University of Strathclyde

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Human-Oriented Design: Automatic Collision Avoidance by Better Man-Machine Interaction and Information Flow

by

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A thesis presented in fulfilment of the requirements for the degree of Doctor of Philosophy

Glasgow, UK

2020

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Hesham Abdushkour *Date:* 24/02/2020

Acknowledgement

To my first supervisor, Professor Osman Turan, I would like to have the chance to express my most profound appreciation and thankfulness, for resolving all the obstacles I faced and giving me the opportunity to start my PhD. Afterwards, I cannot find a word to thank you enough for the great journey of the PhD with all the support, advice and guidance, which made it possible to accomplish this research, after the will of Allah.

I would also greatly thank my second supervisor, Dr Evangelos Boulougouris for the instrumental conversations and advice, which brought up ideas and hints that I could not reach alone. Additionally. I thank all my colleagues and staffs in the department for the great help and support in every day being in the research centre.

For the short periods that I managed to get out of the isolation of the PhD, my family; father, mother, brother and sisters were the greatest escape on my holidays back home. Despite the short holidays, we had countless memories and great moments, which helped me to carry on my journey. Not forgetting to mention their continued encouragement and support they gave me in order to reach where I am now. Also, I would like to thank my whole extended family and family-in-law for the great visits and support during my time in Saudi Araba.

Speaking about the minute-by-minute available person, my wife, you have been hugely supportive and patient during the whole journey and my ups and downs. I am grateful for all that you have done for me to go through all the challenges and make this happen alongside with your master then PhD duties. To our kids, Zaina and Hamza, I just want to thank you for keeping our hands full all the time, still, your present with us brought the happiness and joy in our lives and you were the greatest motivation to work harder. My wife and children, thank you very much.

My buddy, Mohammad Hittah, you have been, and still, a fantastic “brother” that I am glad to have you around with all the support, especially during your master degree here in Glasgow. I always enjoy our meaningful discussions.

Lucy Williams, thank you for your encouragement and valuable help for proofreading some pieces of my writing, which helped me a lot to improve my writing skills.

Great thanks go to the Maths Skills Support Centre at the University of Strathclyde for the help in the mathematical part; it is an excellent service that you are providing. A special thanks to Emma for being very helpful and cooperative.

Finally, I would like to thank King Abdulaziz University and the government of the Kingdom of Saudi Arabia for funding my PhD and allowing me to have this great opportunity. Also, I would like to thank the Faculty of Maritime Studies in Jeddah, Saudi Arabia, for the fantastic marine simulator centre, where I have performed my experiments. I would like to thank all the faculty’s staffs for their appreciated help during my time there.

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Table of abbreviation

Abbreviation	Full name
AIS	Automatic Identification System
ARPA	Automatic Radar Plotting Aid
ASM	Application-Specific Messages
ATC	Air Traffic Control
BRM	Bridge Resource Management
CAA	Collision Avoidance Logic
COG	Course Over Ground
COLREG	The International Regulation for Prevention Collision at Sea 1972
CPA	Closest Point of Approach
CSF	Critical Success Factors
CTPA	Collision Threat Parameters Area
DCPA	Distance to Closest Point of Approach
ECDIS	Electronic Charts Display and Information System
ENS	Electronic Navigational Charts
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FMA	Faculty of Maritime Studies, King Abdulaziz University
GLONASS	Global Navigation Satellite System
GPS	Global Positioning System
IALA	The International Association of Marine Aids to Navigation and Lighthouse Authorities
IMO	International Maritime Organisation
IMOC	Inter-Governmental Maritime Consultative
INS	Intelligent Navigational System
ISM	The International Safety Management Code
ITU	International Telecommunication Union
KPI	Key Performance Indicators

LPG	Liquefied Petroleum Gases
LPS	Local Port Services
MAIB	Marine Accident Investigation Branch
MCDM	Multiple-Criteria Decision Making
MMIS	Maritime Mobile Service Identity
MSP	Maritime Services Portfolios
NIS	Negative Ideal Solution
NM	Nautical Mile
NSA	Navigational Assistance Services
OOW	Officer of the Watch
PIS	Positive Ideal Solution
RA	Resolution Advisories
ROR	Rules of the Road
RO-RO	Roll On- Roll Off
SIP	Strategic Implementation Plan
SOG	Speed Over Ground
SOLAS	The International Convention of the Safety of Life at Sea, 1974
TA	Traffic Advisories
TCAS	Traffic Alert and Collision Avoidance System
TCPA	Time of Closest Point of Approach
TMAS	Telemedical Assistance Services
TOPSIS	The Technique for Order of Preference by Similarity to Ideal Solution
TTS	Traffic Separation Scheme
UTC	Coordinated Universal Time
VDES	VHF Data Exchange System
VHF	Vert High Frequency
VTS	Vessel Traffic Services
XTE	Cross-Track Error

Abstract

Despite the technological advancement and the automation of operations, yet, human involvement plays a fundamental role in ships navigation. Human is indispensable in any operation for their intellectual abilities of decision-making skills, based on available inputs and outputs. Moreover, the maritime industry has one of the most demanding operational obligations, where a single mistake can lead to catastrophic consequences that threaten lives, properties and environment. However, maritime accident statistics have revealed that more than 75% of maritime accidents are directly or indirectly linked to human errors (Chauvin, 2011). Out of all the accidents at sea; collision, contacts and grounding are estimated to be around 54.4%. It is obvious that reducing human errors will essentially enhance maritime safety and reduce the frequency of accidents at sea.

