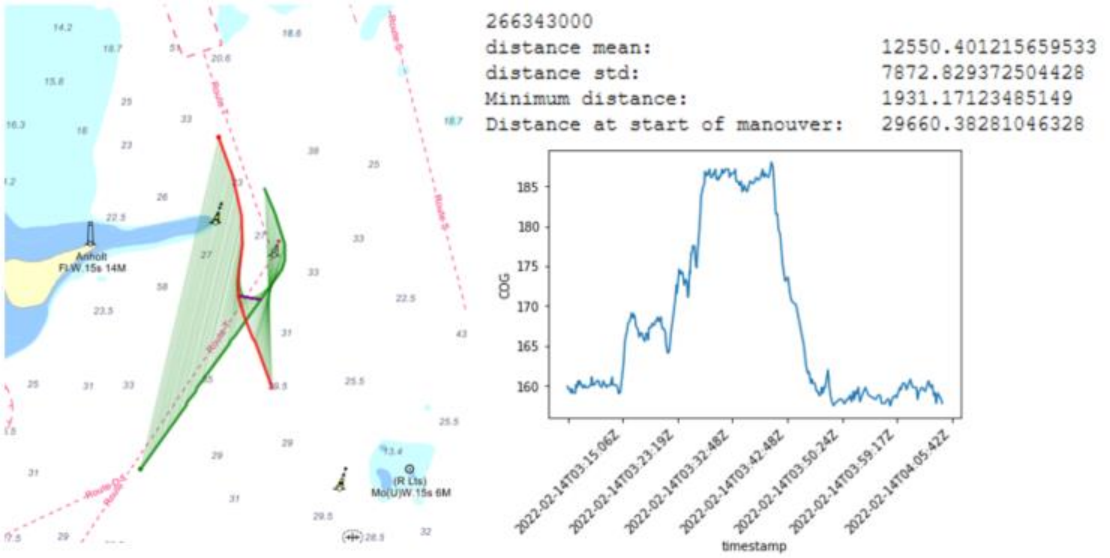
To model the ship behaviour, it is often suggested to make use of AIS data of real world traffic situations to accurately analyze manoeuvring aspects which are relevant for collision avoidance (Vestre, Bakdi, Vanem, & Engelhardtsen, 2021) and/or to build regional deep learning frameworks for trajectory prediction and collision risk detection (Murray, 2021, van Westrenen & Baldauf, 2019). It has also been suggested that AIS data may be used to identify and characterize situations where navigators deviate from the COLREGs and that this data may be used to design how AI may handle these situations (Madsen, Aarset, & Alsos, 2022).

However, using AIS data alone may have several pitfalls.

1. The data does not reflect the environmental conditions such as wind and waves, the visibility, the manoeuvring characteristics of the ship, other ships not sending AIS data, the competency of the navigators, possible VHF conversations etc. which may all be major factors in the outcome of traffic situations.
2. Erroneous AIS data may lead to an incorrect assessment of a COLREG situation (Engler, Banys, Engler, Baldauf, & Torres, 2021).
3. A safety domain of a ship based on AIS data from real ship encounters does not give any indication of when/at what distance ships in a collision situation took action nor what this action encompassed. It simply depicts the "final" stage of an encounter. Few studies address real-world close quarters situations and when and at what distance ships take action. AIS data may be used but this data has the disadvantage that it does not give any indication about the monitored route, the weather, visibility and sea

state conditions, other ships without AIS in the vicinity, etc. Analysis of real collision avoidance manoeuvers, based on AIS transmissions from 13 days covering the Norwegian exclusive economic zone, identifies that the TCPA mean value of ships taking action ranges between about 18 to about 20 minutes in overtaking crossing and head-on situations and result in a mean passing distance of about 1.2 km (0.6 NM) (Vestre, Bakdi, Vanem, & Engelhardtsen, 2021). However, the study also showed a large distribution of the data, indicating that there is a big variance in both CPA and distance when ships initiate their manoeuver.

In the case of complex traffic scenarios with more than 2 ships involved or generally dense traffic it may even be unclear as to which target ship the action taken by one ship really applies. Analysis of AIS data at the Anholt junction illustrates the challenges when using AIS data where an isolated situation between 2 ships may be easily analyzed (Figure 1) but where multiple ship encounters pose a serious challenge to determine which action on which ship at which distance was taken for which other ship (Figure 2) making it extremely challenging to analyze AIS data. Adding ships to the scenery which do not necessarily broadcast any AIS, such as sailing boats, may lead to other incorrect conclusions.



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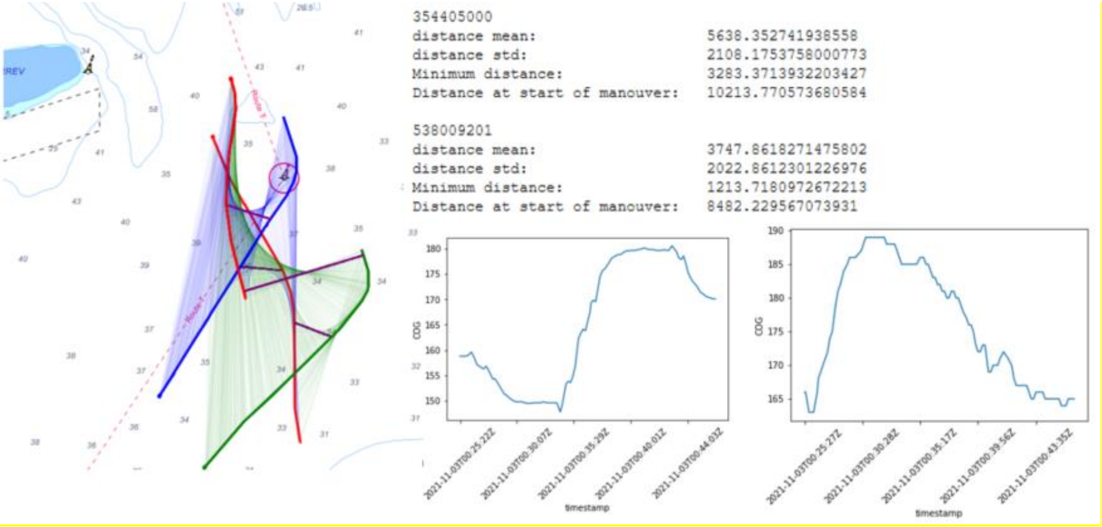
266343000
distance mean:                     12550.401215659533
distance std:                      7872.829372504428
Minimum distance:                  1931.17123485149
Distance at start of manouver:     29660.38281046328
```

Figure 1 Simple traffic situation between at Anholt junction



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354405000
distance mean:                    5638.352741938558
distance std:                     2108.1753758000773
Minimum distance:                 3283.3713932203427
Distance at start of manouver:    10213.770573680584

538009201
distance mean:                    3747.8618271475802
distance std:                     2022.8612301226976
Minimum distance:                 1213.7180972672213
Distance at start of manouver:    8482.229567073931
```

Figure 2 Complex traffic situation at Anholt junction

4. To indiscriminately use real AIS data and assume that autonomous ships should behave in an equal way may also disregard the possibility that the AIS based "normal behaviour" may not be safe in principle and that COLREG rules may be breached. Although the COLREGS in Rule 2 allow a departure from the rules, not all deviations are necessarily based on "*due regard shall be had to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved, which may make a departure from these Rules necessary to avoid immediate danger*".

6.3 Algorithmic decision making based on live AIS and Target Tracking data

As the COLREGs are based on the ship's heading (HDG) and Speed through Water (STW), developers need to make sure that the algorithm is calculating with these values and that using Course over Ground (COG) and Speed over Ground (SOG) may result in an incorrect application of the rules. In academic papers most approaches rely on AIS, radar and ARPA data (with a preference on AIS data). However, the broadcasted AIS information is SOG, COG and HDG, and an ARPA radar may use either SOG or STW. The effect of using different data sources on the application of the COLREGs is particularly noticeable in areas affected by current. As an example, a head on situation using STW and HDG may be interpreted as a crossing situation when using COG and SOG (Figure 3 COLREG speed and heading sourcesFigure 3).

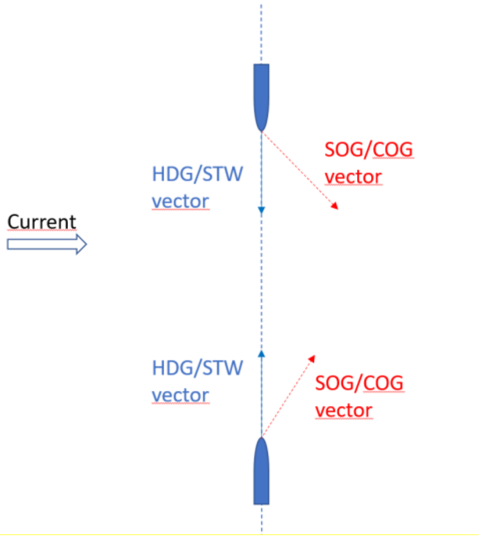


Figure 3 COLREG speed and heading sources

Both ARPA and AIS data also suffer from inherent accuracy issues in calculation of the CPA. The performance standard for ARPA states that the equipment must fulfill a Tracked Target Accuracy (95% probability) for the CPA of 0.3 NM but acknowledge that such accuracy may be significantly reduced by the own ship's motion and manoeuvre of the target (IMO, 2004). AIS data in turn are dependent on GNSS positioning and a correct set Common Consistent Reference Point (CCRP) (and possibly further equipment configuration concerning sensor input), which may lead to a misevaluation of the collision risk and even make it impossible to identify an existing collision risk if only relying on CPA/TCPA warnings (Engler, Banys, Engler, Baldauf, & Torres, 2021).

However, in most papers the reliability and accuracy of sensors were tacitly assumed to be in perfect operation (Wróbel, Gil, Huang, & Wawruch, 2022). According to Burmeister et.al (2021), only the paper by Kufoalor et al. (2019) identified and considered sensor uncertainties where the authors also concluded that the AIS data was not always accurate in their tests, possibly due to significant AIS signal delays, especially when the obstacles were maneuvering (Kufoalor, Wilthil, Hagen, Brekke, & Johansen, 2019). In good visibility navigators rely not only on data from the ARPA but also on a visual observation of the target and can rapidly detect if a target alters course but only 2 papers included camera sensors (Burmeister & Constapel, 2021). AIS and radar data typically lag, and smaller course changes might not be notable depending on the angle of observation and distance to the target ship. Cross referencing of target detection systems using AIS and radar with visually observed data is needed.

6.4 Decision making based on sensor perception

Adhering to the COLREG regulations by relying solely on AIS and radar target tracking is clearly insufficient. Other sensors will be required to act as proxies for the human lookout and the OOW (Burmeister H.-C. , Constapel, Ugé, & Jahn, 2020) as the COLREGs encompass various signals such as sound, day, and navigation lights, which play a crucial role in collision avoidance and maneuvering of ships. Without a human operator in the loop, to include the additional information of visual- and sound-signals to the decision-making process, important information may be missed. To overcome this, ships must be equipped with sensors such as e.g., cameras and microphones with processing algorithms to gather relevant information from the environment. Creating a digital representation of the surroundings presents significant challenges, as noted in the Lighthouse study "Nya Senorer – autonom säkerhet" (Rylander, Sandberg, Sjöblom, & Benderius, 2021). The report highlights among others the need to choose camera performance based on the smallest target to be recognized at a given operational distance. Additionally, determining a ship's navigational state, such as "not under command" and the interpretation of blinking lights can be challenging to detect through perception sensors.

7 Simulators and algorithms used

7.1 Wärtsilä NTPro

Most of the simulations in this project were performed with Wärtsilä NTPro 5000 simulator and 3 separate workstations (WS) enabling uploaded ship models to run autonomously using Wärtsilä's Advanced Intelligent Manoeuvring (AIM) software.

7.1.1 Wärtsilä Advanced Intelligent Manoeuvring AIM

This project performed numerous simulations using Wärtsilä's Advance Intelligent Manoeuvring (AIM) software, which essentially is a decision support tool requiring the user to accept a suggested manoeuver before it is executed. However, it also included the possibility to run ships with "automatic manoeuver acceptance" making it possible to simulate traffic scenarios with autonomous ships but it must be emphasized that AIM is not (yet) intended to be used in automatic mode. The software is still under development and due to commercial reasons, Wärtsilä's algorithm is not explicitly described. In general terms and according to the developers at Wärtsilä (2022), the algorithms are based on

- A mathematical hydrodynamic model of the Own Ship (OS) representing the manoeuvring capability of the ship,
- Nautical chart data (bathymetric data, navigational marks, etc. from ENC),
- The operator set Safety Depth/Contour
- The OS monitored route
- ARPA
- AIS information from target ships (TG)

The triggers to calculate and execute a manoeuver in automatic mode were based on:

- The operator’s setting of the Safety Domain
- The operator’s setting of the TCPA

AIM evaluates collisions and searches for manoeuvres based on the safety domain and TCPA only. The link between CPA and the safety domain will according to Wärtsilä be implemented in the near future (Wärtsilä, 2022).

Due to technical reasons ARPA/ radar data could not be integrated in the AIM workstations. However, as there was no wind or current in the simulation scenarios, AIS data was considered as being acceptable although not compliant with the COLREGs.

7.2 SHIPMAN

SHIPMAN is a time domain simulation program developed by SEAMADE for representation of ship motions in open sea as well as in confined waters. The program allows, in the present version, up to three vessels to be simulated simultaneously. All three ships are dynamically modelled with mathematical models as briefly described below:

Four degrees of freedom

The model comprises four degrees of freedom: surge, sway, roll and yaw. Each degree of freedom is represented by a force/moment equation with mass and acceleration on one side of the equation and all the forces acting on the ship on the other side.

Forces considered in the mathematical model are:

- Resistance, based on hull form, speed and water depth
- Hull forces in sway, roll and yaw motions, based on hull form, speed and water depth
- Rudder forces based on speed, propeller thrust, rudder engine characteristics and water depth
- Propeller thrust with consideration to propeller characteristics (diameter, pitch ratio propeller rate etc.) and engine limitations.
- Wind forces based on wind velocity and ship specific wind coefficients
- Side bank effects

7.2.1 SHIPMAN algorithm for COLREGs

The desktop simulator SHIPMAN allows up to three autonomous vessels to be simulated simultaneously, each of them controlled by a track-keeping algorithm and algorithms for representation of the basic COLREG steering rules (crossing, meeting and overtaking) in good visibility. A more detailed description is available in research report “Simulator based risk identification for autonomous shipping” (RISE, 2022).

In principle, the COLREG algorithm is a basic reactive algorithm, meaning that the identification of a risk of collision and selection of applicable steering rule are based on the operator's set distance between the ships and the operator's defined navigable water. A simplified description of the rules is given below.

Crossing

In crossing situations, the algorithm will steer the ship towards a point astern of the stand-on vessel. This point is defined by the operator. If there are limits in navigable waters and the manoeuver cannot be performed, the ship will slow down instead.

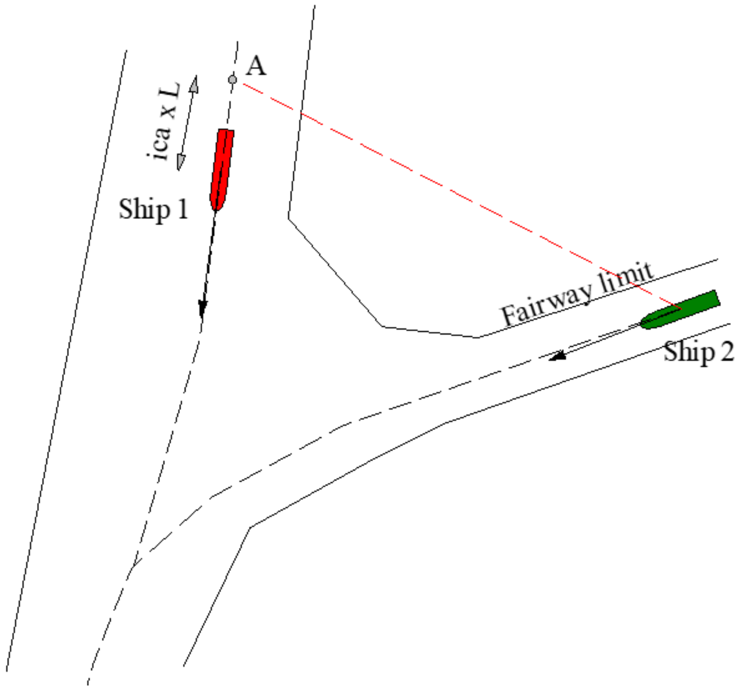


Figure 4 SHIPMAN: Crossing situations with fairway limits

In the scenario depicted in Figure 4, Ship 2 cannot, due to the fairway limitation on the starboard side, directly change course towards point A behind Ship 1. Instead, it will reduce speed and eventually, when the fairway limits allow, turn to starboard behind Ship 1.

Meeting

In meeting situations, the algorithm will deviate the ship to starboard of its monitored track (or the meeting ship if this is closer) by an operator set distance (Figure 5) and will return to its track once the other ship is abeam.

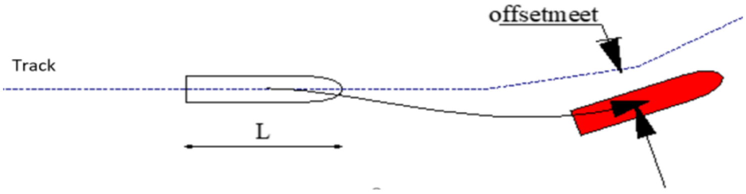


Figure 5 SHIPMAN: meeting

<u>Overtaking</u>

In open waters, overtaking takes place on the overtaken vessel's starboard side and the overtaking vessel deviates with a heading change of 10° to pass the overtaken vessel at an operator set lateral distance. If there is not sufficient clearance to overtake on that side i.e., due to shallow waters, the other side is chosen (Figure 6).

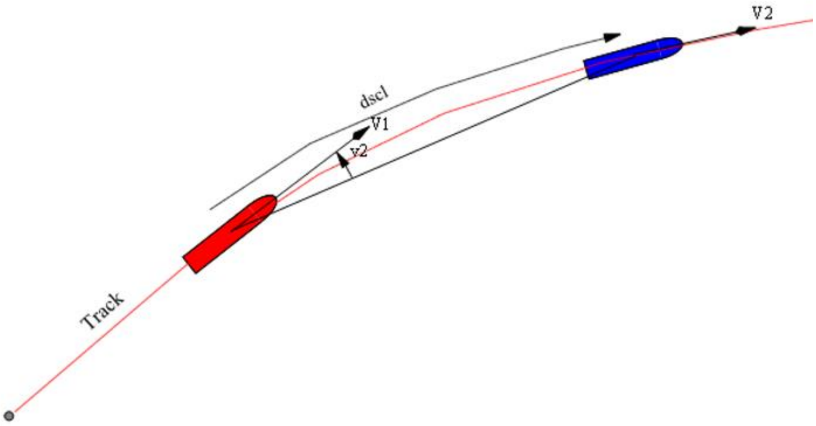


Figure 6 SHIPMAN: overtaking

<u>Stand-on vessels</u>

Stand-on vessels using SEAMADE algorithm keep their course and speed.

7.2.2 Common Scenarios

To enable the exchange of data between different simulation software i.e., Wärtsiläs Full Mission NTPro 5000 simulator and SEAMADE's SHIPMAN application, the standard for DIS (IEEE Std 1278.1-1995) protocol was used for communicating essential data.

8 Result of traffic scenarios involving 2 ships

Even if only two ships are involved in a situation with the risk of collision, there is virtually an unlimited number of traffic scenarios possible. Using different algorithms, ship models, variances in the relative approaches between ships in crossing, overtaking and meeting situations, differences in speeds, proximity of shallow waters, monitored routes, etc. may provide different and potentially additional results.

To obtain insight in the effects and potential consequences of algorithms and their parameters in 2 ships traffic situations basic COLREG scenarios were simulated according to Table 1.