The main aim of this research is to prevent these accidents by developing an Automatic Collision Avoidance System and by designing a human-oriented communication flow on the ship's navigational bridge. This will increase the situational awareness of the crew to take necessary and timely actions, including speed reduction and manoeuvring. Additionally, this will allow crew members to make objective decisions based on real and correct information, rather than wrong decisions built on a wrong interpretation of the surrounding situation.

The developed automatic collision avoidance system has been inspired by the well-known safety reputation, aviation industry. In aviation, to prevent mid-air collisions, the aeroplanes are fitted with the Traffic Alert Collision Avoidance System (TCAS). This is an independent system that automatically detects collision situation, alerts the pilots about the collision risk and provide the best avoidance action to prevent mid-air collisions.

The ship's bridge navigational simulator has been utilised to validate the effectiveness and operation of the automatic collision avoidance system against the classical approach. Real ships collision investigation reports, from the Maritime Accident Investigation Branch (MAIB), were utilised to create scenarios for validation experiments, which were constructed using these real collision scenarios in the simulator environment to quantify the performance of the participants (OOW).

1 Introduction

1.1 Introduction

From 2011 to 2018, the navigational events have attributed to 54.4% of maritime accidents, where collisions are attributed to 26.2% of these accidents, contact 15.3% and grounding 12.9% (EMSA, 2018). Moreover, a comparison between the total number of the navigational related accidents (Figure 1) and the number of vessels sailing at sea (Figure 2) has revealed an interesting and logical relation (Table 1) (EMSA, 2018, Equasis, 2019). The number of accidents is correlating positively with the number of vessels, where the number of vessels has increased, and in a similar manner, the accidents have correspondingly increased too. Furthermore, the growth in the international maritime transportation and trade, which is increasing considerably since the 2009 economic crisis, is showing a high demand on the maritime industry (Figure 3) (UNCTAD, 2019). Accordingly, this has boosted the interest of scholars, organisations and countries to critically look at the maritime safety aspects and find the best possible approaches to enhance the safety level in the maritime industry.

Table 1 The number of vessels (≥ 500 GT) and navigational accidents from 2011 to 2017. Source: (EMSA, 2018, Equasis, 2019)

Year	Number of vessels ≥ 500n GT	Navigational related accidents
2011	50,788	890
2012	50,628	1025
2013	51,902	1375
2014	53,854	1410
2015	55,097	1342
2016	56,448	1305
2017	56,963	1390

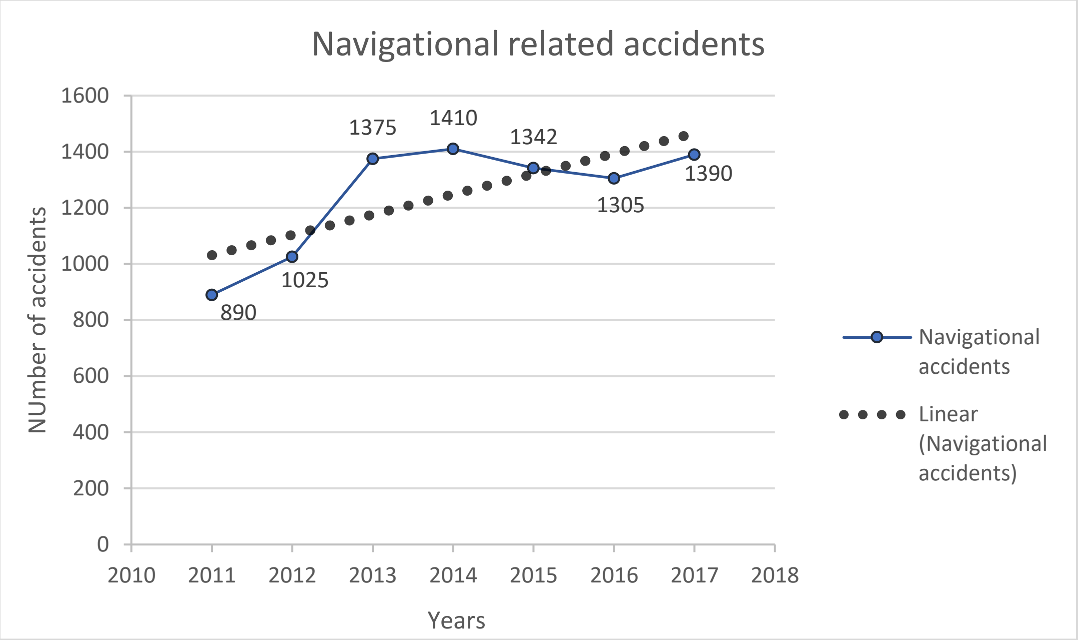


Figure 1 The increasing number of navigational related accidents over time. Source: (EMSA, 2018)