Table 1 Two ship scenarios overview

Potential influence of input parameter	Use case	Goal
TCPA	Crossing situation at Anholt (coastal navigation)	Highlighting possible actions by autonomous vessel depending on TCPA
Safety Domain and TCPA in crossing situations	Open sea crossing situation	Highlighting possible actions by autonomous vessel depending on the size of the Safety Domain
Safety Domain and TCPA in overtaking situations	Open sea crossing situation	Highlighting possible actions by autonomous vessel depending on the size of the Safety Domain
Safety Domain and TCPA in meeting situations	Open sea crossing situation	Highlighting possible actions by autonomous vessel depending on the size of the Safety Domain
Restricted navigable water in meeting situation	Meeting situation with shallow water	Highlighting the challenges in "not running aground" vs. "not collide"
Navigational marks	Crossing situation at Anholt (coastal navigation)	Highlighting the challenges differing

		navigational marks and vessels
Monitored route of give-way vessel	Open sea overtaking situation	Highlighting the potential influence of the monitored route on the action taken by the give-way vessel
Monitored route of stand-on vessel	Crossing situation at Anholt (coastal navigation)	Highlighting the potential influence of the monitored route on the action taken by the stand-on vessel
Path planning algorithms	Crossing situation at Anholt (coastal navigation) Meeting situation Halland (coastal navigation)	Highlighting how path planning algorithms may trigger unwanted COLREG situations and/or not recognise a COLREG situation
Underactuated ships	Meeting/Crossing situation Anholt (coastal navigation)	Highlighting the possible consequences of underactuated ships

The results in this section are primarily based on simulations using a path planning algorithm developed by Wärtsilä, and serve to highlight some of the challenges in codifying the COLREGs. However, it is also believed that many of the findings and suggestions in this section are directly applicable for any type of algorithm for autonomous ships.

8.1 The effect of varying TCPA

As explained in 6.1.1, the action and manoeuvre required to avoid a collision is time dependent and may vary. In principle, the earlier a manoeuvre by a give-way vessel is performed, the lesser course and or speed changes are required to pass at a safe distance. To follow COLREG Rule 8 and take action in *"ample time"*, algorithms need to either be triggered by a distance or by the TCPA and decide on the safest manoeuver to avoid a collision. In addition, COLREG Rule 8 states that the change of course for collision avoidance must be clearly shown to the stand-on vessel. To illustrate the effect of the TCPA setting on the suggested action by the algorithm used in AIM, a traffic scenario involving 3 ships was run in manual mode (i.e., no automatic execution of a suggested manoeuvre) with TCPA settings of 18, 12, 6 and 3 minutes. The default suggested action (i.e., the action which would be performed in automatic mode) of the SW bound ship being in a give-way situation, provided that the other ships involved kept their course and speed is, depicted in Figure 7, Figure 8, Figure 9 and Figure 10. Note that the suggested action was likely also influenced by the navigational mark, as it was indicated as a dangerous object. The potential influence of navigational marks is further described in 8.3.2.

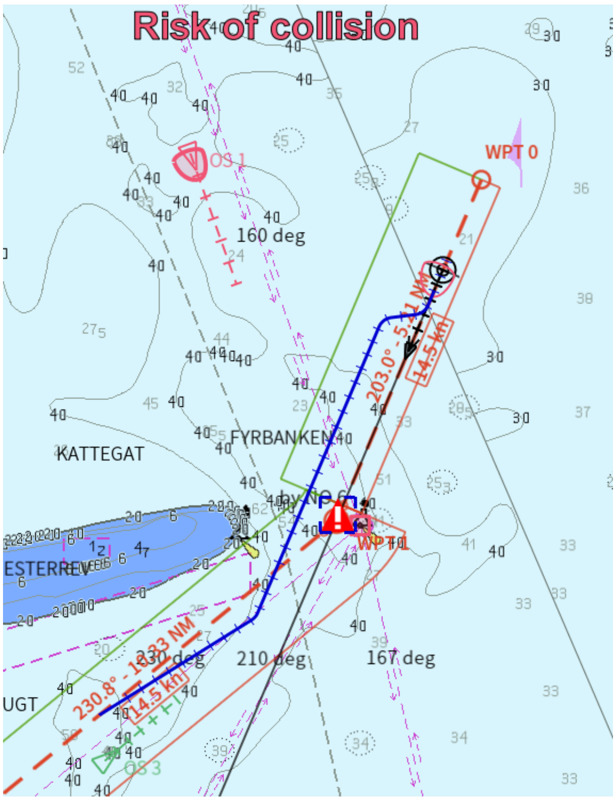


Figure 7 TCPA setting 18 minutes

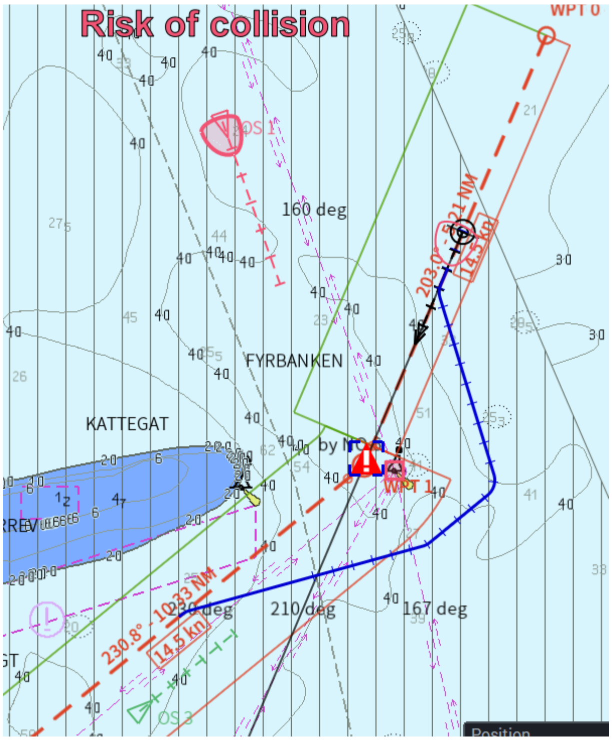


Figure 8 TCPA setting 12 minutes

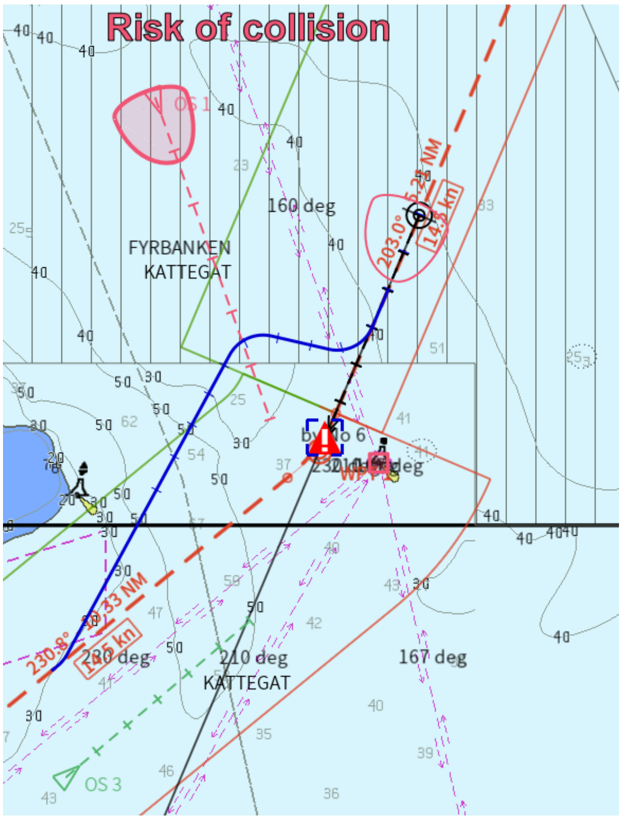


Figure 9 TCPA setting 6 minutes

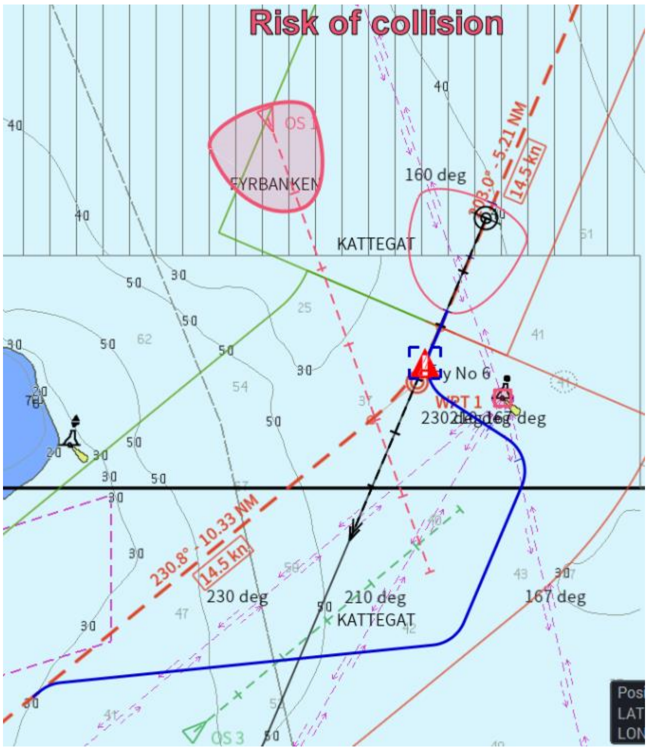
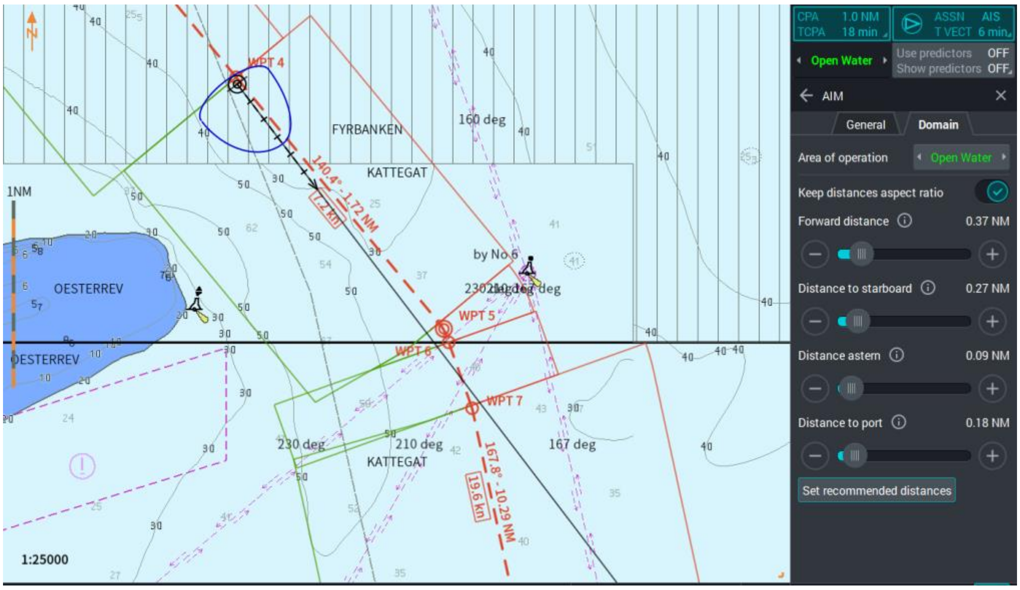


Figure 10 TCPA setting 3 minutes

The shown variability of the suggested manoeuvres and dependency on the set TCPA is rather obvious. What may be more surprising is that the suggested actions are not consistent i.e., same type of manoeuvre which in turn results in poor predictability of traffic situations involving autonomous ships with different TCPA settings.

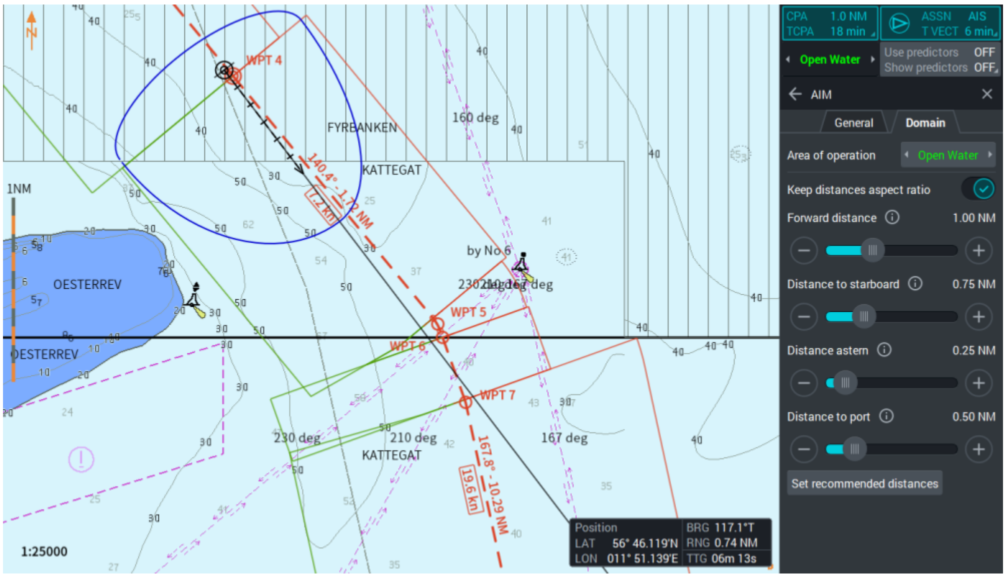
8.2 The effect of varying Safety Domains on avoiding collision manoeuvers

As there is no universal ship domain and that the domain may even vary depending on factors described in 6.1.2, it is difficult to envisage what may happen if autonomous ships using different safety domains are involved in a traffic situation. The ship domain used in AIM was of a decentralized somewhat elliptical shape with, either different default configurations depending on area chosen (open water, port or heavy traffic) derived from real data (AIS) from various geographic areas and applicable for various ship types (Wärtsilä, 2022), or operator own dimensions settings (Figure 11 and Figure 12).



CPA 1.0 NM
TCPA 18 min
ASSN AIS
T VECT 6 min
Open Water
Use predictors OFF
Show predictors OFF
Area of operation: Open Water
Keep distances aspect ratio ✓
Forward distance 0.37 NM
Distance to starboard 0.27 NM
Distance astern 0.09 NM
Distance to port 0.18 NM
Set recommended distances

Figure 11 AIM: Safety Domain Default setting for open water



CPA 1.0 NM
TCPA 18 min
ASSN AIS
T VECT 6 min
Open Water
Use predictors OFF
Show predictors OFF
Area of operation: Open Water
Keep distances aspect ratio ✓
Forward distance 1.00 NM
Distance to starboard 0.75 NM
Distance astern 0.25 NM
Distance to port 0.50 NM
Set recommended distances

Position
LAT 56° 46.119'N
LON 011° 51.139'E
BRG 117.1°T
RNG 0.74 NM
TTG 06m 13s

Figure 12 AIM: Safety Domain operator own settings

8.2.1 Open sea crossing situations 2 ships

Four performed simulations illustrate the effect of the Safety Domain parameters in an open sea crossing situation. All simulations used a TCPA setting of 12 minutes. The goal of the simulation was to illustrate the dependency of the size of the course change of the give-way vessel, in relation to the Safety Domain and the relationship of the Safety Domain of the stand-on vessel and its potential action.

8.2.1.1 Example 1: Default Safety Domain settings

Table 2 Crossing simulation 1: Safety Domain setting

Ship model used		Safety Domain setting (in NM) Recommended setting in AIM		
OS 1 (red track)	OS 2 (green track)		OS 1	OS 2
Feeder	Chemical tanker	Forward	0.37	0.39
Speed 20 knots	Speed 14.5 knots	Starboard	0.27	0.29
		Astern	0.09	0.1
		Port	0.18	0.19

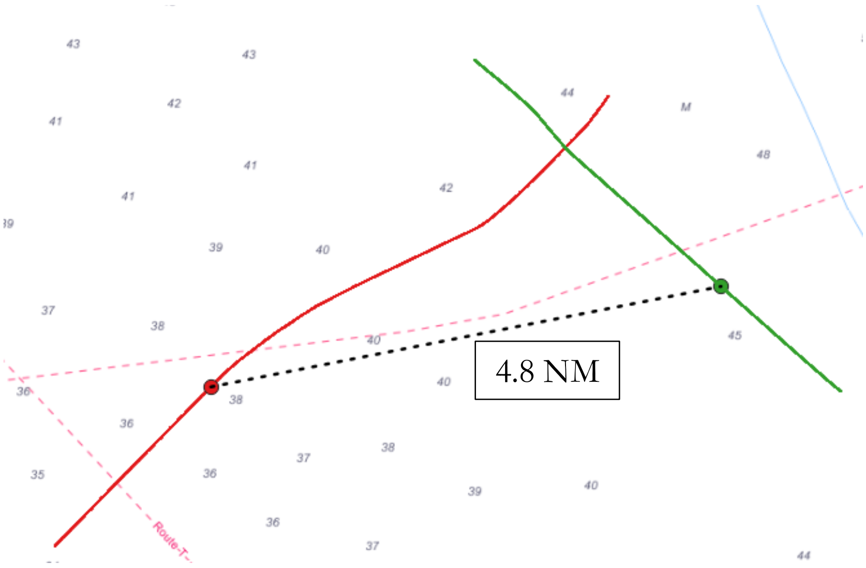


Figure 13 2 OS Crossing with recommended domain settings

The position when OS 1 executes the manoeuvre and the corresponding position for OS 2 are indicated by the red and green dots (Figure 13).

8.2.1.2 Example 2: Crossing with user defined equal Safety Domain settings

Table 3 Crossing simulation 2: Safety Domain settings

Ship model used		Safety Domain setting (in NM) User setting		
OS 1 (red track)	OS 2 (green track)		OS 1	OS 2
Feeder	Chemical tanker	Forward	1.0	1.0
Speed 20 knots	Speed 14.5 knots	Starboard	0.75	0.75
		Astern	0.25	0.25
		Port	0.5	0.5

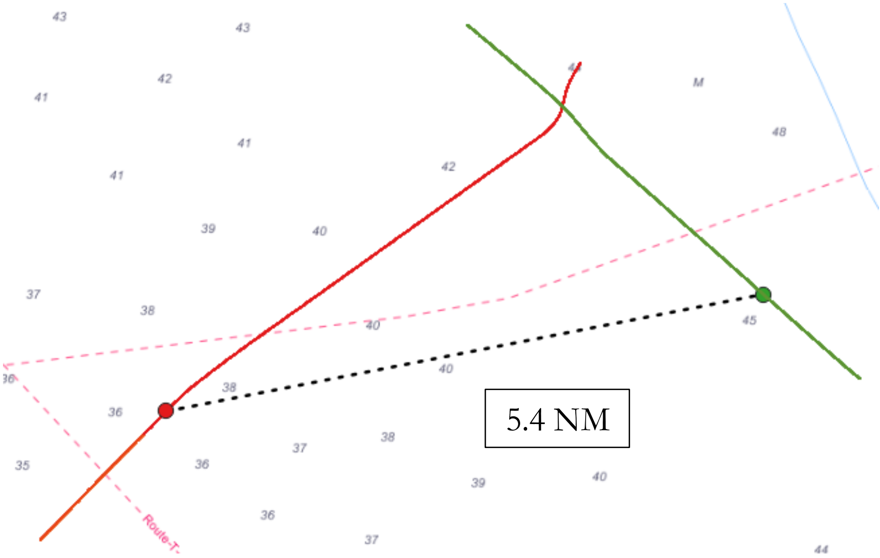


Figure 14 2 OS Crossing with larger domain settings

The position when OS 1 executes the manoeuvre and the corresponding position for OS 2 are indicated by the red and green dots (Figure 14).

8.2.1.3 Example 3: Crossing with user defined settings and different Safety Domains

Table 4 Crossing simulation 3: Safety Domain settings

Ship model used		Safety Domain setting (in NM) User setting		
OS 1 (red track)	OS 2 (green track)		OS 1	OS 2
Feeder	Chemical tanker	Forward	1.0	2.0
Speed 20 knots	Speed 14.5 knots	Starboard	0.75	1.5
		Astern	0.25	0.5
		Port	0.5	1

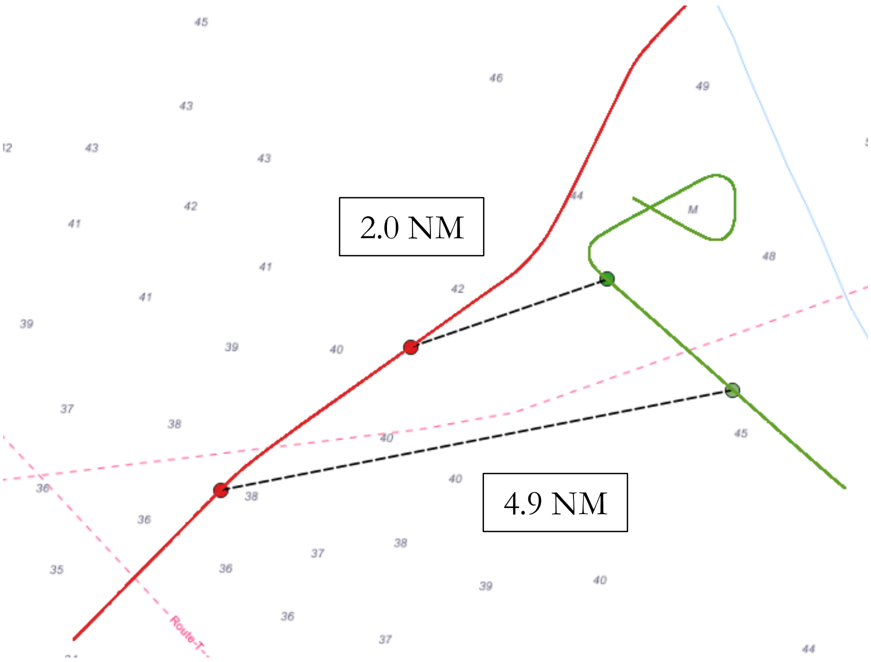


Figure 15 2 OS Crossing with different domain settings

The position when OS 1 and OS 2 execute course changes and the corresponding position for OS 2 and OS 1 are indicated by the red and green dots (Figure 15).

8.2.1.4 Example 4: “Crossing ahead or not” using different user defined Safety Domain settings

In a crossing situation, a give-way vessel is to avoid crossing ahead of the stand-on vessel. However, there are often situations where the OOW needs to decide whether there is a risk of collision at all e.g., it may be considered safe to pass ahead of another ship at a distance of 1 NM (bow crossing distance, BCR). To investigate such an effect with an algorithm based on a Safety Domain, a crossing scenario with a BCR of 0.5 NM at the start was executed.

Table 5 Crossing simulation 4: Safety Domain settings

Ship model used		Safety Domain setting (in NM) User setting		
OS 1 (red track)	OS 2 (green track)		OS 1	OS 2
Feeder	Chemical tanker	Forward	0.37	1.0
Speed 20 knots	Speed 14.5 knots	Starboard	0.27	1.0
		Astern	0.09	0.33
		Port	0.18	0.67

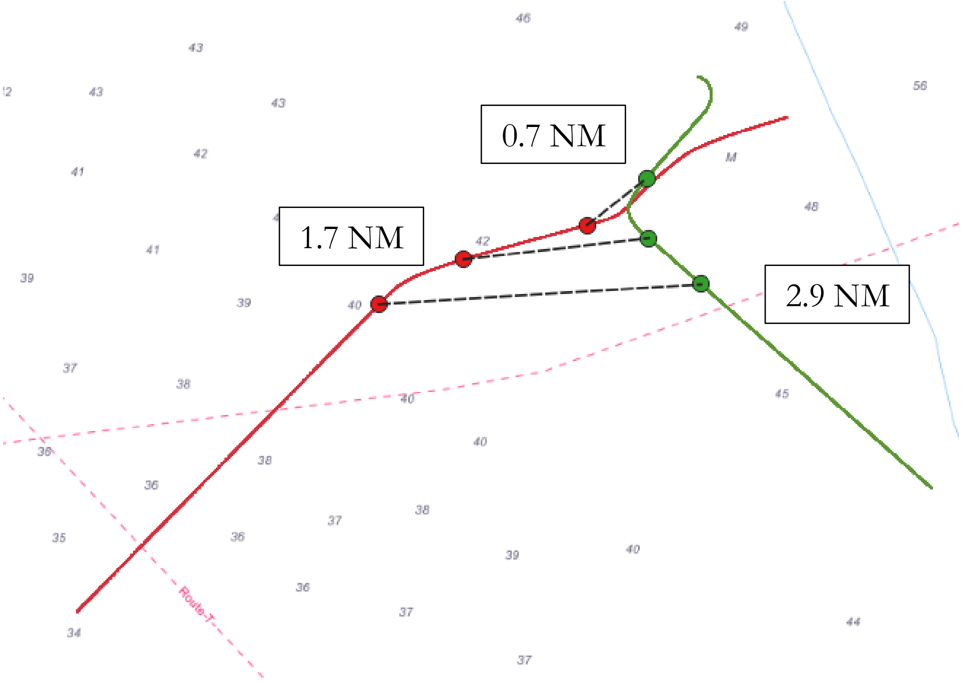


Figure 16 Crossing ahead or astern

In this case the algorithm on the red ship did initially not consider the green ship as a dangerous target and eventually fluctuated between it being dangerous and not. However, the closer the red ship came, the algorithm evaluated the projected track of the green ship as a risk of collision and altered course to starboard. As this course change and predicted trajectory of the red ship, violated the Safety Domain of the green ship, the latter changed its course notably to starboard. That in turn "invited" the algorithm on the red ship to keep the green ship just outside of its Safety Domain which resulted in a port turn (Figure 16).

8.2.2 Input for developers regarding crossing situations

The challenge with using COLREG algorithms based on Safety Domain settings in open sea crossing situations may be:

1. The Safety Domain of a ship even when based on data from real ship encounters does not give any indication on when ships in a collision situation took action nor what this action encompassed. It simply depicts the "final" stage of an encounter. Regardless, depending on the circumstances such as traffic density, vicinity of land and shallow areas, wind, etc. a safety domain needs to be adaptable to the actual conditions and location.
2. COLREG Rule 8 (b) states that "*Any alteration of course and/or speed to avoid collision shall, if the circumstances of the case admit, be large enough to be readily apparent to another vessel observing visually or by radar; a succession of small alterations of course and/or speed should be avoided.*"
   According to Cockcroft et. al (2011) "*A giving-way ship which alters course to pass astern of the other vessel should preferably turn sufficiently to bring the other vessel on to the opposite bow, so that at night a different sidelight would be visible, then gradually turn back maintaining the same relative bearing, until the original course is resumed*".

   In practice that basically means that on open sea a give-way vessel in a crossing situation would alter her course to starboard pointing at some distance astern of the stand-on vessel and then gradually turn back to her original course as depicted in **Error! Reference source not found.** and **Error! Reference source not found.**, depicting a crossing situation using the algorithm developed by SEAMADE.

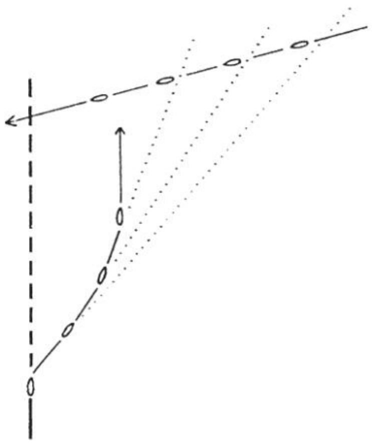


Figure 17 2 OS Crossing expected behaviour

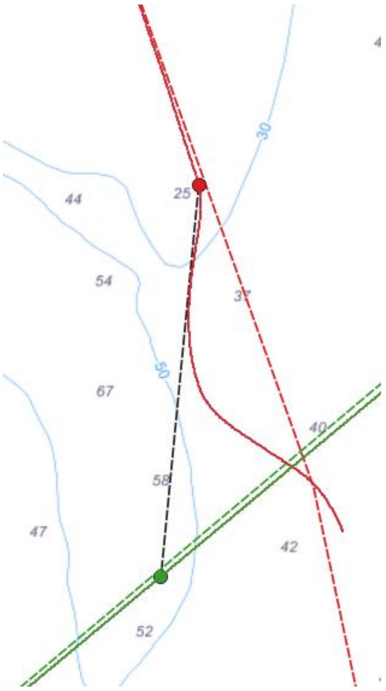


Figure 18 Crossing using SHIPMAN algorithm

This common practice is not observed in the algorithm based on a Safety Domain. In contrast to using a reactive algorithm like SHIPMAN coded to steer towards a point astern of the stand-on vessel (**Error! Reference source not found.**), algorithms based on the Safety Domain and TCPA may not make an enough distinct course change. The black dashed lines in Figure 13 to Figure 16 give an indication of the required course change to make it obvious to the stand-on vessel. Developers need to make sure that the course alteration by the give-way vessel is such that the heading after the alteration points astern of the stand-on vessel.

3. The setting of the safety domain and having different settings on the autonomous ships will obviously influence the outcome of a crossing

situation. However, that will not necessarily be a problem in a simple crossing situation involving 2 ships in open sea, but it raises the question if the size of the Safety Domain should be dependent on the ship being a give-way or stand-on vessel or even if algorithms can be solely based on the Safety Domain parameter.

4. When evaluating passing ahead or astern (simulation 4, Figure 16) the algorithm seemed to need a lot of calculating time or rather may not detect a dangerous target (as its calculated trajectory not infringing on the OS safety domain). On the other side, the Safety Domain on a stand-on vessel may worsen the outcome of a crossing situation.
5. OS 1 (give-way vessel) in simulation 4 (Figure 16) is "chasing" OS 2 probably due to attempting to follow its route as closely as possible while keeping the other ship outside its Safety Domain. It is noteworthy that "Safety Domain thinking" only considers the own ship but not the target ship and that Rule 8 stating that "*A vessel which, by any of these Rules, is required not to impede the passage or safe passage of another vessel shall, when required by the circumstances of the case, take early action to allow sufficient sea-room for the safe passage of the other vessel*" may not be followed.

8.2.3 Overtaking situations open sea 2 ships

Several overtaking simulations were performed with recommended and user defined domain settings in open sea and TCPA 12 minutes. The goal of the simulation was to illustrate the potential dependency of the type of overtaking (i.e., overtaking on starboard or port) of the give-way vessel in relation to the Safety Domain and the relationship of the Safety Domain of the stand-on vessel and its potential action.

8.2.3.1 Example 1: Overtaking with Default Safety Domain

Table 6 Overtaking simulation 1: Default Safety Domain Settings

Ship model used		Safety Domain setting (in NM) Recommended setting in AIM used		
OS 1 (red track)	OS 2 (green track)		OS 1	OS 2
Feeder	Chemical tanker	Forward	0.37	0.39
Speed 20 knots	Speed 14.5 knots	Starboard	0.27	0.29
		Astern	0.09	0.1
		Port	0.18	0.19

As the Safety Domain is non symmetric with a larger lateral distance on the ship's starboard side than port side, the implication of the recommended non-symmetric safety domain used in AIM may be that the overtaking ship will favour to overtake on the overtaken ship's starboard side when coming from dead astern or nearly dead astern. However, as the overtaken ship's safety domain is equally non-symmetrical, that ship will get a domain violation by the overtaking ship and take action. This action consisted in changing course to starboard (in the direction of the overtaking ship) possibly based on the same "reasoning" that as the lateral distance of the safety domain is less on port side, the overtaken ship strives to be overtaken on her port side. The position when the stand-on vessel executes a starboard turn, and the position of the overtaking ship are depicted by green and red dots connected by a black dashed line (Figure 19).

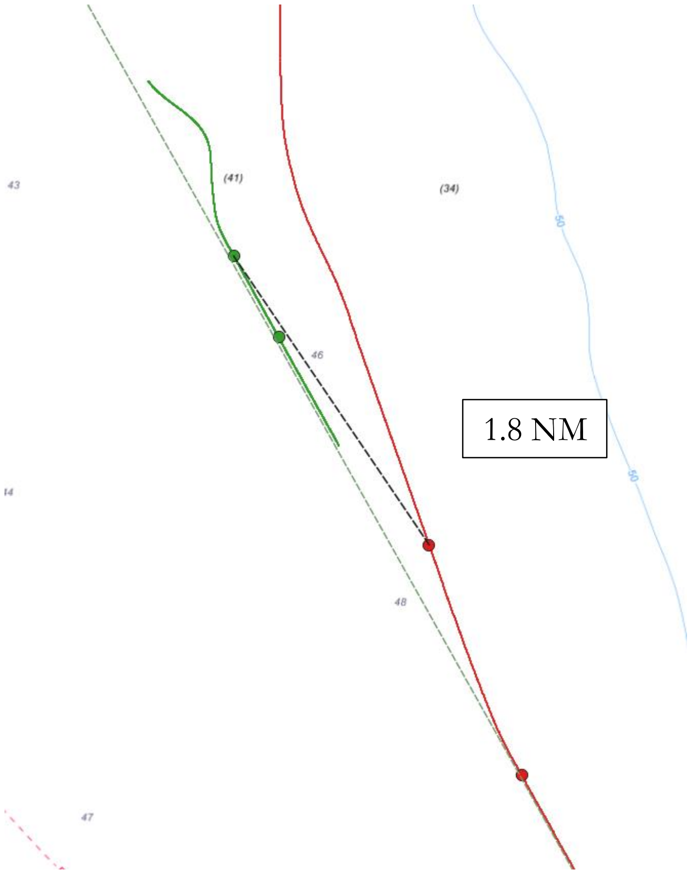


Figure 19 Overtaking open sea

8.2.3.2 Example 2: Overtaking with increased lateral distance with default Safety Domain settings

However, the overtaking ship will overtake on port side if the initial lateral distance between the two ships is such that the algorithm favours overtaking on the overtaken ship's port side. In the simulations this still resulted in the overtaken ship to take action to starboard because the overtaking ship made a course change to starboard to resume its original track, which triggered the manoeuvre (Figure 20).

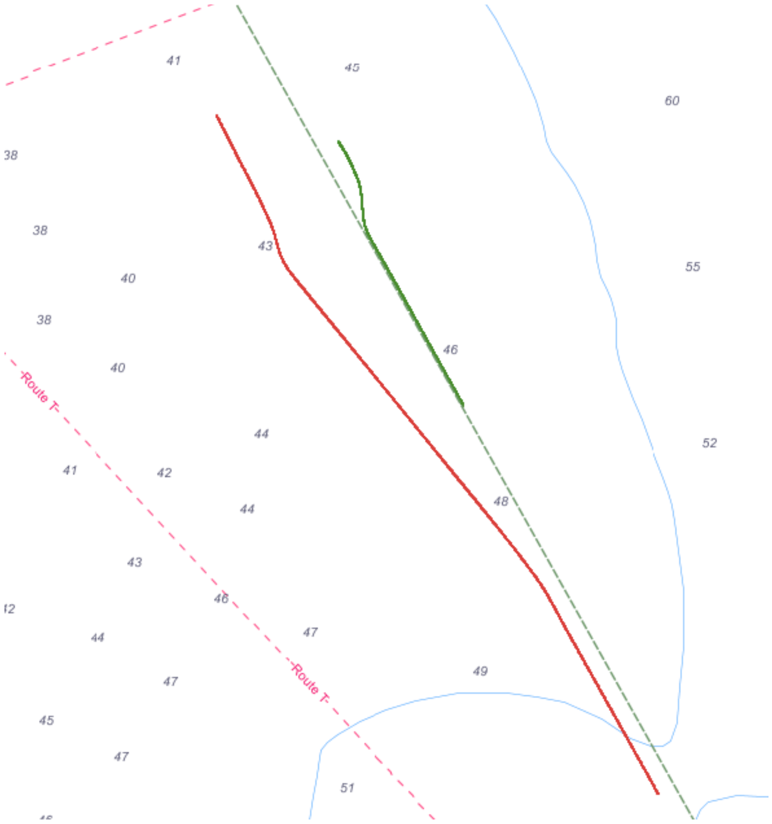


Figure 20 Overtaking on port side

8.2.3.3 Example 3: Overtaking with different user defined Safety Domain settings

Having significant differences in the size of the Safety Domain with larger values on the stand-on (overtaken) ship, resulted in a series of "re-calculations" on both ships and an eventual passing at close range (Figure 21).

Table 7 Overtaking simulation 2: Safety Domain Settings

Ship model used		Safety Domain setting (in NM)		
OS 1 (red track)	OS 2 (green track)		OS 1	OS 2
Feeder	Chemical tanker	Forward	0.37	2.0
Speed 20 knots	Speed 14.5 knots	Starboard	0.27	1.5
		Astern	0.09	0.5
		Port	0.18	1

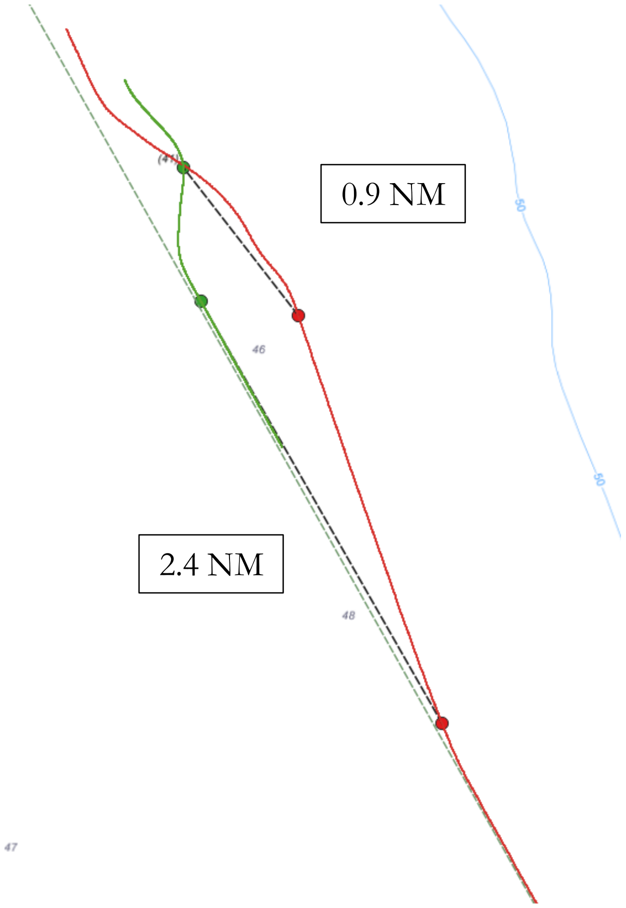


Figure 21 Overtaking with different Safety Domain settings

Further overtaking simulations using various Safety Domain settings and with a combination of the overtaking ship dead astern, slightly to port or starboard and with slight oblique angles (i.e., not the same course as the overtaken ship) resulted all with different outcomes (Figure 22). However, especially notable is the fact that the stand-on vessel never kept its course and speed.

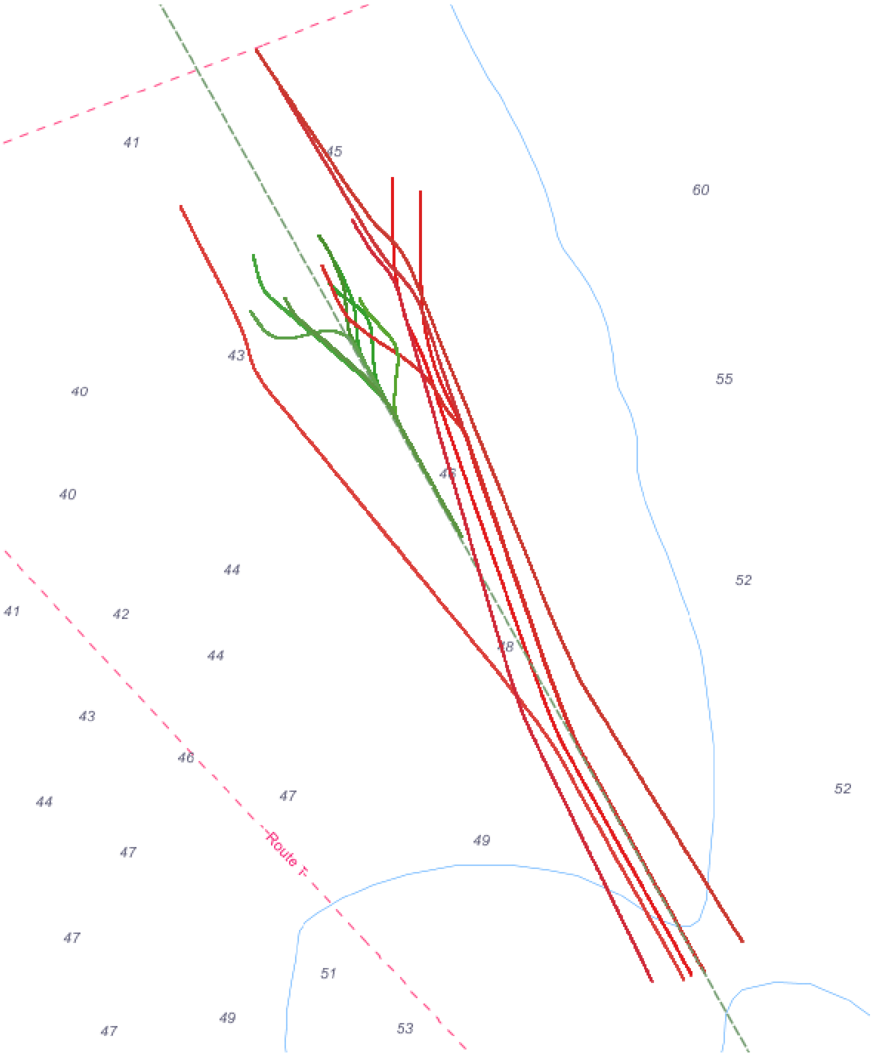


Figure 22 Overtaking scenarios

8.2.4 Input for developers regarding overtaking

1. The shape of the Safety Domain is likely to influence the decision on the give-way vessel as to which side the overtaking takes place. In most simulated cases, the overtaking took place on the starboard side of the overtaken vessel.
2. The domain setting on the stand-on vessel triggers an action either to port or starboard with poor predictability, possibly breaching COLREG Rule 17.
3. An algorithm such as used in AIM calculates “constantly” if there are any threatening targets and suggests/executes a manoeuvre. That even applies if such target is performing a turn during which (albeit only for a while) it is considered as threatening and may therefore trigger a new manoeuvre on the OS. The consequence may be a very erratic behaviour of autonomous ships.