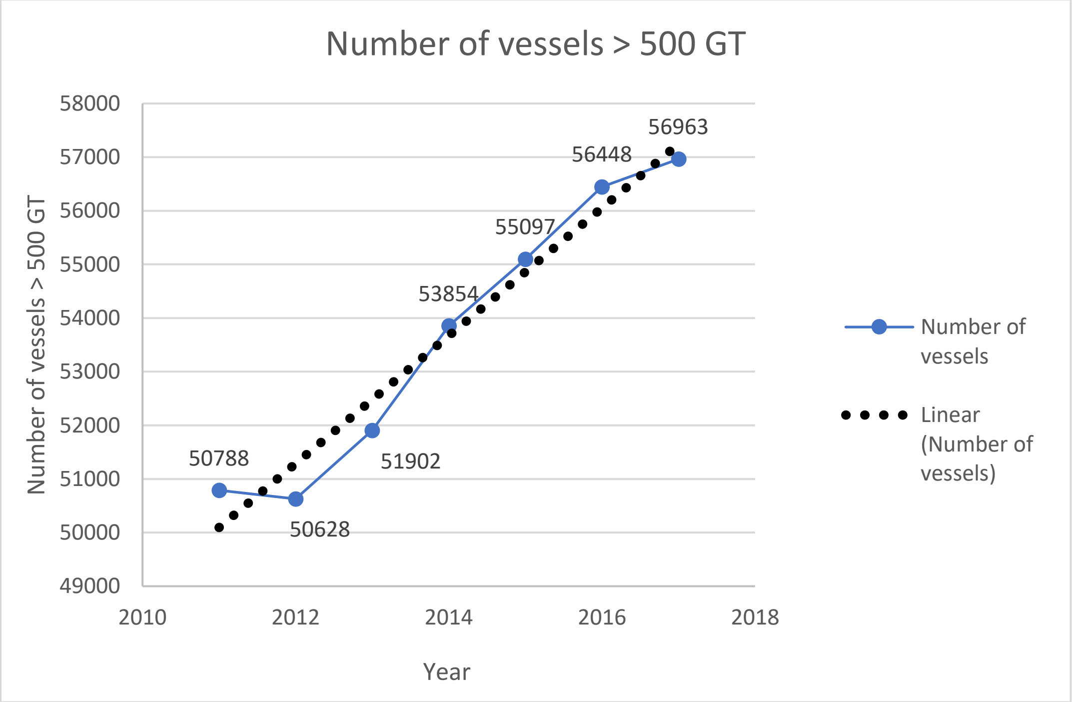


Figure 2 The increasing number of vessels (> 500 GT) over time. Source: (Equasis, 2019)