4. Rapid large course changes may (depending on ship) also result in substantial overshoot angles which may trigger a reaction on the other autonomous ship. It may be necessary that autonomous ships avoid taking any action as long as the target shows a defined maximum rate of turn.

8.2.5 Meeting situations 2 ships open sea

All head-on and nearly head-on simulations with varying Safety Domain settings resulted in a safe passing according to the COLREGs (Figure 23). As all simulations used an asymmetric ellipse shape of the Safety Domain with a shorter distance on port side, this result was expected.

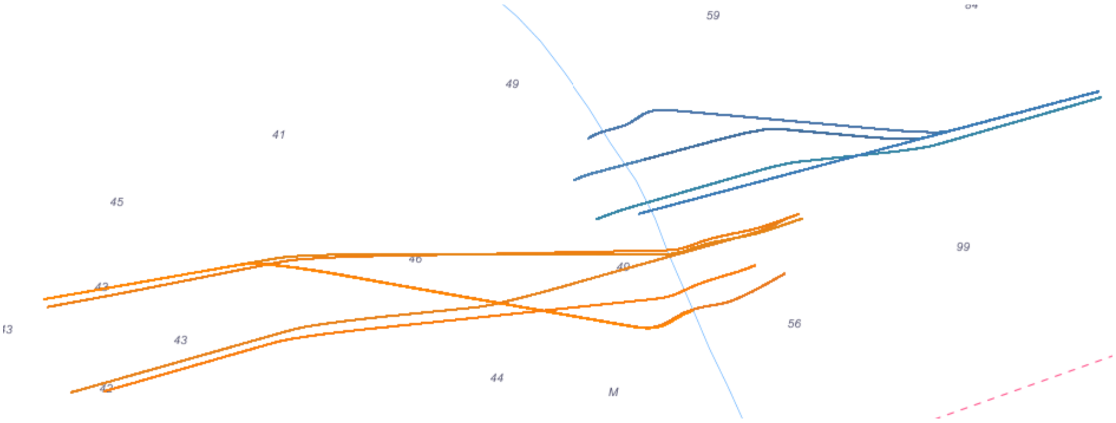


Figure 23 Head-on and nearly head-on situations

8.3 Setting priorities in ”not run aground” vs. “not collide”

Although traffic situations can be challenging in deep and open waters, shallow waters may complicate matters further as the navigator not only needs to follow the COLREGs but by doing so, also avoid running aground. For an algorithm, a straightforward head on situation between two ships in good visibility may result in 3 options i.e., either breach COLREG rule 14 (Head-on situation), reduce the Safety Domain and pass closer the shallow water than planned or if done at an early stage slow down to meet the SW-bound ship before the shallow patch.

Figure 24 depicts a head-on situation where the NE-bound ship (blue track) meets a SW-bound ship (orange track) with shallow water to the east. The safety depth/contour settings on both ships are such that the light blue and blue area on the chart are regarded as unsafe. For the orange ship, the situation is straightforward as by following Rule 14 (i.e., turn to starboard) she will avoid shallow waters. However, the algorithm of blue ship executed a manoeuvre to port to avoid shallow waters and thereby breaching Rule 14.

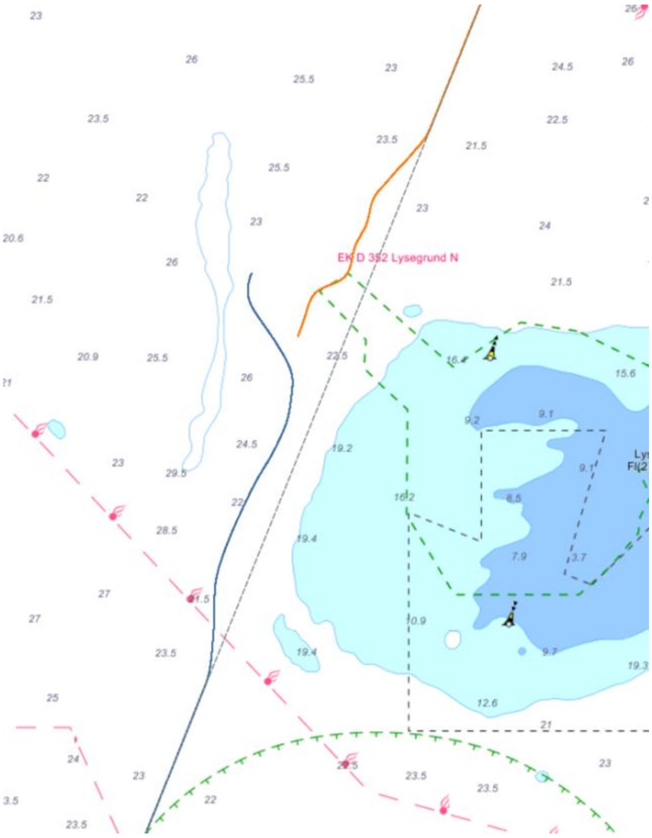


Figure 24 Meeting head-on with shallow water

Depending on the Safety Domain settings in some simulations the NE bound ship followed Rule 14 i.e., changing course to starboard and automatically reduced the pre-set Safety Domain (Figure 25).

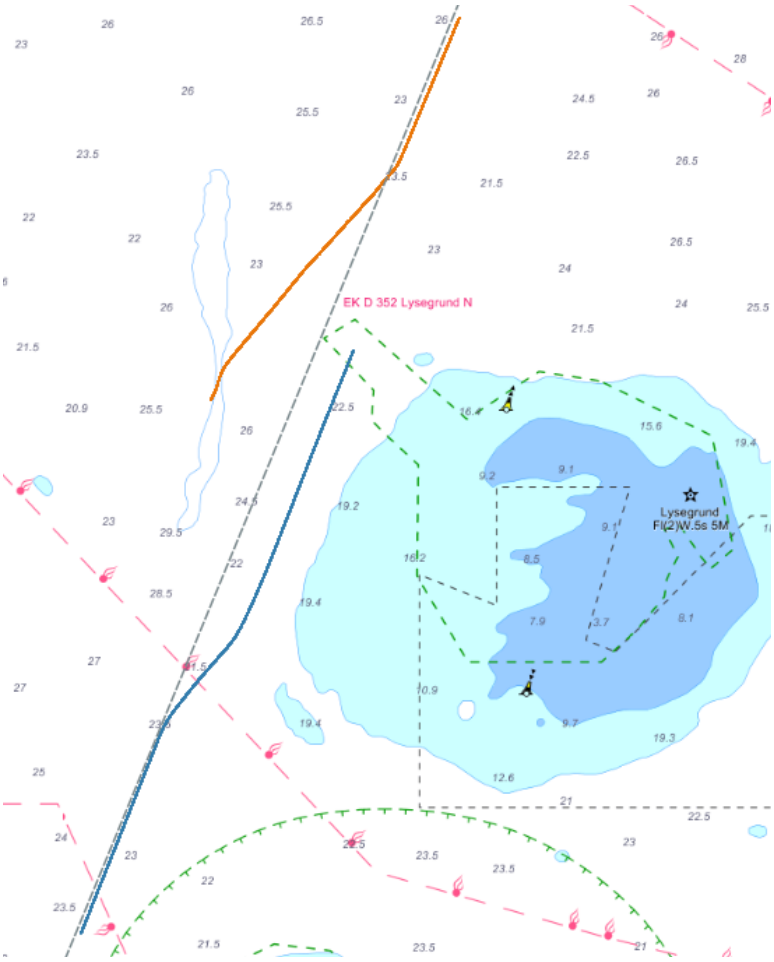


Figure 25 Reduced Safety Domain to follow COLREG

To investigate the reduction of the pre-set Safety Domain, a non-moving fishing boat target (with activated AIS) was placed between the NE bound ship's route and the shallow area. As in the previous example, the NE bound ship followed Rule 14 and avoided the fishing boat by a further reduction of its Safety Domain resulting in a passing distance to the shallow waters of 0.14 cables (260m) (Figure 26). Depending on weather conditions, such distance must be regarded as very dangerous. Additionally, the quality and accuracy of the survey data depicted on the ENC (CATZOC) may well be with an error of more than 2m vertically and more than 500m horizontally, possibly enough for a ship with a reduced Safety Domain to run aground.

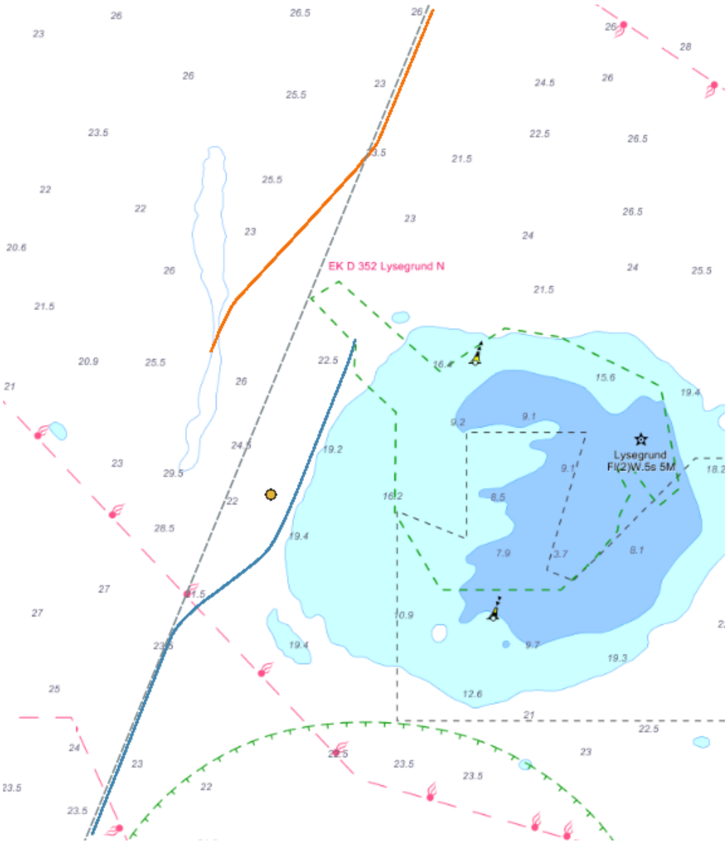


Figure 26 Reduction in Safety Domain passing close to shallows

The above examples also show that the normal use of the steering and sailing rules of the COLREGs may be of limited applicability when shallow waters (or for that matter other obstacles) limit the manoeuvring space of one ship involved. In such cases, navigators may need to refer to Rule 2 requiring the navigators to comply with the rules also in regard to "*the ordinary practice of seamen*" and having due regard *"to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved, which may make a departure from these Rules necessary to avoid immediate danger"* (IMO, 1972).

In practical terms that could mean that the SW-bound ship will be aware of the NE-bound ship's inability to follow Rule 14 i.e., due regard to *"the limitations of the vessels involved"*, therefore making a timely and bold alteration of course to starboard letting the NE-bound ship keep her course and speed. The NE-bound ship may also inform the SW-bound ship by VHF communication about her limited manoeuvring space and inability to follow Rule 14. The option for the NE-bound ship to alter course to port is unlikely acceptable as there may not be a case of "immediate danger". However, depending on the settings of the algorithm on an autonomous ship it may well assume that there is a case of "immediate danger" and act against Rule 14.

To develop algorithms which cover special circumstances and actions, which may be required by the ordinary practice of seamen and good seamanship, is an extremely challenging task. Although the expression "good seamanship" is only appearing once in Rule 8(a) it is the highest principle of the COLREGs (Zhou, Huang, Wang, Wu, & Liu, 2020). Developers of algorithms mainly focus on Overtaking, Crossing and Head-on situations but no papers include traffic situations where Rule 2 may be applicable (Burmeister & Constapel, 2021).

However, Kufoalor et al. (2019) acknowledge that as the COLREGs advocate "good seamanship" probably due to the uniqueness of every situation, it is difficult to make the decision process autonomous based on existing technology and rules (Kufoalor, Wilthil, Hagen, Brekke, & Johansen, 2019). For developers of algorithms without the experience of having been an OOW the term "good seamanship" may be difficult to grasp, let alone codify even without delving into departure from the Rules as permitted by Rule 2 (Wróbel, Gil, Huang, & Wawruch, 2022). To incorporate good seamanship into artificial intelligence and algorithms would require machine learning, more advanced neural networks, and a massive amount of data. This data is difficult to obtain and regional specific and even if such data may eventually be available, the fundamental question of what is considered as possibly violating the COLREGS versus acting according to "good seamanship" remains (Weber, Aylward, MacKinnon, Lundh, & Hägg, 2022).

8.3.1 Input for developers regarding ”not run aground” vs. "not collide"

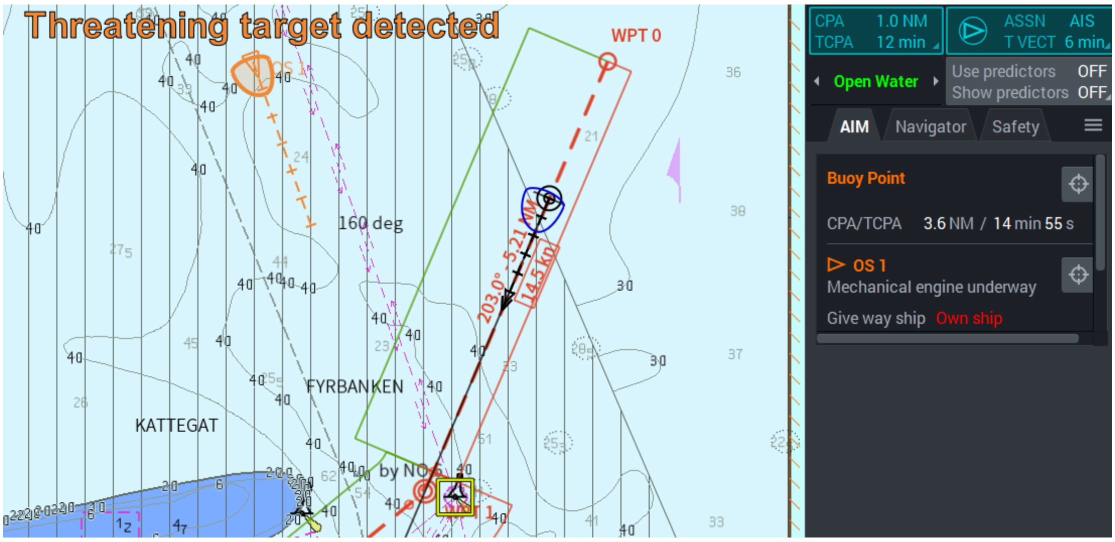
There are several items that developers need to consider and test their algorithms for regarding anti-collision versus anti-grounding:

1. As described in the previous examples, there may be a conflict between solving the traffic situation strictly following the COLREGs and not taking the ship into shallow waters.
2. A reduction of the Safety Domain and passing close to shallow waters may be extremely dangerous depending on weather conditions.
3. The level of tide should be considered as it may directly affect the space of navigable water.
4. The quality and accuracy of the bathymetric data used in the ENC (CATZOC) must be included as a parameter in an algorithm.
5. Ordinary practice of seaman: Asking navigators to define ordinary practice of seamen i.e., good seamanship itself may provide multiple and possibly differing answers (Aylward, Weber, Lundh, MacKinnon, & Dahlman, 2022) and clarifying definitions will be required if the COLREGs are to be implemented for MASS without amendments (Hannaford, Maes, & van Hassel, 2021). Numerous court cases and Court judgements on how Rules have been interpreted are part of Cockcroft and Lameijer's Guide to the Collision Avoidance Rules (Cockcroft & Lameijer, 2011) and a Google search on the practical applicability of Rule 2 provides additional examples which must be studied in detail to gain an understanding of its importance.

8.3.2 Setting priorities “navigational marks” vs. targets

Similar to avoid grounding, an algorithm based on Safety Domain parameters for solving traffic situation will also need to be able to differentiate between targets such as ships and navigational marks e.g., buoys (Figure 27)Figure 27 Buoy and threatening target. It would be unreasonable to apply the same dimensions of a Safety Domain to both traffic and navigational marks but at the same time, collisions with buoys must obviously be avoided as well. While floating navigation marks have a given position on the chart, the actual position of the floating navigation mark needs to be ascertained by other means as floating marks can be adrift.

Navigational marks can be categorized further into fixed navigation marks i.e., objects fixed to the bottom or on land, floating navigation marks i.e., buoys with well-defined positions in the chart and floating navigation mark not included in chart information, such as fishing gear. All these navigation marks need to be avoided and may have an impact in a traffic situation. Fishing gear is especially challenging as they are hard to detect, can have complex forms and can be spread out over a large geographical area.



CPA 1.0 NM
TCPA 12 min

ASSN AIS
T VECT 6 min

Open Water

Use predictors OFF
Show predictors OFF

Buoy Point
CPA/TCPA 3.6 NM / 14 min 55 s

OS 1
Mechanical engine underway
Give way ship Own ship

Figure 27 Buoy and threatening target

8.4 Monitored route vs COLREGs: Challenges for path planning algorithms

8.4.1 Influence of route on decision

Most academic papers on collision avoidance using algorithms only cover basic rules for crossing, head-on and overtaking situations (Burmeister & Constapel, 2021) with ships moving on a straight trajectory. However, no papers were found which consider how a monitored route including planned course changes may have an influence in the calculation and subsequent manoeuvre.

How the monitored route affects the manoeuvre can be clearly seen in overtaking situations, as described in section 8.2.3, when the overtaking ship's monitored route includes a waypoint with a course change to port (Figure 28).