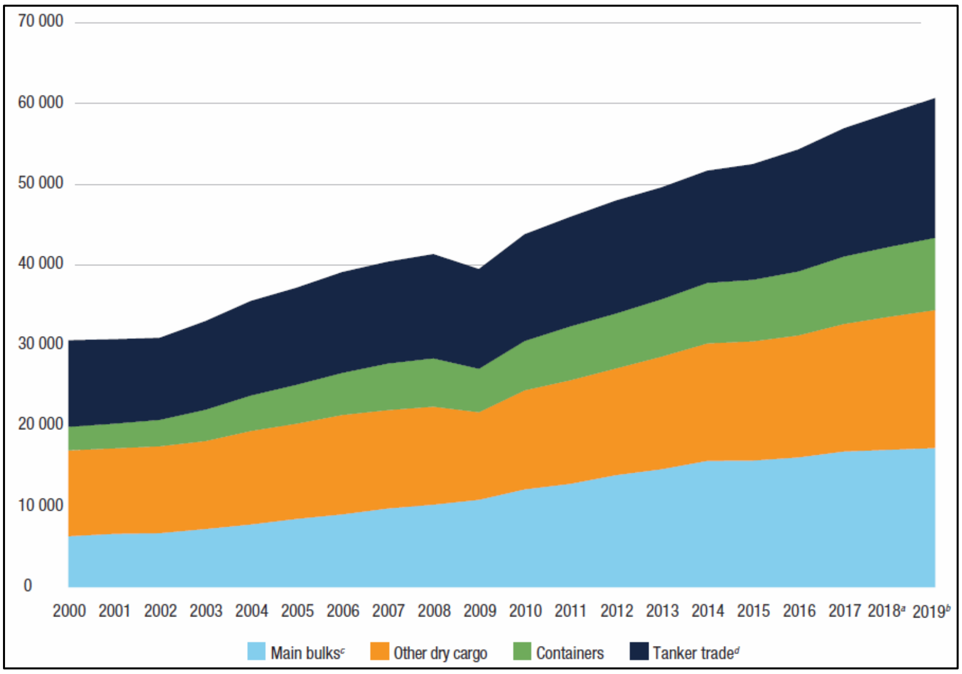


Figure 3 The growth in the international maritime trade (cargo ton-miles) (UNCTAD, 2019)

With further investigation carried on maritime accidents and its nature, it has appeared that the human factor was the most common underlying reason on-board ships that caused accidents. The human factor has been recognised in 75% to 96% of the cases that caused or led to accidents at sea (Allianz, 2017). Moreover, human action and respond to the emergency situation was the highest contributing factor that leads to an accident event, wherein 65% of the cases human action was the contributing factor of the accident (EMSA, 2019).

Based on the statistics mentioned above about the increasing demand for the maritime industry and, the numbers of accidents occurring every year at sea, preventive actions should be taken to enhance maritime safety. Historically, the global maritime community has been actively responding to enhance maritime safety since the tragedy of the Titanic, which sank in 1912. This tragic accident triggered the first version of the International Convention of the Safety of Life at Sea (SOLAS) in 1914, and since then it has been frequently amended (IMO, 2019b). The main aim of SOLAS convention is to determine the minimum standards for the construction, equipment and operation that are related to the safety of properties, lives and the environment at sea. Accordingly, in the last two decades three crucial safety developments in the maritime industry have been introduced;

- The International Safety Management Code, this code is related to the standardisation of the shipping management operation. This code entered into force in 1998 (IMO, 2019d).

- The Automatic Identification System (AIS), this is an automatic mean of sharing information between ships and shore centres. This system became mandatory for all ships above 300 GT built-in or after 2002 (IMO, 2019a).

- The Bridge Resources management (BRM), this is a new training requirement for the seafarers that motivate better communication skills between the crew members and a better utilisation for all the available resources on the navigational bridge. This training requirement has become mandatory under the STCW Convention, Manila 2010 amendments, and it has entered into force in 2012 (IMO, 2019c).

This historical background about the development in the maritime industry and the safety-related aspects has demonstrated the need for a more radical approach that enables sustainable maritime development. In the previous approaches, it was all about human-oriented strategies to enhance maritime safety, where it has been proven that human is the main factor to blame; thus, all the approaches were about improving the seafarer's performance to prevent human errors rather than looking into the whole human-system interaction holistically. Therefore, the accidents are still happening at sea. Additionally, an upsurge in fleets' and ships' sizes brings a higher potential for catastrophic accidents with undesirable consequences. Moreover, by reviewing the available navigational equipment on the bridge and its operational procedures, it has given the impression that they are all information systems only. These systems do not support the user in decision making. Instead, they only display the information, and the user is required to collect the information, process and make the decision. However, the increased number of ships made it beyond the human capabilities to deal with the tremendous amount of information at the same time. Thus, the likelihoods of human errors have increased significantly despite all attempts that have been made to improve human performance, without considering the utilisation of new decision support technologies on the bridge.

The most admitted accidental event at sea has been recognised as the navigation-related events; collision, contact and grounding. Moreover, the last introduction of a navigational system that aimed to help the Officer Of the Watch (OOW) in conducting a safe navigational duty was the AIS, almost two decades ago. Also, this is an information system that helps the OOW to acquire the required information about ships in the vicinity, but this does not help in decision making.

The motivation to conduct this research has been driven from the fact that the navigational bridge is in need for a technological revolution. This includes a better information flow that is simply accessible by the end-user when it is needed the most, man-machine interaction. Furthermore, the availability of such a reliable decision support system will have a significant impact on the performance of OOW and navigational safety. This will remove the boredom of collecting the required information, analyse it and make the best decision to get out of the critical situation. Additionally, this will remove the uncertainty of the decision making, whether the taken action is efficient to avoid a collision situation or further action is required. Where collision situation is one of the most occurring accident events, it would be a great safety achievement if these accidents can be eliminated or reduced. Furthermore, by reviewing other industries' techniques for collision avoidance, the aviation industry has an appealing opportunity that can be implemented for the ships to achieve a satisfying level of safety. One of these techniques is the Air Traffic Collision Avoidance System (TCAS). This system is a fully automatic system that detects any collision situation, alert the pilot about the situation and provide the best avoidance action (Abdushkour et al., 2018, Murugan and Oblah, 2010). The only action is required by the pilot is to execute the avoidance action based on the system instructions. Therefore, developing an automatic collision avoidance system that is suitable for the maritime practises being implemented on-board ships will help the OOW to avoid collision situations that threaten the safety of his ship.

1.2 Thesis structure

A summary of the thesis structure is provided below:

- Chapter 1 states the background of the historical development in maritime safety and the introduction of new conventions and regulations that aim to improve the safety level in the maritime industry. The recent increases in fleets sizes and their relationship with the occurrence and causes of the maritime accident are presented in this chapter.

- Chapter 2 provides the aim of this research and the objectives that will be achieved from this study. This includes the motivation behind this research and the problem definition.

- Chapter 3 presents the critical review on the topics related to the maritime accidents to identify the main reasons for these accidents and the main contributing factors, to reflect on the weaknesses and strengths of the processes and procedures, which are fruitlessly preventing the accidents, and to focus on the collision prevention techniques to understand their role in the navigational procedure. Reviewing the literature about the developed studies on automatic collision avoidance systems and other industries for the interest of developing a better collision avoidance procedures and system.

- Chapter 4 provides the adopted methodology that has been followed to conduct this research. This includes a demonstration of the utilised methods and techniques that have followed in this study.

- Chapter 5 details the technical specifications of the available navigational equipment on-board ships with its operational standards. Additionally, a detailed study on the aviation collision avoidance procedures and the TCAS system is explained in this chapter. This chapter provides thorough information, which is essential to develop a state-of-art automatic collision avoidance system.

- Chapter 6 proposes the framework of the automatic collision avoidance system, which describes the structure of the system with the technical and operational specifications for the utilisation of the new automatic collision avoidance system.

- Chapter 7 details the utilisation of mathematical techniques and formulas to develop the automatic collision avoidance system model. These formulas are used for the collision risk assessment and the calculation of the avoidance manoeuvres.

- Chapter 8 demonstrates the validation experiments, which are performed in the full-mission bridge navigational simulator, to test the new automatic collision avoidance system. This includes the utilisation of the Key Performance Indicators (KPI) to measures the performances of the participants against the classical procedures for collision avoidance at sea.

- Chapter 9 discusses the outcome of the research and achieved benefits of the developed automatic collision avoidance system. This details the achievement of the aim and objectives of the research and the gaps in the study with the recommendation for the best development of the system to continue for future research.

- Chapter 10 present the conclusion of the research with the key contributions that have been achieved through this research.

2 Aims and objectives

2.1 Problem definition

Although the shipping industry has proven its efficiency as a mode of transport with an adequate safety level, it still has a high potential for catastrophic accidents. For example, an accident in a tanker ship can cause severe impact on the environment, potentially lasting more than a decade, with costs reaching up to billions of US Dollars, such as the oil spill of Deepwater Horizon in the Gulf of Mexico. Similarly, other shipping sectors may cause different types of disasters: take passenger ships, for instance, with a carrying capacity of more than thousands of passengers on-board, has the potential for fatal consequences. For example, the collision and grounding of the passenger ship Costa Concordia, which has 4229 passengers and crew on-board, where 32 people have lost their lives in this accident (MIT, 2013). It is therefore vital to ensure a high level of safety is achieved and maintained in such an industry. Accordingly, the maritime accidents' statistics show that more than 80% of accidents are caused directly or indirectly by human error, with more than 50% of those accidents due to contact, collision and grounding (EMSA, 2017, Allianz, 2017). Human performance can be affected by many factors, such as fatigue, heavy workload, inexperience, language difficulties, skills, omission, etc., and these factors have many dangerous consequences on the navigational duties. As a result, the overall situational awareness on the bridge could deteriorate, contributing to more human errors, giving the operators wrong perception about their surrounding environment. Due to misunderstanding and/or misinterpretation, the OOW may base his decisions on inaccurate information, which could be the root cause of a collision at sea. Additionally, the high amount of data-flow on the navigational bridge, which comes from the navigational equipment, is beyond the human capability to handle, based on the cognitive load theory. Thus, this research is focusing on developing techniques and systems to enhance human reliability and support the OOW in the collision avoidance decision process.

2.2 Motivation

Surprisingly, there are no automatic collision avoidance systems on-board ships, yet. However, all the available navigational aids on-board ships are information systems, which provide navigational information to the OOW. The OOW then needs to understand this information, analyse it and then take the most appropriate action, to avoid a collision. On the other hand, the aviation industry uses the TCAS system, which provides the pilot with both visual and verbal avoidance alert and necessary manoeuvre automatically without any interaction from the pilot. Moreover, the TCAS system is mandatory by regulation, and it has proven its reliability as an automatic collision avoidance system over the time of development of the system.