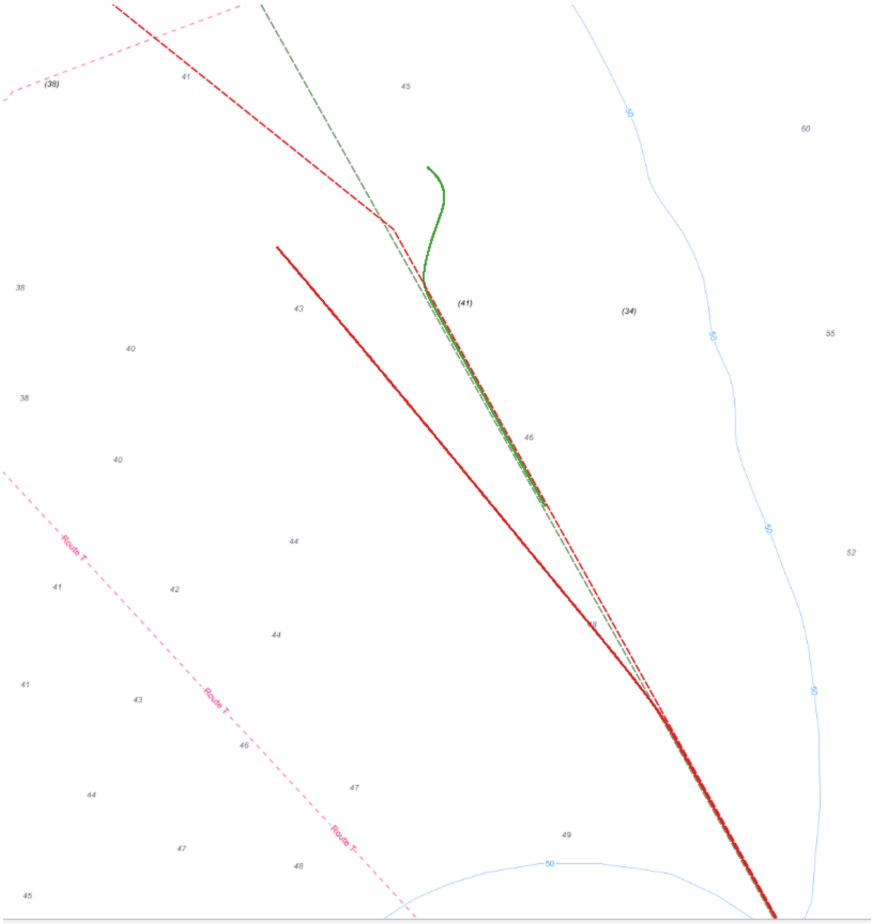
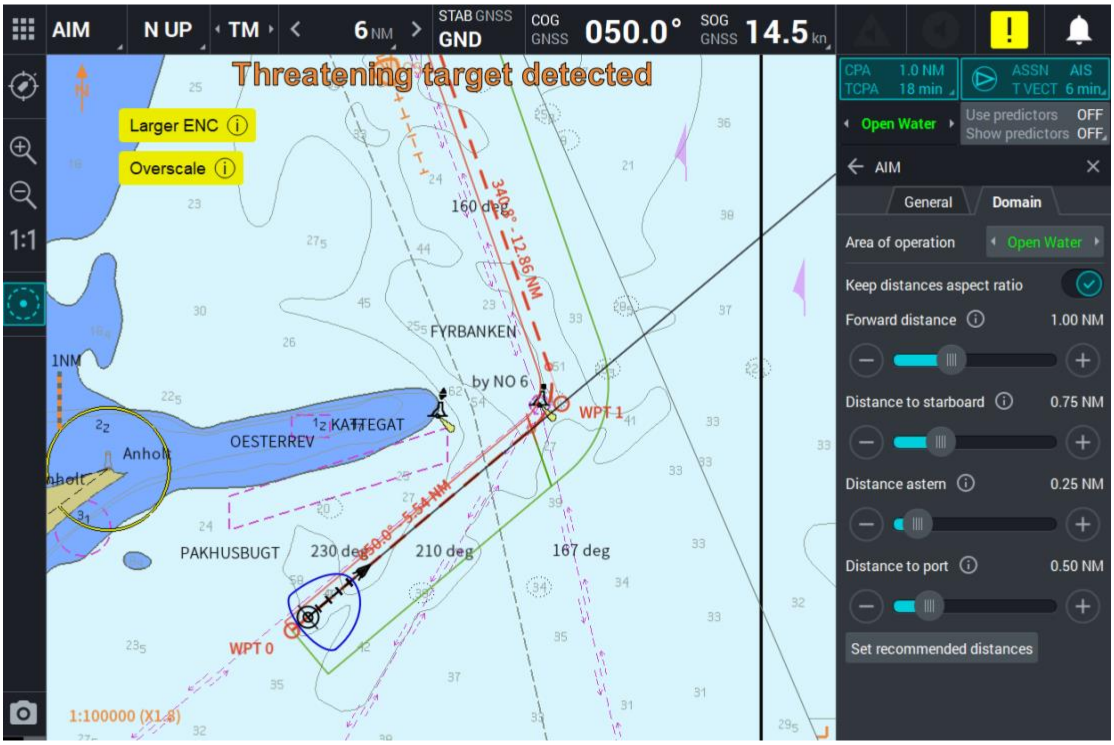


Figure 28 Influence of monitored route in overtaking situation

In contrast to the simulations without any course changes in the overtaking ship's monitored route where the overtaking was predominantly made on the overtaken ship's starboard side (Figure 22), the overtaking was made on the other side. This indicates that both the Safety Domain and the monitored route will influence the manoeuvre performed. Note that the stand-on vessel changed course to starboard due to its predicted Safety Domain infringement.

8.4.2 Influence of monitored route on stand-on vessel

For ships in a stand-on situation, a manoeuver according to the COLREGs must always be prioritized and the monitored route should not have any influence on the decision by the algorithm. To illustrate how a monitored route may affect the outcome one can consider a crossing situation where the stand-on vessel approaches a waypoint with a course change to port (Figure 29).



STAB GNSS GND

COG GNSS 050.0°

SOG GNSS 14.5 kn

CPA 1.0 NM

TCPA 18 min

ASSN AIS

T VECT 6 min

Open Water

Use predictors OFF

Show predictors OFF

Area of operation: Open Water

Keep distances aspect ratio ☑

Forward distance 1.00 NM

Distance to starboard 0.75 NM

Distance astern 0.25 NM

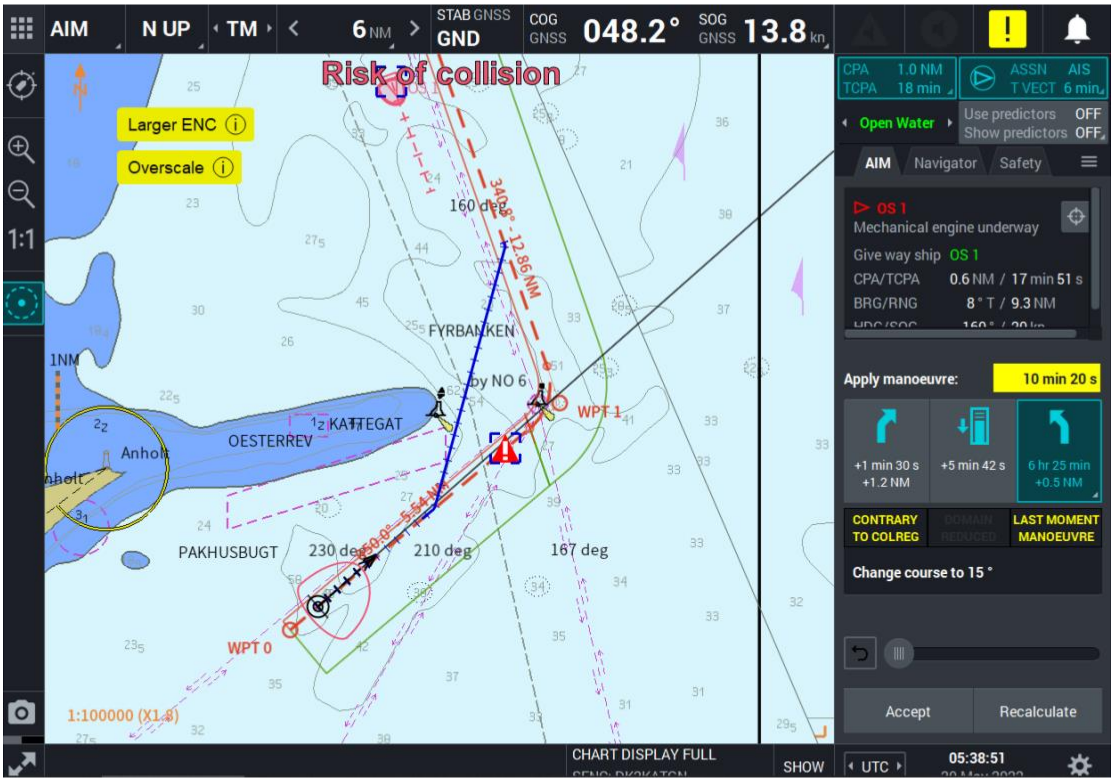
Distance to port 0.50 NM

Figure 29 Stand-on vessel with route change to port

8.4.3 Priority setting route vs. COLREGs

It is not uncommon for ships to take "short-cuts" at waypoints to solve traffic situations and the shown example invites the question whether it would be permissible for a "stand-on vessel" in a crossing situation to alter course to port if done very early or to phrase it differently, at what distance do the COLREGs apply? This issue has been raised in numerous court cases (Zhao, 2008) but is depending on context and likely impossible to quantify.

For unknown reasons (however, possibly influenced by the monitored route) the algorithm in the above case suggests (and executes in automatic mode) the default manoeuvre to port albeit indicating that this manoeuvre is considered as both a last moment manoeuvre and against the COLREGs (Figure 30, Figure 31).



COG GNSS 048.2°

SOG GNSS 13.8 kn

CPA 1.0 NM

TCPA 18 min

ASSN AIS T VECT 6 min

Open Water

Use predictors OFF

Show predictors OFF

OS 1

Mechanical engine underway

Give way ship OS 1

CPA/TCPA 0.6 NM / 17 min 51 s

BRG/RNG 8 ° T / 9.3 NM

Apply manoeuvre: 10 min 20 s

+1 min 30 s +1.2 NM

+5 min 42 s

6 hr 25 min +0.5 NM

CONTRARY TO COLREG

LAST MOMENT MANOEUVRE

Change course to 15 °

05:38:51

Figure 30 Stand-on vessel with suggested course change to port

COG GNSS 050.1°

SOG GNSS 13.8 kn

CPA 1.0 NM

TCPA 18 min

ASSN AIS T VECT 6 min

Open Water

Use predictors OFF

Show predictors OFF

Waiting manoeuvre:

CONTRARY TO COLREG

TTG : 9 min 49 s End WP :

DTG : 2.3 NM WP6

OS 1 (Closest target)

CPA : 0.9 NM TCPA : 17 min 40 s

Reset to user route 9 min 49 s

05:39:23

Figure 31 Stand-on vessel with executed course change to port

Grasping the encounter stage for a stand-on vessel and understanding its corresponding obligation are the prerequisites for taking appropriate action (Du, Valdez Banda, Goerlandt, & Kujala, 2020). Coded correctly, an algorithm should not trigger nor suggest an action for a stand-on vessel contrary to COLREGs and there is no such thing as *"contrary to the COLREG"* as a *"last moment manoeuver"* (as depicted in Figure 30) because any successful manoeuver to avoid an imminent collision will be acceptable.

While this may be semantics or lack of knowledge, developers of algorithms need to specifically understand the intricacies of Rule 17 stating that the stand-on vessel:

1. "…*may however take action to avoid collision by her manoeuvre alone, as soon as it becomes apparent to her that the vessel required to keep out of the way is not taking appropriate action in compliance with these Rules"* and in a crossing situation *"if the circumstances of the case admit, not alter course to port for a vessel on her own port side"* (IMO, 1972).
2. *When, from any cause, the vessel required to keep her course and speed finds herself so close that collision cannot be avoided by the action of the give-way vessel alone, she shall take such action as will best aid to avoid collision"* (IMO, 1972)

The word "may" in the first paragraph does however not mean "shall" and a stand-on vessel taking action before it can reasonably be assumed that the give-way vessel is not taking any action is likely to be partially blamed if the situation resulted in a collision (Cockcroft & Lameijer, 2011). Having the obligation to act is not applicable until it becomes obvious that the give-way vessel cannot avoid a collision by her manoeuvre alone.

Having the Safety Domain of a stand-on vessel triggering an avoiding action too early may in other words be regarded as a breach of the COLREGs and therefore raises the question if the parameters of the Safety Domain for a ship can be applied in both stand-on and give-way situations, or alternatively whether other (possibly additional) parameters for stand-on ships are required as suggested by e.g., Szlapczynski et al. (2018) or Du et al. (2020).

Other cases where the route may influence the decision made by an algorithm are planned speed changes. Planned and monitored routes do not only consist of waypoints and legs but also planned speeds for each leg. In other words, a waypoint may not necessarily be exclusively used for a course change but only for a speed change (i.e., no course change). It is therefore possible that autonomous stand-on ships, in a traffic situation involving a risk of collision reach such a waypoint, reduce speed and thereby breach the COLREGs.

These examples illustrate that algorithms must be checked and validated by including traffic situations with ships monitoring routes which consist of combinations of course changes and planned speed changes to verify if the algorithm follows the COLREGs. However, it must be emphasized that the AIM software used in the example is not (yet) intended to be used in automatic mode and it may be assumed that the OOW would select a different manoeuvre.

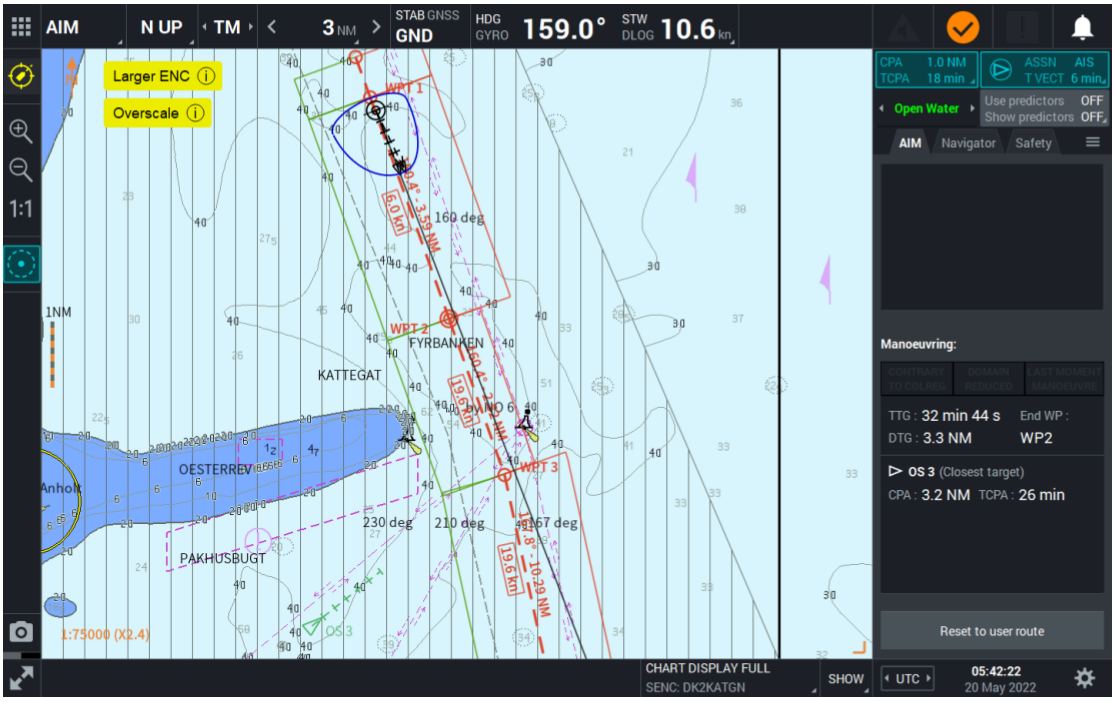
8.4.4 Algorithms have no memory

Path planning algorithms basically provide a "new" route including speeds for the route legs to steer clear of obstacles such as ships, shallow areas, buoys, etc. If the dangerous targets perform other actions than keeping course and speed, or if further dangerous targets are detected, a modified route based on the presently (and not the original) monitored one is executed and subsequently monitored. The initial traffic situation and its applicable rules are disregarded, meaning that the algorithm has no memory of the original traffic situation which triggered the initial action.

This behaviour may lead to surprising effects as the following examples try to illustrate.

8.4.4.1 Algorithms have no memory: Example 1

In the crossing scenario described in section 8.4 the North Easterly (NE'ly) bound stand-on vessel executes and subsequently monitors a new route, which was based on the original route (Figure 31). For the South Easterly (SE'ly) give-way vessel, there is still a risk of collision as neither the speed nor course of the stand-on vessel has changed. Therefore, the give-way vessel reduces her speed to let the other ship pass ahead (Figure 32).

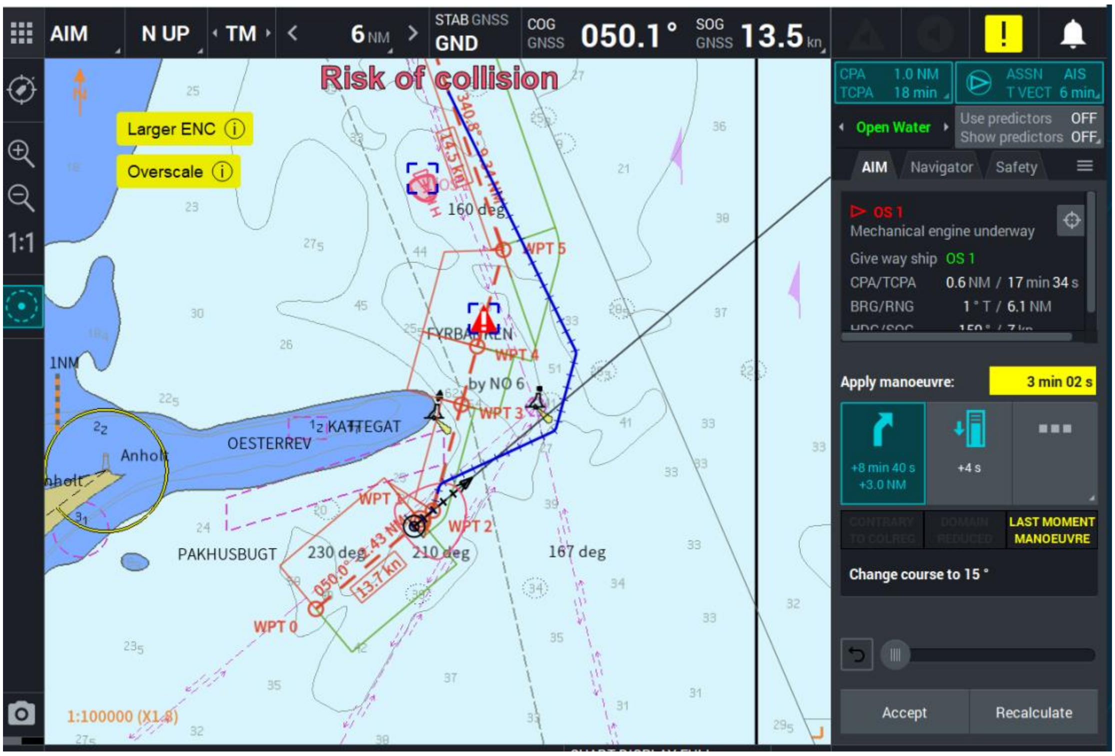


STAB GNSS GND
HDG GYRO 159.0°
STW DLOG 10.6 kn
CPA 1.0 NM
TCPA 18 min
ASSN AIS
T VECT 6 min
Use predictors OFF
Show predictors OFF
Manoeuvring:
TTG : 32 min 44 s
DTG : 3.3 NM
End WP : WP2
OS 3 (Closest target)
CPA : 3.2 NM TCPA : 26 min
CHART DISPLAY FULL
SENC: DK2KATGN
05:42:22
20 May 2022

Figure 32 Give-way vessel reducing speed

Figure 32 also indicates that the reduction of speed is a successful manoeuvre and that the other ship is no longer a threatening target.

However, from the stand-on vessel's perspective and based on the presently monitored route, the give-way vessel is once again a threatening target and a manoeuvre based on the presently monitored route (not the original) is suggested and executed (Figure 33, Figure 34).