2.3 Gaps

- There is no automatic coordination and information exchange between collision avoidance systems in the maritime industry. This will help in sharing the same mental model and ensuring all targets are aware about the avoidance manoeuvre.

- There is a lack of standardisation in the display and operation of the navigational systems.

- There is no interaction between operators (OOW) and systems to ensure an adequate level of situational awareness, man-machine interaction. This means if the OOW is not reacting to alarms going off due to dangerous situation, there is no other procedures to prevent accidents from happening.

- The collision avoidance models in the literature are about unchangeable ships' parameters.

- No approved standardisation of the collision avoidance parameters to support the OOW in decision making. Such as minimum Closest Point of Approach (CPA) and minimum time to CPA (TCPA).

2.4 Aims

The main aim of this research is to develop an automatic collision avoidance system to support the OOW in taking the most appropriate avoiding action, objectively. These actions are taken based on the real surrounding environment and targets. In addition, any subjectivity in the OWW's actions will be avoided. Where most of the times the OOWs are taking correct navigational actions, yet, in some cases, they make subjective decisions based on wrong interpretation of the situation around the ship and that can lead to dangerous accidents at sea. Thus, the intelligent E-navigation framework, aviation technologies and more enhanced procedures will be developed/used to conduct this research. In order to achieve this, integration between all navigational aids on-board ship will be utilised and displayed in the new system, with a user-friendly display unit. The concept of the new system will consider the human-centred design approach in the layout, displaying information and provide the OOW with warnings and optimum avoiding actions. Moreover, this will enhance the overall situational awareness on the bridge, and the maritime safety generally by reducing the number of accidents at sea.

2.5 Objectives

- Critically review the available literature on maritime safety and the factors that cause the maritime accidents. Also, review other industries' approaches for accidents prevention.

- To develop the system's architecture (framework) of the automatic collision avoidance system. This includes the coordination and information exchange function between ships' systems in collision situations, with the acknowledgement of manoeuvres to ensure all ships are aware of the situation and the appropriate actions to be taken.

- To develop the automatic collision avoidance system, which can evaluate the risk of collision, calculate the optimum avoidance decisions and provide guidance/instructions to OOW.

- To test and validate the developed automatic collision avoidance system in the full-mission ship's bridge simulator, to examine the efficiency and capability of the system in real scenarios collision avoidance abilities.

3 Critical review

3.1 Introduction

This chapter will illustrate the literature and critical review that are related to the general topic of maritime navigational safety and focusing on the development of the automatic collision avoidance system for ships. The structure of the chapter as follows; the first section is a brief statistical analysis about the maritime accidents. Then, the discussion of the causes of the maritime accident, this includes the human factors, bridge procedures for collision avoidance, bridge ergonomics and the human psychology of decision making. After this, the review of the COLREG regulation and its difficulties will be performed. Available system in the bridge and its weaknesses will be discussed. The next section will be discussing the differences between the procedures in the maritime and aviation with regard to collision avoidance. Finally, the critical review of the research topics of the automatic collision avoidance models will be presented. The chapter will be concluded with a discussion about the main critical outcomes that need to be addressed in this research to develop an efficient automatic system that can help the OOW in decision making for collision avoidance.

3.2 Maritime accidents statistics

In order to unravel the issue of maritime accidents, it is important to identify the problem as this will explain the main contributing factors for maritime accidents. The following two pie charts illustrate the most frequent marine accident types and the contributing factors that lead to these accidents (EMSA, 2017). In (Figure 4), the percentage of each type of accident is shown, where 50% of these accidents are; collision, contact or grounding (EMSA, 2017). Accordingly, by reducing the frequency of these navigation-related accidents, the total number of accidents will be reduced.

Furthermore, (Figure 5) shows the main contributing factors that lead to accidents in the maritime industry, which are; the human factor that causes 60% of the accidents, equipment failure with 23%. However, it is important to reduce human errors, and enhance the reliability of the navigational systems and equipment to reduce navigational related accidents. Based on these statistics, mitigating the number of navigational related accidents and the main contributing factors of these accidents (human errors and equipment failures) will reduce the maritime accidents drastically and enhance the maritime safety dramatically.

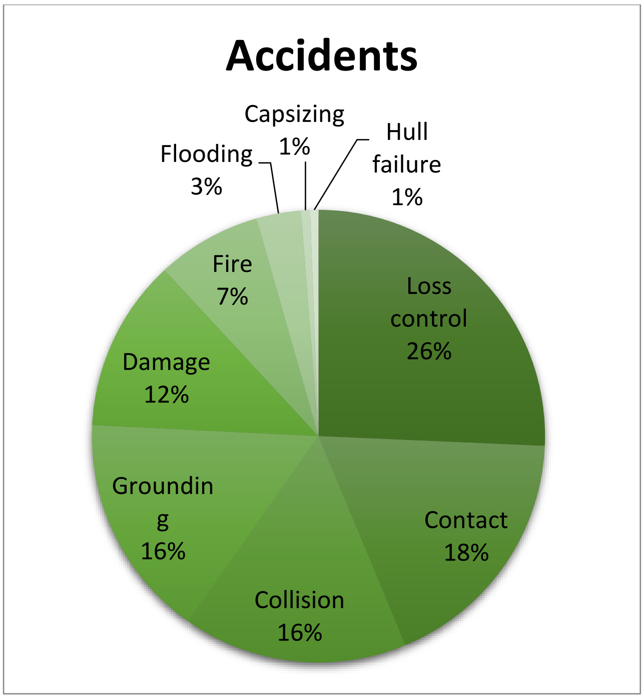


Figure 4 Maritime accidents events (EMSA, 2017)

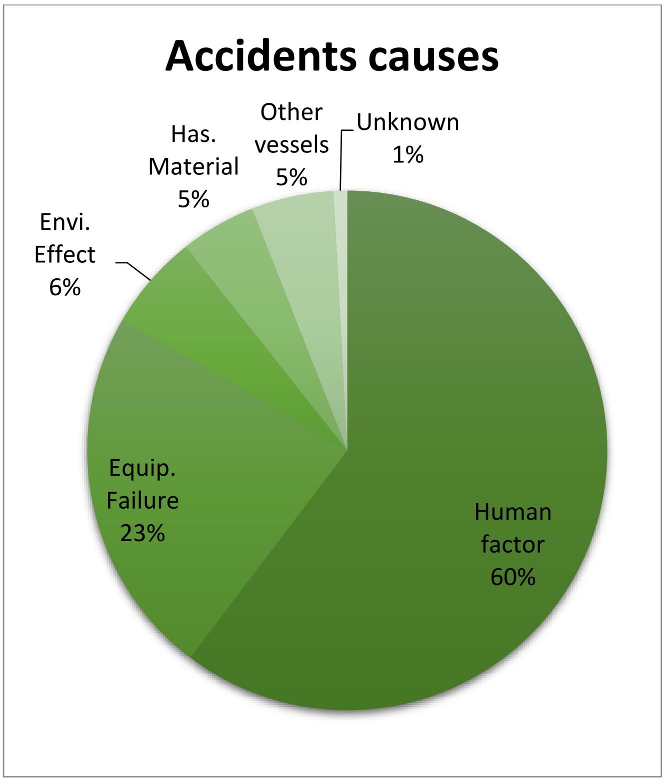


Figure 5 Maritime accidents causations (EMSA, 2017)

3.3 Main Causes of Maritime Accidents

Maritime transportation is an essential player in the global economy, in which over 90% of the world's trade is carried by ships (ICS, 2017). Moreover, ships are, by far, the most cost-effective mode of transport goods and raw materials across the world (Hetherington et al., 2006). The maritime industry has proven its efficiency in transporting almost every type of goods in competitive expenses, comparing to other modes of transportation (ICS, 2017). In addition, ships' enhancement in terms of performance and capacity has offered superior services to end-users through better optimisation in the supply chain services.

On the other hand, a catastrophic marine accident can be highly harmful to the environment, properties and lives (Chauvin, 2011). Maritime accident investigations have revealed that around 80% of all maritime accidents are directly or indirectly linked to human errors (Baker and McCafferty, 2005, Rothblum, 2000). By revealing the root causes of maritime accidents, this will considerably help to find preventive solutions, which therefore, reduce the maritime risk through reducing the frequency or/and consequences of those accidents (Rothblum, 2000, Montewka et al., 2017).

This section will investigate the relationship between human element, bridge procedures, bridge ergonomics and automation. Moreover, the contributing factors that either; enhance or deteriorate the maritime safety and collision avoidance procedures.

3.3.1 Human Element

Human is involved in almost all marine operations, with different levels of engagement, depending on the automation advancement on-board ships (Popa, 2015, Hetherington et al., 2006). Nonetheless, the role of the human is changing according to technological advancement. Previously it was human who performs all the operations, such as; mooring, mechanical operation, calculation and measurement (Hetherington et al., 2006). Nowadays, the role of human has changed to monitoring and controlling the performance of computerised and automated operations (Rothblum, 2000). However, this does not stop or eliminate human error, the other way around; this produced more opportunities for operators to make different kinds of errors due to the complexity and increased number of the navigational equipment and the information they provide. With the availability of the navigational equipment, OOWs tend to make mistakes in acquiring, proper interpretation and usage of the information and the efficient monitoring of the navigational equipment. Nevertheless, human has the ability to adapt according to the situation to make the best judgment in a specific case, they need to build their decisions based on correct information. Whereas, automated systems have better calculation ability and accuracy, yet, they act according to the available information. Accordingly, computer systems do not have the intellectual abilities to solve real world problems (Stranks, 2007).