STAB GNSS GND

COG GNSS 050.1 °

SOG GNSS 13.5 kn

CPA 1.0 NM
TCPA 18 min

ASSN AIS
T VECT 6 min

Open Water

Use predictors OFF
Show predictors OFF

OS 1
Mechanical engine underway
Give way ship OS 1
CPA/TCPA 0.6 NM / 17 min 34 s
BRG/RNG 1 ° T / 6.1 NM

Apply manoeuvre: 3 min 02 s

+8 min 40 s
+3.0 NM

+4 s

CONTRARY TO COLREG
DOMAIN REDUCED
LAST MOMENT MANOEUVRE

Change course to 15 °

Figure 33 Suggested manoeuvre for stand-on vessel

STAB GNSS GND

COG GNSS 050.2 °

SOG GNSS 13.5 kn

CPA 1.0 NM
TCPA 18 min

ASSN AIS
T VECT 6 min

Open Water

Use predictors OFF
Show predictors OFF

Waiting manoeuvre:

CONTRARY TO COLREG
DOMAIN REDUCED
LAST MOMENT MANOEUVRE

TTG : 2 min 28 s
End WP : WP10
DTG : 0.6 NM

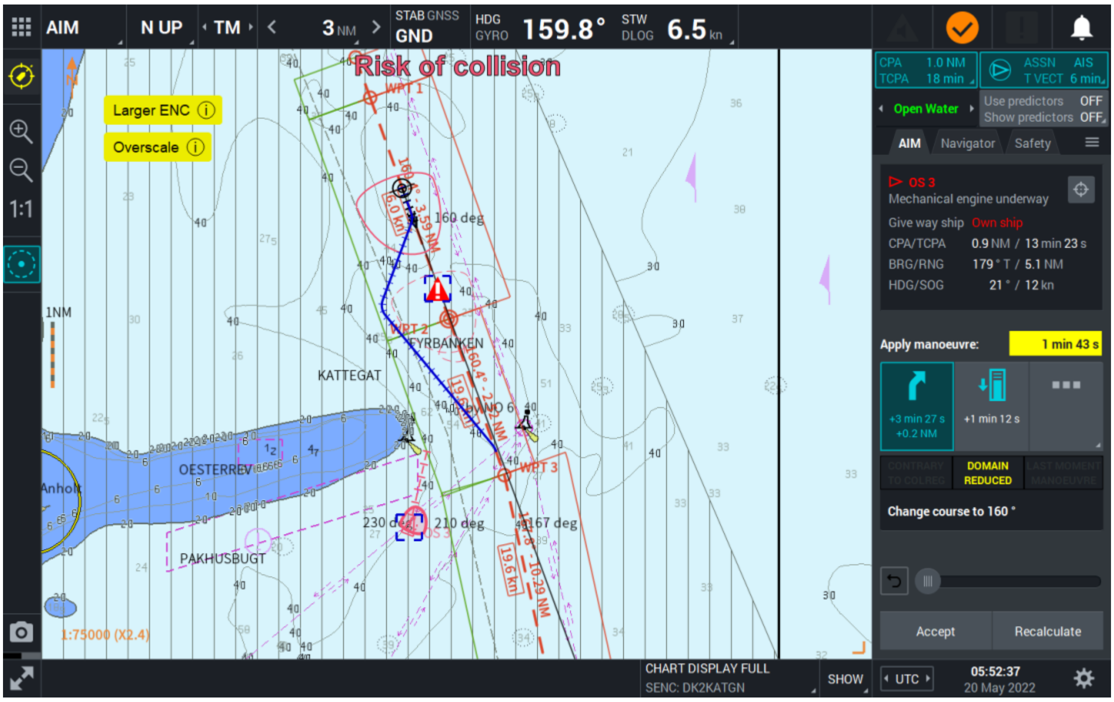
OS 1 (Closest target)
CPA : 1.3 NM TCPA : 25 min 40 s

Reset to user route
2 min 28 s

05:49:37

Figure 34 Executed manoeuvre with new monitored route

As this new route is based on the presently monitored route, the ship initially turns to port. This turn to port triggers a new manoeuvre on the give-way vessel (Figure 35).



CPA 1.0 NM
TCPA 18 min
ASSN AIS
T VECT 6 min
Open Water
Use predictors OFF
Show predictors OFF

AIM Navigator Safety

OS 3
Mechanical engine underway
Give way ship Own ship
CPA/TCPA 0.9 NM / 13 min 23 s
BRG/RNG 179 °T / 5.1 NM
HDG/SOG 21 ° / 12 kn

Apply manoeuvre: 1 min 43 s

+3 min 27 s +0.2 NM
+1 min 12 s

CONTRARY TO COLREG
DOMAIN REDUCED
LAST MOMENT MANOEUVRE

Change course to 160 °

Accept
Recalculate

05:52:37
20 May 2022

Figure 35 Manoeuvre by give-way vessel

Eventually, the situation was solved satisfactorily concerning safe distances but further simulations of the same traffic scenario, with various Safety Domain settings on the ships involved, showed that the predictability of the manoeuvres of autonomous ships may be very low in even fairly simple crossing situations including monitored routes as shown by the tracks in Figure 36.

Figure 36 Ships tracks in crossing situation with monitored route

8.4.4.2 Algorithms have no memory: Example 2

Path planning algorithms with monitored routes may also lead to traffic scenarios where only one ship is detecting a COLREG situation with subsequent manoeuvers that may lead to near misses or even collisions. A traffic scenario with 3 autonomous ships involved in a combination of meeting, crossing and overtaking situation is shown in Figure 37.

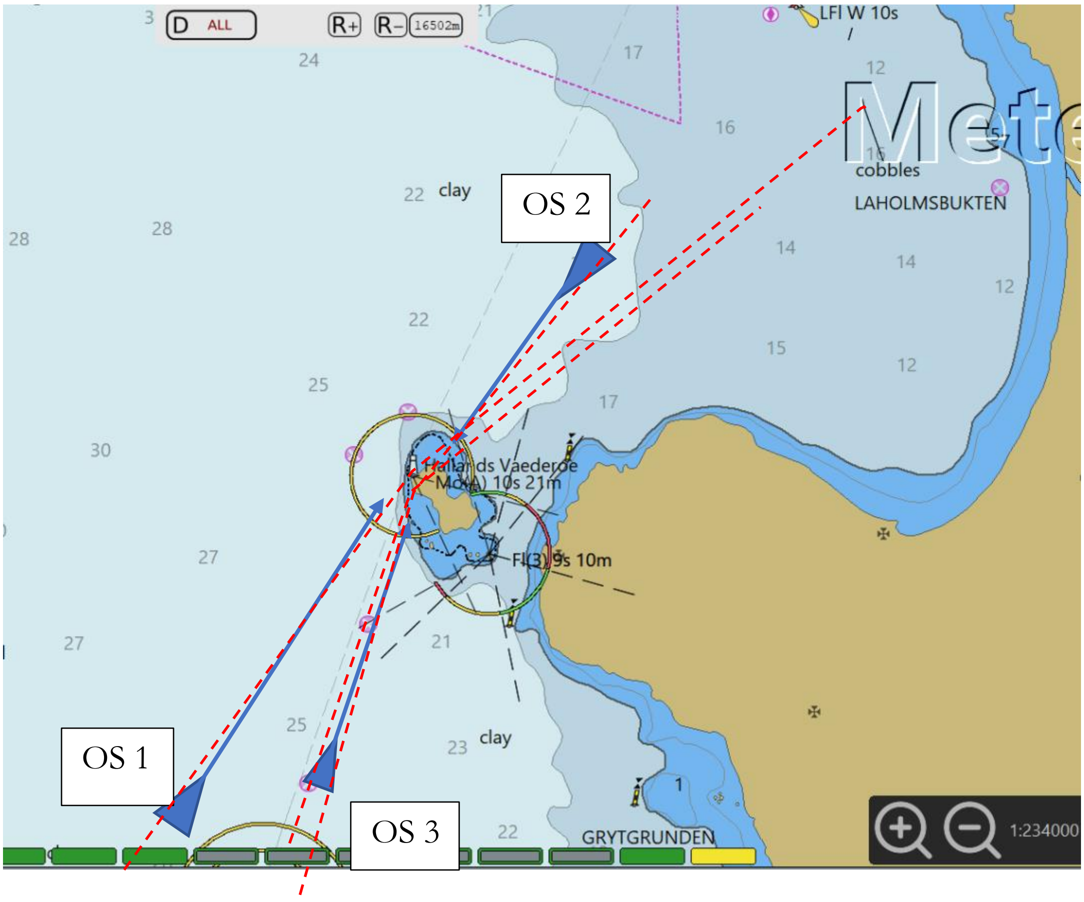


Figure 37 Meeting/crossing and overtaking scenario

The action taken on ship OS 1 was a course change to port and on ship OS 2 a course change to starboard (Figure 38)

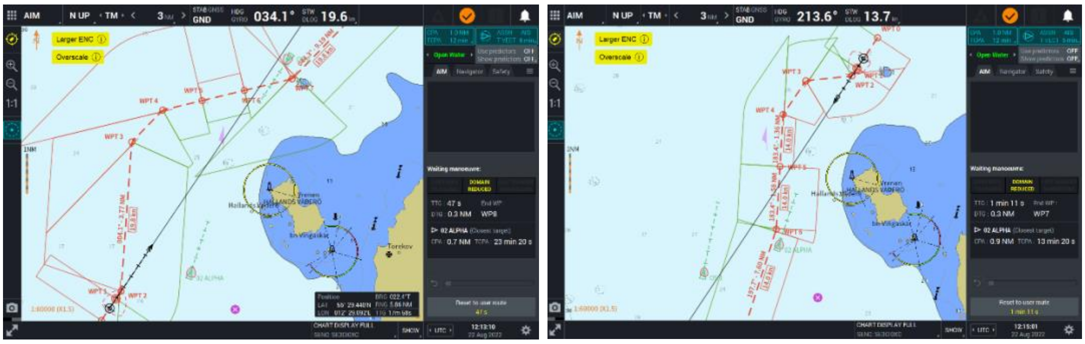


Figure 38 Action taken by autonomous ships

While one may discuss whether the action by OS 1 is fully compliant with the COLREGs, the interesting situation develops once these ships are progressing along their new routes. OS 1 detects that she is the give-way vessel involved in a crossing situation with OS 2 whereby a new route is recalculated and monitored (Figure 39).

Figure 39 Collision situation for OS 1

At the same time, OS 2 does not interpret the situation as a COLREG case as her monitored route is avoiding all traffic (Figure 40).

Figure 40 Perspective of OS 2

Meanwhile OS 1 is monitoring an updated route (Figure 41) which will pass astern of OS 2.

Threatening target detected

HDG GYRO 004.1° STW DLOG 19.3 kn

CPA 1.0 NM TCPA 12 min

ASSN AIS T VECT 6 min

Open Water

Use predictors OFF
Show predictors OFF

02 ALPHA

Give way ship Own ship
CPA/TCPA 0.5 NM / 12 min 49 s
BRG/RNG 82 ° T / 2.2 NM
HDG/SOG 19 ° / 14 kn

Waiting manoeuvre:

TTG : 1 min 25 s End WP :
DTG : 0.5 NM WP5

02 ALPHA (Closest target)
CPA : 0.5 NM TCPA : 12 min 49 s

Reset to user route
1 min 25 s

CHART DISPLAY FULL
SENC: SE3CIOXC

UTC 12:19:53 22 Aug 2022

Figure 41 Updated route for OS 1

At the same time OS 2 is approaching her waypoint and initiates a course change to port (Figure 42)

HDG GYRO 264.7° STW DLOG 11.0 kn

CPA 1.0 NM TCPA 12 min

ASSN AIS T VECT 6 min

Open Water

Use predictors OFF
Show predictors OFF

Manoeuvring:

TTG : 20 min 38 s End WP :
DTG : 4.3 NM WP7

02 ALPHA (Closest target)
CPA : 0.9 NM TCPA : 8 min

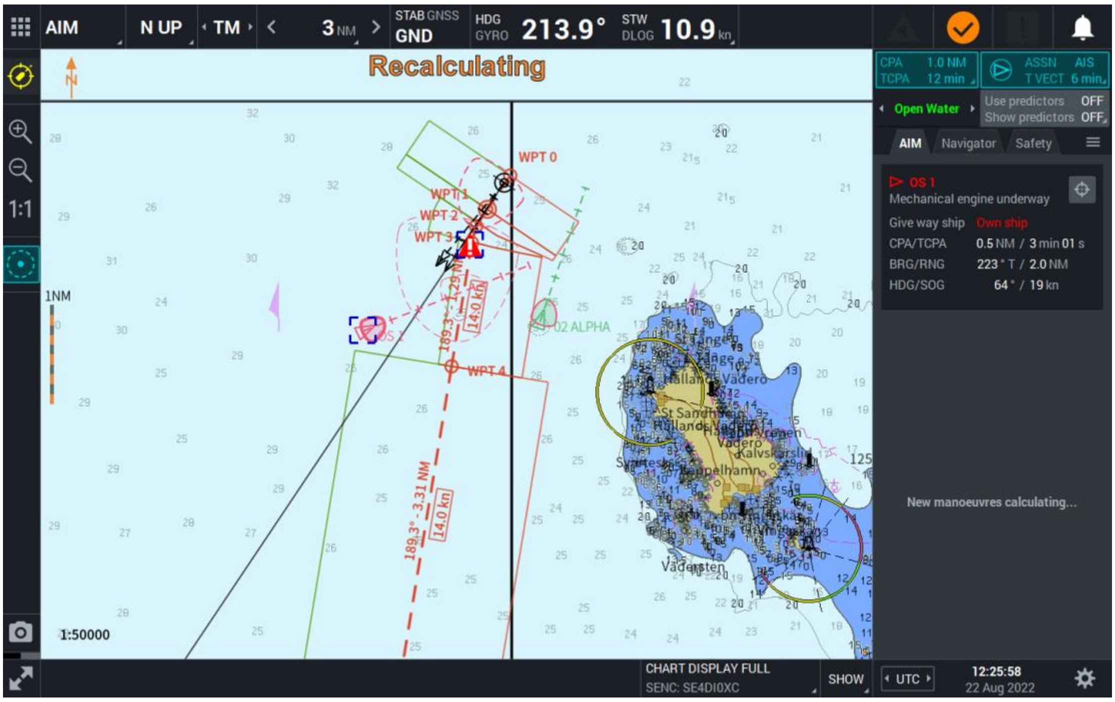
Reset to user route

CHART DISPLAY FULL
SENC: SE3CIOXC

UTC 12:20:23 22 Aug 2022

Figure 42 OS 2 following route to port

Both ships are more or less performing their manoeuvers at the same time, resulting in further calculations and updating of the monitored routes. As the calculation takes a certain amount of time and the ships are frequently changing their course, there is a risk that the calculations eventually enter in a loop without providing a solution (Figure 43).


AIM | N UP | TM | 3 NM | STAB GNSS GND | HDG GYRO 213.9° | STW DLOG 10.9 kn

Recalculating

CPA 1.0 NM
TCPA 12 min
ASSN AIS
T VECT 6 min
Open Water
Use predictors OFF
Show predictors OFF

OS 1
Mechanical engine underway
Give way ship Own ship
CPA/TCPA 0.5 NM / 3 min 01 s
BRG/RNG 223 ° T / 2.0 NM
HDG/SOG 64 ° / 19 kn

New manoeuvres calculating...

CHART DISPLAY FULL
SENC: SE4DIOXC
UTC 12:25:58
22 Aug 2022

Figure 43 Calculation in loop

8.4.5 Input for developers on algorithms having no memory

1. A prudent OOW should always take particular care when action is taken which could conflict with the action which is likely to be taken by the other vessel (Cockcroft & Lameijer, 2011). However, many proposed algorithms for COLREGs are based on linear extrapolation of straight-line vectors and do not encompass any probability of a certain manoeuver by the other ships. In reality, navigators may in addition base their decisions on additional factors such as previously gained experience of ship behaviour in the region (Murray, 2021).
2. Path planning algorithms will provide multiple course changes/legs, solving the traffic situation. The detection of threatening targets will then be based on this new monitored track and not necessarily based on COLREGs as described in the second example above.
3. An algorithm such as used in AIM calculates “constantly” if there are any threatening targets and suggests/executes a manoeuvre. That even applies if such target is performing a turn during which (albeit only for a while) it is considered as threatening and may therefore depending on the “reaction time” setting (i.e., the time between identifying a dangerous target and executing an evasive manoeuvre) trigger a new manoeuvre on the OS. The consequence may be a very erratic behaviour of autonomous ships.

4. Manoeuvers are planned and executed based on the actual speed of the OS and the speed of the target as received by AIS and/or ARPA sensors. Due to the inertia of ships, a change of speed will not be immediately noticeable and may further contribute to an erroneous depiction and subsequential calculation by the algorithm.
5. An algorithm for collision avoidance might need to include a prediction model for each target's long and short-term navigation strategy and goal.

8.5 Mathematical ship model used to calculate avoiding action

Algorithms used for the application of the COLREGs as well as avoiding groundings and allisions must be based on a hydrodynamic ship model representing the actual state of the real ship. Major parameters which define the outcome of a manoeuver are the turning and stopping ability of the ship. These parameters are in turn dependent on the Under Keel Clearance (UKC), the displacement and the environmental conditions (i.e., wind, current, waves, etc.). As these factors change throughout the voyage, a dynamic ship model needs to be developed. Furthermore, minimum, maximum and recommended turning radii need to be applied depending on the situation. For example, in adverse weather conditions certain manoeuvers may need to be avoided to eliminate the risk of heavy rolling.

8.5.1 Track keeping capability and ship controllability

Even if the algorithm is based on a particular mathematical ship model representing its maneuverability, various unexpected and undesirable motions related to manoeuvring behaviour can be expected (Perera & Batalden, 2019). Ships are under-actuated, meaning that ships have fewer control inputs than the number of degrees of freedom i.e., most ships are only controlled by propulsion and rudder and cannot directly control their position or orientation in the water. The majority of the research concerning algorithms for autonomous ships neglects the effects of under-actuation, especially if the ships are proceeding at slow speed or are reducing speed (Perera & Murray, 2019). The result of under-actuation can be:

- Difficulty in keeping the monitored route using track-steering at slow speed or when ship needs to slow down rapidly.
- Large overshoot angles when turning.
- Difficulty in keeping course and speed in rough weather.

Path-planning algorithms typically provide an ideal track but overshoot angles after large turns and depending on the ship’s course stability may in turn trigger a manoeuver on other autonomous (or manned) ships resulting in actual tracks (blue and green solid lines) as depicted in Figure 44. Having the rate of turn of targets as an input to the algorithm needs to be considered and it may be necessary that autonomous ships avoid taking any action as long as the target(s) shows a defined maximum rate of turn.

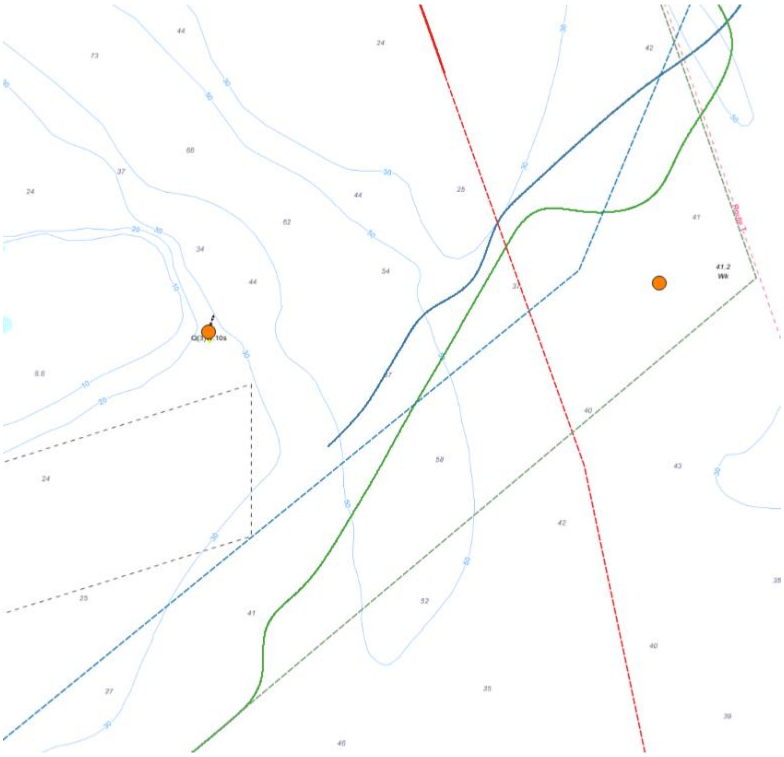


Figure 44 Track keeping of underactuated ships

9 Results of traffic scenarios with multiple ships

Based on the findings described in the previous sections it becomes obvious that there are numerous parameters and their settings which may or may not be an input to the calculation by the algorithm and eventually the action taken by it. Most approaches by researchers do not focus on encounter situations in high-density traffic areas and are therefore only partly applicable for more complex decision-making scenarios (Burmeister H.-C. , Constapel, Ugé, & Jahn, 2020). Therefore, the combined effect on a traffic situation involving three ships with equal and varying parameter settings is difficult to foresee, especially if a particular ship potentially finds itself in both a give-way and stand-on situation.

To investigate and illustrate possible outcomes in traffic scenarios involving autonomous ships, the same scenarios used in the Lighthouse project "Operationalizing COLREGs in SMART ship navigation" (Weber, Aylward, MacKinnon, Lundh, & Hägg, 2022) with manned ships as described in Table 8 were run by autonomous ships based on the assumptions and expectations that:

- Being perceived as at least as safe as modern manned ship is a prerequisite for the successful acceptance of autonomous ships (Wróbel, Gil, Huang, & Wawruch, 2022)

- The interpretation of the COLREGs made by humans and algorithms needs to have a high level of consistency to avoid near-misses and collisions (Perera & Batalden, 2019)
- Initially it is expected that autonomous ships will need to follow the existing COLREGs due to the mixed environment of both manned and un-manned ships (Perera & Batalden, 2019).
- Multiple autonomous ships interacting in the same sea area will need to perform complex decision-making as reliable as human operators with the difference that humans may be more adaptive (Kim, Perera, Sollid, Batalden, & Sydnes, 2022).

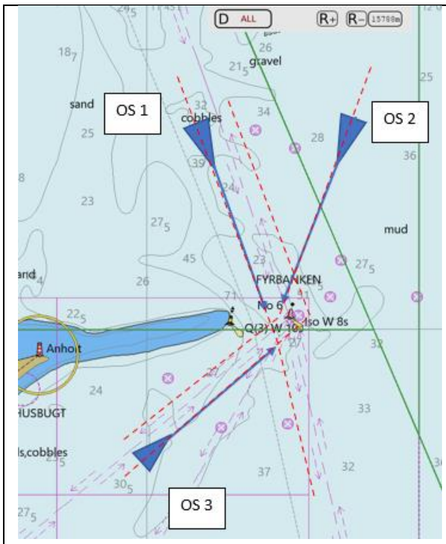
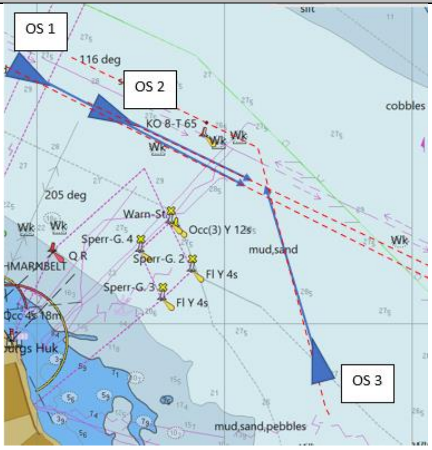
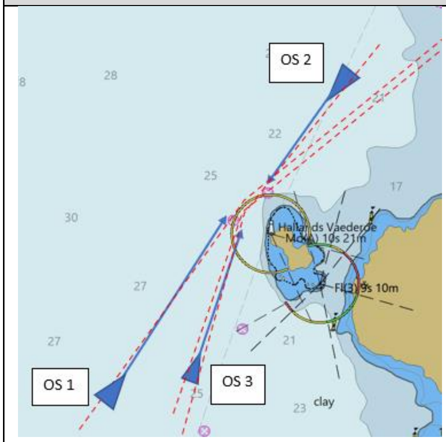
Using the same scenarios as in Lighthouse project "Operationalizing COLREGs in SMART ship navigation" (Weber, Aylward, MacKinnon, Lundh, & Hägg, 2022) enabled the project to visualize the:

1. Outcome of traffic situations of ships using the same algorithm but with different settings for the Safety Domain and TCPA (AIM software).
2. Outcome of traffic situations using algorithms by different developers (AIM and SHIPMAN software).
3. Comparing the outcome of traffic situations solved by humans and algorithms.

As the combination of all possible parameter setting in an algorithm is extremely high, testing gets very time consuming. Also, even small changes in courses, speeds, etc. by the involved ships may lead to a large variety of outcomes. Within this project the possible effect of only a limited number of parameters (i.e., TCPA/Safety Domain settings for ships running with AIM and fixed distance parameters for SHIPMAN) were investigated.

Table 8 Simulation scenarios 3 ships

Scenario	**Scenario Description**	**Distance between ships**			
Anholt			**OS 1**	**OS 2**	**OS 3**
	According to the COLREGs OS 2 is crossing in relation to OS 1 and therefore give-way vessel. OS 1 is give-way vessel regarding OS 3 but is	OS 1	X	4.6NM	10NM
		OS 2	4.6NM	X	9.7NM

	limited in manoeuvring space to starboard. OS 3 is stand-on vessel to both OS 1 and OS 2 and shall keep course and speed.	OS 3	10NM	9.7NM	X
Fehmarn			**OS 1**	**OS 2**	**OS 3**
	OS 1 is overtaking OS 2, and both are give-way ship for OS 3. Manoeuvring space to the starboard side of both OS 1 and OS 2 is limited due to a prohibited military area marked by special marks.	OS 1	X	2.1NM	10.9NM
		OS 2	2.1NM	X	8.9NM
		OS 3	10.9NM	8.9NM	X
Halland			**OS 1**	**OS 2**	**OS 3**
	OS 1 is overtaking OS 3and in a head-on situation with OS 2. All ships have limited manoeuvring space to their East. OS 3 is stand-on vessel in	OS 1	X	12.3NM	2.9NM
		OS 2	12.3NM	X	10.2NM

	regard to OS 1 and give-way vessel in regard to OS 2.	OS 3	2.9NM	10.2NM	X

9.1 Outcome of traffic situations of ships using the same algorithm but with different settings for the Safety Domain and TCPA (AIM software)

All three scenarios were run multiple times with combinations of different Safety Domain and TCPA settings as described in Table 9.

Table 9 Safety Domain and TCPA settings

Ship type and approximate dimensions Length, Beam, Draft in meters			TCPA	Safety domain (NM)			
OS1	OS2	OS3	minutes		OS1	OS2	OS3
Feeder Cont.	Tanker	Tanker	12 or 18	Forward	0.37 or 1.0	0.39 or 1.0	0.31 or 1.0
169 x 27 x 9.55	183 x 27 x 10.9	144 x 22 x 9.15		Starboard	0.27 or 0.75	0.29 or 0.75	0.23 or 0.75
Track colour				Astern	0.09 or 0.25	0.1 or 0.25	0.08 or 0.25
🟥	🟦	🟩		Port	0.18 or 0.5	0.19 or 0.5	0.16 or 0.5

The color-coded dashed lines represent the monitored route of respective ship and yellow dots represent fairway/navigational marks.

9.1.1 Tracks Anholt scenario

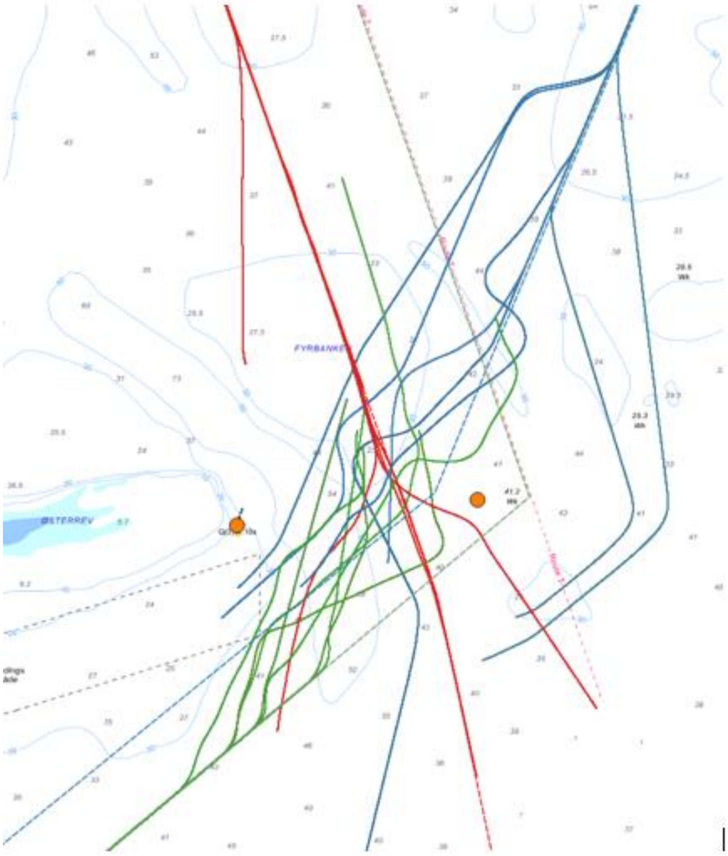


Figure 45 Tracks Anholt scenario autonomous

9.1.2 Tracks Fehmarn scenario

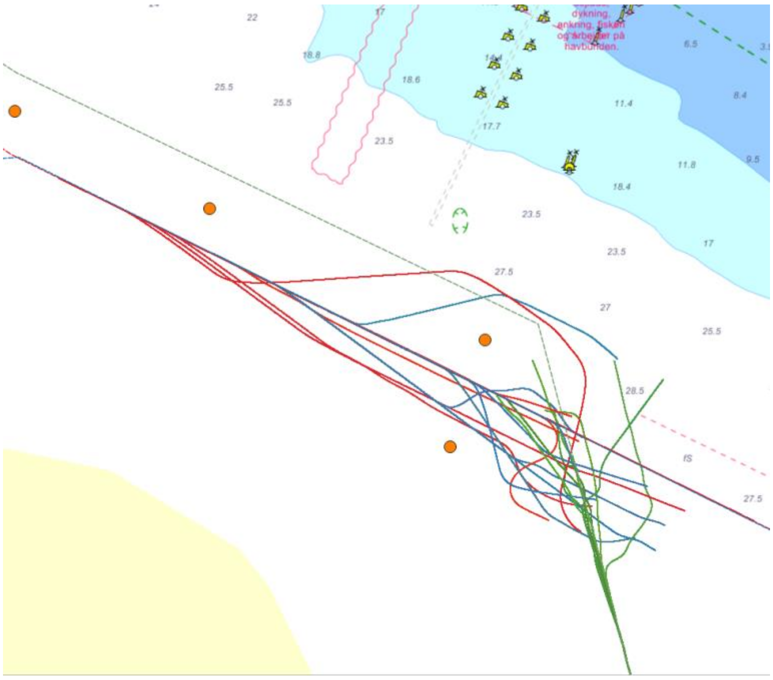


Figure 46 Tracks Fehmarn scenario autonomous

9.1.3 Tracks Halland Scenario

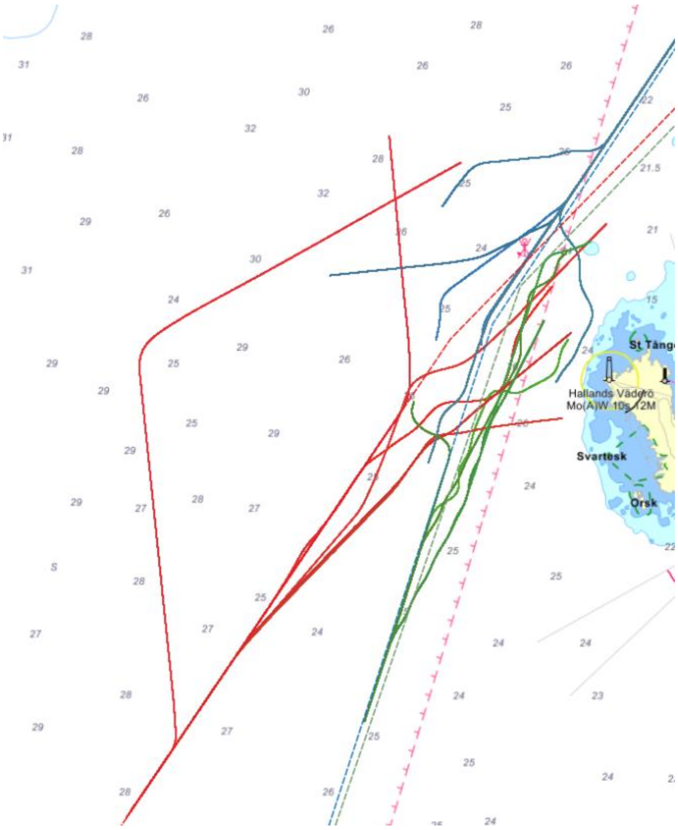


Figure 47 Tracks Halland scenario autonomous

9.2 Outcome of traffic situations using algorithms by different developers (AIM and SHIPMAN software)

Multiple simulation runs of the Halland scenario were performed with combinations of 3 autonomous ships using either the AIM or SHIPMAN algorithm according to Table 10, where the SHIPMAN models had approximately the same dimensions and manoeuvring characteristics as the Wärtsilä ship model.

Table 10 Combination of autonomous ships

	OS 1	OS 2	OS 3
Run 1	SHIPMAN	AIM	AIM
Run 2	AIM	SHIPMAN	AIM
Run 3	AIM	AIM	SHIPMAN
Run 4	SHIPMAN	SHIPMAN	AIM
Run 5	SHIPMAN	AIM	SHIPMAN
Run 6	AIM	SHIPMAN	SHIPMAN

9.2.1 First trial: AIM Default Safety Domain Settings and SHIPMAN fixed settings

The settings listed in Table 11 and Table 12 were used in the first simulation trial according to Table 10.

Table 11 First trial: AIM default Safety Domain and TCPA settings

Ship type and approximate dimensions Length, Beam, Draft in meters			TCPA	Safety domain (NM)			
OS1	OS2	OS3	minutes		OS1	OS2	OS3
Feeder Cont.	Tanker	Tanker	12	Forward	0.37	0.39	0.31
169 x 27 x 9.55	183 x 27 x 10.9	144 x 22 x 9.15		Starboard	0.27	0.29	0.23
Track colour				Astern	0.09	0.1	0.08
🟥	🟦	🟩		Port	0.18	0.19	0.16

Table 12 First trial: SHIPMAN settings

	COLREG Situation		
	Meeting	Overtaking	Crossing
Activation range for manoeuvre	40 x L	30 x L	30 x L
Manoeuvre description and objective	Turning to starboard to meet other ship with an off-set distance of 25 x B	Overtaking on other ship's starboard side with distance of 20 x B (navigable water permitting)	Turning to starboard to pass astern of other ship with a distance of 5 x L

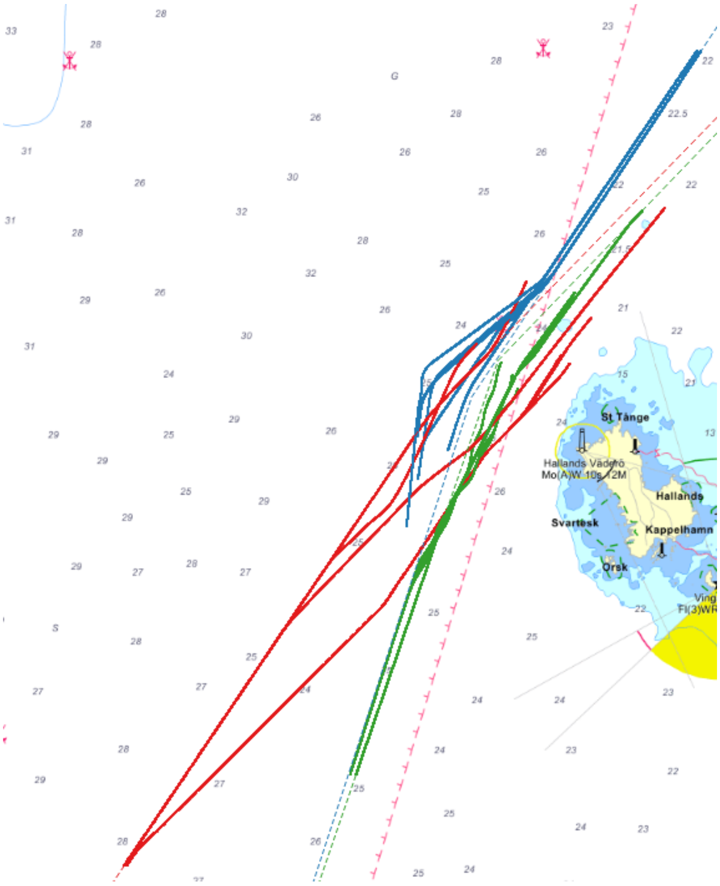


Figure 48 First trial: Tracks SHIPMAN-AIM (default settings)

9.2.2 Second trial: User set AIM Safety Domain setting and fixed SHIPMAN settings

The settings listed in Table 13 and Table 12 were used in the second simulation trial according to Table 10.

Table 13 Second trial: AIM user settings of Safety Domain

Ship type and approximate dimensions Length, Beam, Draft in meters			TCPA	Safety domain (NM)			
OS1	OS2	OS3	minutes		OS1	OS2	OS3
Feeder Cont.	Tanker	Tanker	12	Forward	1.0	1.0	1.0
169 x 27 x 9.55	183 x 27 x 10.9	144 x 22 x 9.15		Starboard	0.75	0.75	0.75
Track colour				Astern	0.25	0.25	0.25
🟥	🟦	🟩		Port	0.5	0.5	0.5

Table 14 Second trial: SHIPMAN settings

	COLREG Situation		
	Meeting	Overtaking	Crossing
Activation range for manoeuvre	40 x L	30 x L	30 x L
Manoeuvre description and objective	Turning to starboard to meet other ship with an off-set distance of 25 x B	Overtaking on other ship's starboard side with distance of 20 x B (navigable water permitting)	Turning to starboard to pass astern of other ship with a distance of 5 x L

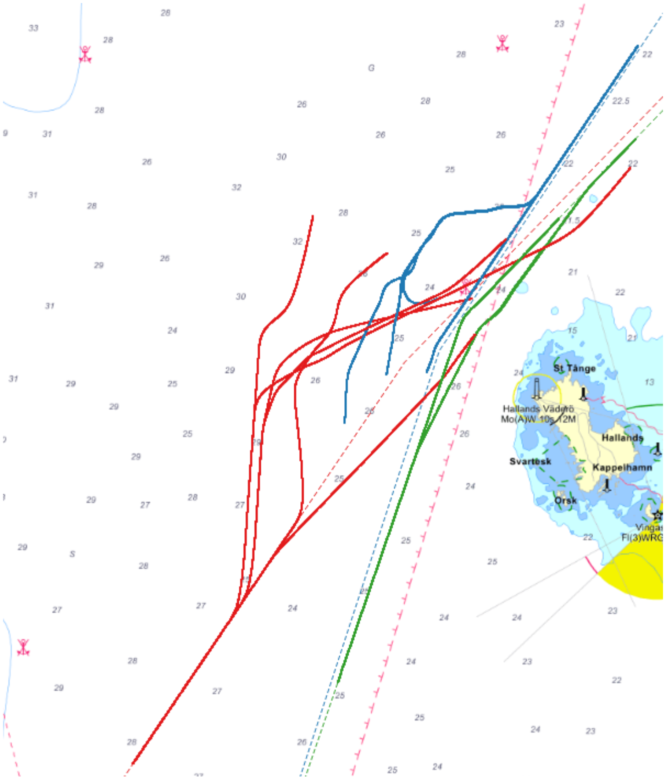


Figure 49 Second trial: Tracks SHIPMAN-AIM (user settings)

9.3 Side by side comparison of the outcome of traffic situations solved by humans and algorithms

9.3.1 Anholt

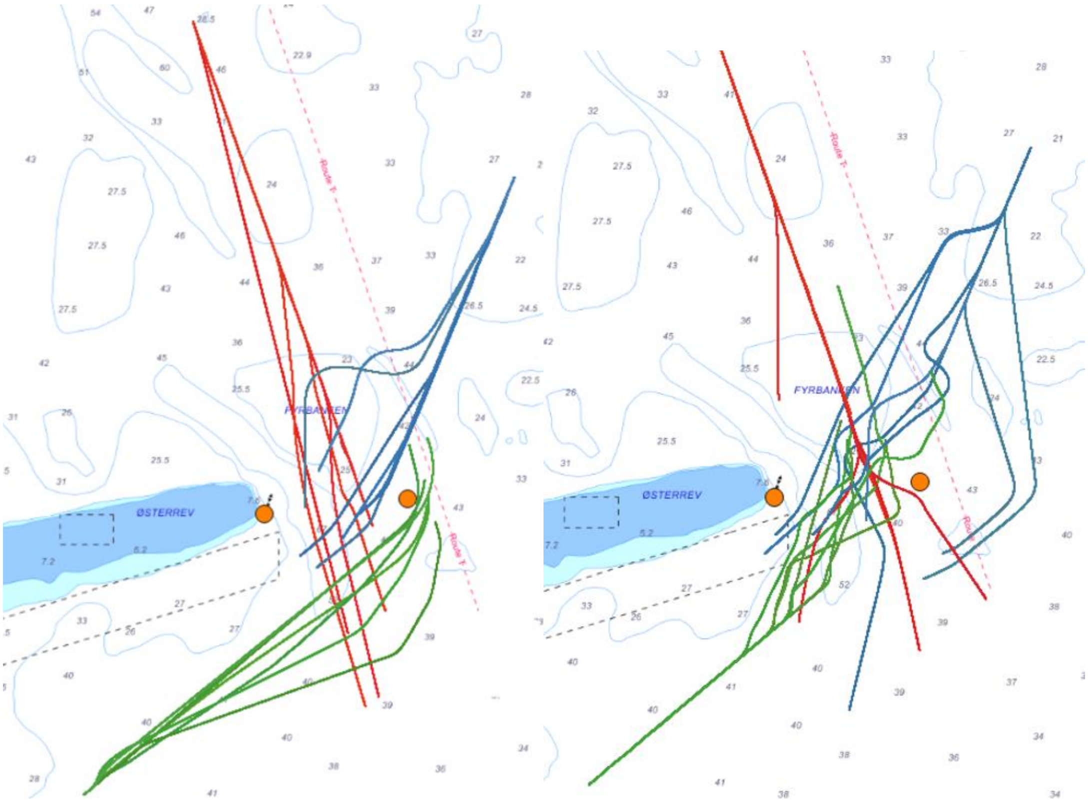


Figure 50 Tracks Anholt: Human vs. autonomous

9.3.2 Fehmarn

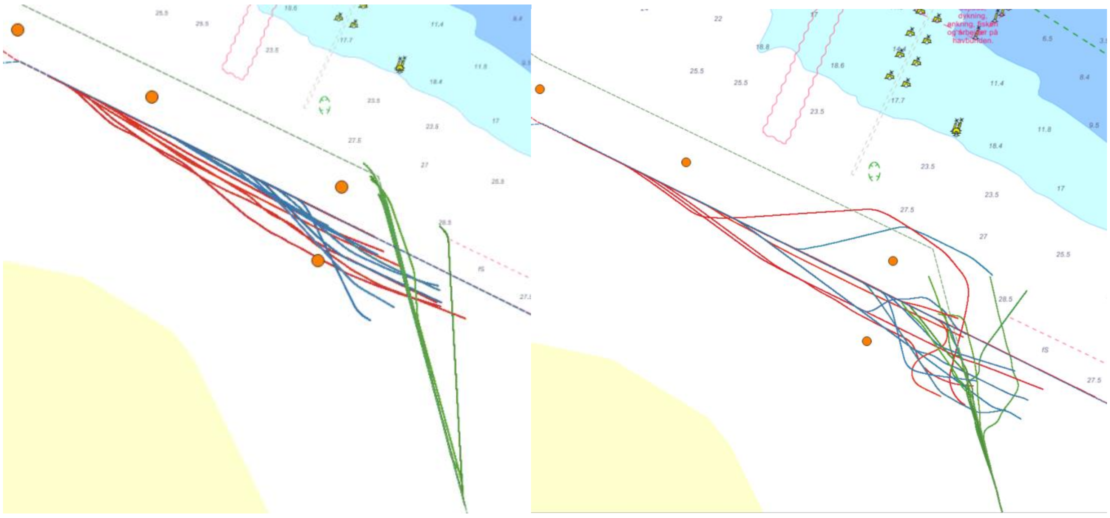


Figure 51 Tracks Fehmarn: Human vs. autonomous

9.3.3 Halland

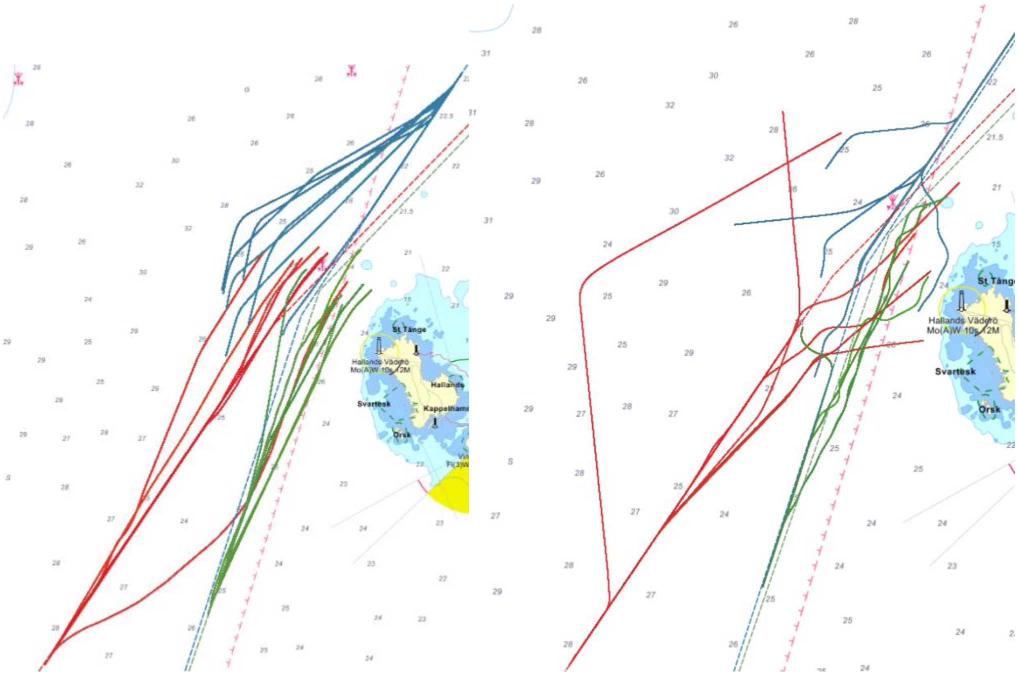


Figure 52 Tracks Halland: Human vs. autonomous

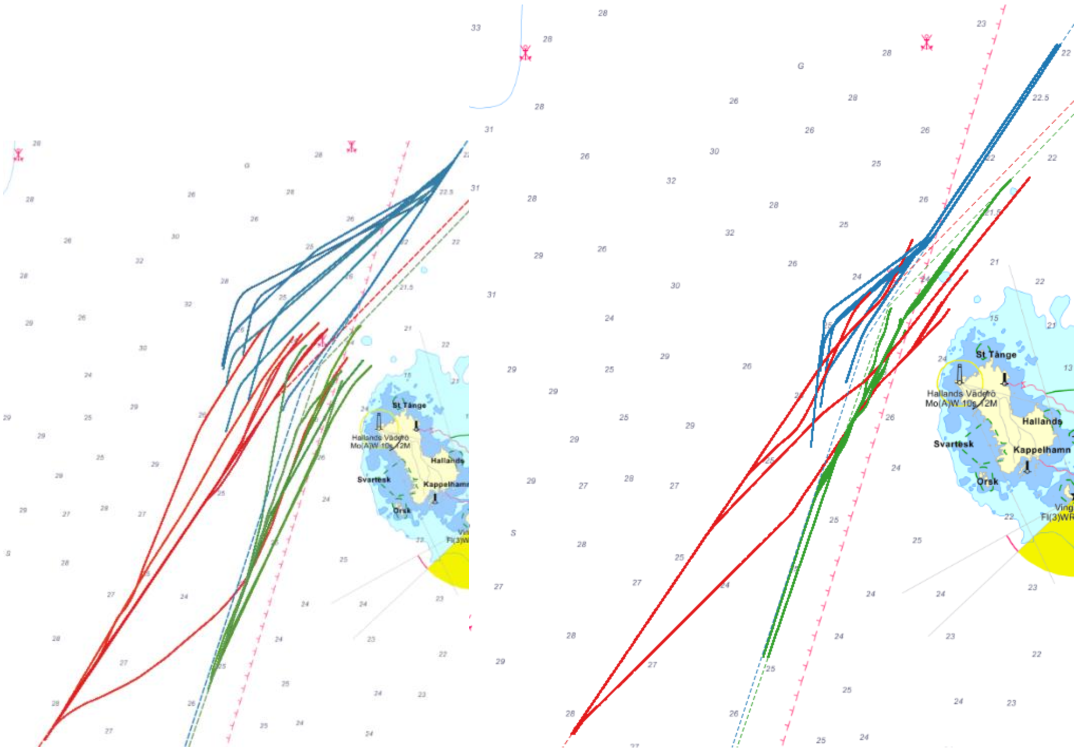


Figure 53 Halland: Human vs. mixed algorithms (AIM, SHIPMAN) 1

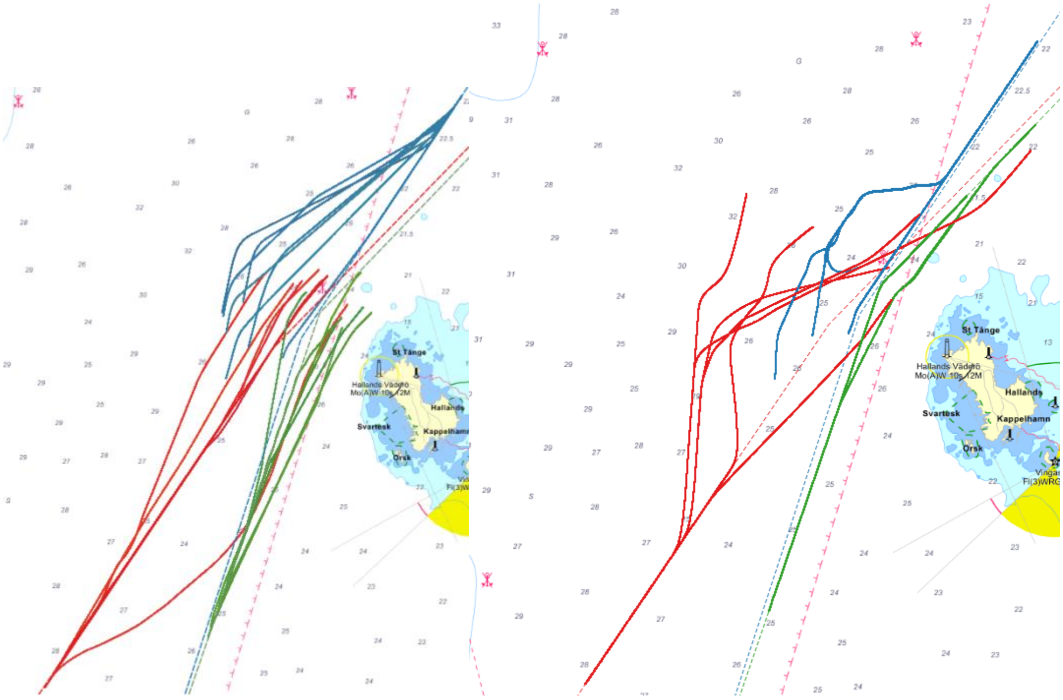


Figure 54 Halland: Humans vs. mixed algorithms (AIM, SHIPMAN) 2

9.4 Evaluation of multiple ship simulations

A visual evaluation of the tracks illustrates rather clearly the possible outcomes of executed avoiding manoeuvers in traffic situations with autonomous ships having different parameter settings. While certain settings and combination of settings may result in, at least visually, "orderly" outcome which is also somewhat consistent with humans solving the situation (described in 9.2.1 and visualized in Figure 48 and Figure 53), other settings result in rather erratic track patterns.

Considering that the simulation experiments were performed in calm conditions without any current and virtually no sensor uncertainties, the result shows that the actions based on the used algorithms in scenarios involving three ships are highly sensitive to:

- The interpretation of the COLREGs (especially for stand-on vessels).
- The time and/or distance when executing a manoeuver.
- The parameters of the Safety Domain if the action is based on time and Safety Domain.
- The vicinity of shallow waters and navigational marks.
- The course stability and track keeping ability of the own ship and target ship(s).
- The monitored route.

The possible effect of each of the above-mentioned factors on their own has been described individually in previous sections in traffic situations involving basically two ships only. While it may be debatable if the actions taken are correct and/ or safe, it is an eye-opener to contrast the combined effect of these factors in traffic situations involving three autonomous ships versus three manned ships.

Considering that humans have individual preferences, experiences and risk behaviour and may even interpret the COLREGs differently, their resulting traffic patterns are nevertheless very orderly and in stark contrast to the patterns resulting from autonomous ships. It is obvious that the level of consistency of the interpretation of the COLREGs made by humans and algorithms is very low, and autonomous ships may in these cases not be perceived as at least as safe as manned ships. The question whether this is due to a similar interpretation of the COLREGs (including the term "good seamanship") or that humans are more adaptive in complex decision making (Kim, Perera, Sollid, Batalden, & Sydnes, 2022) remains open. It is also interesting to note that the test participants in Lighthouse project "Operationalizing COLREGs in SMART ship navigation" generally perceived AIM as an advisory tool playing an important role in allowing the navigators to check their navigational decisions (Weber, Aylward, MacKinnon, Lundh, & Hägg, 2022), and it is reasonable to assume that even the further developed AIM software used in this project would not change that perception. However, in contrast to using AIM in "autonomous mode", participants were not only able to decide which of the suggested manoeuvre to select, but also to adapt or modify the manoeuvre depending on the movements of the other ships. Clearly, the step from a decision support tool to fully autonomous systems will also need to be able to "incorporate" the human ability to be adaptive in ever changing complex traffic situations.

Also, as it is initially expected that autonomous ships will need to follow the existing COLREGs due to the mixed environment of both manned and un-manned ships (Perera & Batalden, 2019), the track patterns of autonomous ships in the simulations performed are a convincing argument that traffic scenarios involving combinations of manned and unmanned ships should be performed.

10 Discussion: Addressing the research questions

As the COLREGs are written primarily for human operators, they are difficult to quantify and are open to some interpretation. To close the potential gap between the experienced navigator and the designers of algorithms, who rarely have the experience of numerous traffic situations and how the COLREGs are applied, practical examples in this report illustrate some potential consequences of using algorithms to solve traffic situations.

Algorithms for autonomous ships will require the input of a sophisticated sensor system and a decision and control system. In this project, the potential effect of only a limited number of input parameters of an algorithm have been investigated. As Wärtsilä's Advanced Intelligent Manoeuvring (AIM) is the only known system which allows mariners to test and verify their algorithm in a realistic and familiar environment, such as a high-fidelity simulator, most of the findings are based on simulations using AIM in automatic mode. However, as all algorithms will need to be based on the codification of the COLREGs, it is believed that many of the findings and suggestions in this report are directly applicable for any type of algorithm for autonomous ships.

Simulations indicate that the variances in parameters and their values result in different actions taken, and that the predictability of autonomous ships in a traffic situation may be poor. Some reasons behind may be simple coding errors, misinterpretations, or differing interpretations of the COLREGs but regardless, using a rule-based approach to codify the COLREGs, varying parameters and differing parameters between involved autonomous ships will influence the outcome of a traffic situation to a large degree.

Traffic scenarios involving three or more autonomous ships using different settings and/or different algorithms highlight the challenges in coding the COLREGs and possibly exacerbate the effects of varying settings. As ships in such scenarios may be both stand-on and give-way vessels, adds to the complexity. It is particularly striking to contrast the combined effect of these factors in traffic situations involving three autonomous ships versus three manned ships. While certain settings and combination of settings of the algorithms on the ships involved may result in, at least visually, “orderly” outcome which is also somewhat consistent with humans solving the situation, other settings result in rather erratic track patterns. However, it will not be sufficient for autonomous ships to use an algorithm which “fits” a particular traffic situation in a particular area and in specific conditions, fixed values and parameters when coding the COLREGs. In contrast to algorithms using a rule-based approach to code the COLREGs with fixed parameter settings e.g., when/at which distance to execute a manoeuvre to avoid another ship at a set distance, humans are flexible and will adapt these settings depending on a multitude of factors such as (among others):

- Type of traffic encounter (i.e., crossing, head-on or overtaking)
- Being stand-on or give-way vessel
- Geographical area including vicinity of land and/or shallow areas
- Traffic density and complexity of the traffic situation
- Environmental conditions (wind, sea state, visibility, etc.) affecting the maneuverability of the own ship
- Type, size and particulars of the ships involved
- The navigational state of the ships involved e.g., restricted in the ability to manoeuver
- Sensor data accuracy and reliability (e.g., radar, AIS)
- The familiarity/experience of the navigator with the area and traffic situation
- Prediction of other ships probable behaviour

- The own ship's monitored route
- Being able to rapidly detect visually, and act upon any changes of aspects (i.e., course changes) of other ships

Considering that humans have individual preferences, experiences and risk behaviour and may even interpret the COLREGs differently, the track pattern of simulations with manned ships points towards a common understanding and agreement among professional mariners on how the COLREGs are to be applied in more challenging and complex situations, even when Rule 2 needs to be used. This "orderly" pattern may well be regarded as a testimony of the strength and elegance of the COLREGs as a legal document, as it effectively balances the need for a set of clear, concise and universally understood regulations for preventing collisions at sea, with the flexibility to accommodate the unique circumstances of different types of ships and changing maritime conditions.

Various approaches including optimization methods, reinforcement learning, fuzzy-logic, neural networks, and Bayesian networks have been proposed to quantitatively evaluate and implement the subjective nature of the COLREGs but the significant drawback in all methods is partly the inability to model uncertainty, as the rules in the COLREGs are conditionals (i.e., requiring IF-THEN statements), which need to be either evaluated true or false, that there are no fixed values for when/at what distance rules are applicable and last but not least the inability to codify the term "good seamanship" and "ordinary practice of seaman".

To include all factors influencing human decision making in traffic situations and to potentially incorporate seafarer experience, flexibility and seamanship into artificial intelligence would require machine learning, more advanced neural networks, and a massive amount of data. Still, there will be the need of a weighing system in which, depending on the situation, the factors are more or less influencing the final decision and the executed manoeuvre. However, even then, autonomous ships with differing algorithms may weigh the factors differently and the potential outcome of a traffic situation ships may be comparable with the ones shown in the previous sections of this report. As it is initially expected that autonomous ships will need to follow the existing COLREGs due to the mixed environment of both manned and un-manned ships, it becomes imperative for there to be clear and universally accepted requirements and standards for autonomous ships, to ensure that all autonomous ships not only follow a common set of rules and algorithms in traffic situations but also that such set of algorithms reflects how professional mariners would handle the situation. The comparison of track patterns of autonomous ships and human operated ships in the simulations performed is a convincing argument that traffic scenarios handled by autonomous ships must be benchmarked against human operated ships and even combinations of manned and unmanned ships should be performed.

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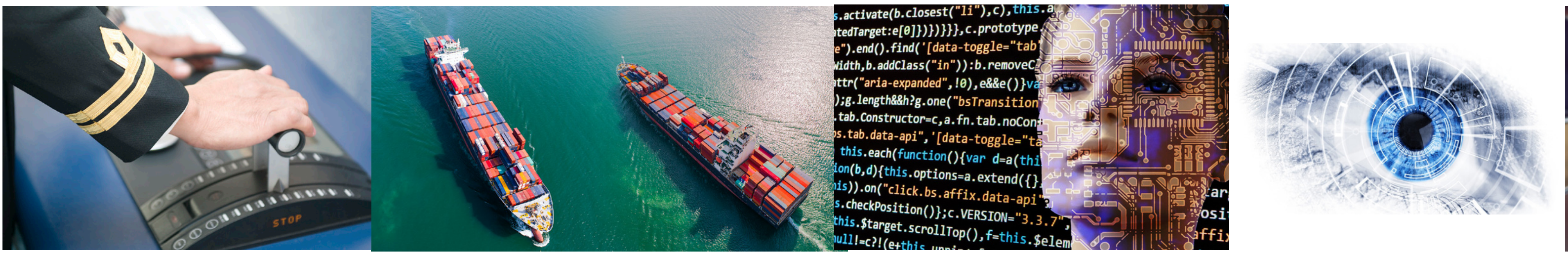

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