Although, there is no doubt in the effective involvement of human in navigational duties and decision-making abilities. However, the increased demand on the maritime industry has made it difficult for the operators to cope with the current situation without support. The increased demand has introduced extra workload on human, such as;

- Increased cargo loading and discharging speed at ports.
- Faster and larger ships.
- Marine traffic congestion leading to more complex navigational condition.
- More navigational equipment to monitor.

- Reduced manning number on-board ships.
- Commercial pressure to meet market requirements.
- Increased regulation fulfilment requirements.

Accordingly, these issues have initiated a dilemma, which has placed operators in a situation that forced them to perform inefficiently (Hetherington et al., 2006, Chauvin, 2011, Stranks, 2007). In addition, the introduction of automation systems, which does not accommodate the human needs, and the reduction of manning level on-board ships has put in extra load on human (Hetherington et al., 2006, Viorica, 2015). Furthermore, the manning reduction on the bridge has resulted in creating more admin work for the OOW. However, the introduction of poorly designed automation systems has moved the workload from being physical loads to mental loads. In conclusion, the above-mentioned dilemma has resulted in the deterioration of human performance. The factors that have impacted on human performance has been diagnosed as following;

- Stress and fatigue.
- Situational awareness.
- Training and communication.

Stress and fatigue

To tackle this problem, the IMO has introduced the work-rest hours regulations to ensure everyone has adequate rest on-board. Despite that, seafarers are still working for long hours without sufficient rest, especially in the case of frequent port operations (loading and discharging). Additionally, the stressful working environment in maritime industry, which is obliged to meet certain requirements, such as, deadlines, increased number of regulations and procedures, self-actualisation and good appraisal for promotion, all this has increased the amount of stresses for seafarers (Popa, 2015, Baker and McCafferty, 2005, Squire, 2005). As a result of extra workload to meet regulation needs and commercial pressures, the likelihood of suffering from fatigue and stress due to lack of proper sleep and rest has increased, which also increased the chances of making errors (Baker and McCafferty, 2005, Squire, 2005). Those errors are contributory factors in the chain of events that end with unpleasant accidents (Chauvin, 2011).

Situational awareness

In order to obtain and perform safe watch, the OOW must be aware of the real situation around his/her ship, with full understanding and interpretation of all targets in the vicinity (Baker and McCafferty, 2005, Hetherington et al., 2006). The misunderstanding or misinterpretation of the surrounding situation, which is triggered by the incorrect risk of collision assessment or wrong reading from navigational equipment has a negative impact on the OOW situational awareness (Kurt et al., 2016).

Training and communication

In general, the training level for the basic and general knowledge in the maritime industry is reaching an acceptable level. However, the problem is in the lack of standardisation of navigational equipment; in such case, the OOWs need to be familiar with different manufactured equipment in different ships (IMO, 2003). However, normally the handover between officers take a few hours, which is not enough to learn about new devices. On the other hand, there is a need for better communication skills among crew and officers with better motivation toward safety culture. Additionally, full implementation of knowledge from the crew/bridge recourse management courses is required to achieve an adequate level of situational awareness (Hetherington et al., 2006, Popa, 2015, Baker and McCafferty, 2005). This will ensure that all people engaged in the navigational process are sharing the same mental model and take decisions based on the real situation.

In summary, the human reaction in a critical navigational situation is being compromised due to the above-mentioned factors, which are negatively influencing the OOW performance. This has affected the OOWs' decision making efficiency and that resulted in most of the accidents at sea. Subsequently, eliminating the factors that cause the stress and fatigues to the OOWs, as well as providing effective methods that support the OOW and allow an increase in the situational awareness level will enhance the OOW's performance in the navigational duties and the maritime safety significantly. Additionally, the importance in the maritime training programmes to ensure the best education level is delivered to the OOW with the latest technologies' available on-board ships.

3.3.2 Bridge Procedures

The procedures have been developed to standardise the operation on-board ships to reduce the human errors and enhance operator' performance. However, these procedures are not applicable all the time, as the scenarios are changeable in real-life situations. In some cases, the OOW cannot comply with the single procedure as he has many tasks to perform in the same time, and each task has different procedures (Kurt et al., 2016). Another issue where the procedures do not match with the specific situation, either because of different layout or different systems need different procedures, or crew member does not follow a specific approach of performing a particular task (IMO, 2003). Moreover, it is the commercial pressure where the crew have to satisfy the needs of higher management level or costumers, which force them to divert from the original procedures or applying a different process to perform tasks and/or take shortcuts within the procedures (Dhillon, 2007, Mearns et al., 2013). Unfortunately, this can increase the possibility of human errors where different people apply different procedures, and in every time a task is performed differently (Kurt et al., 2016). In other words, the lack of standardisation and synchronisation, between the operational standards and the tasks in hand, has forced the operators to develop their own processes or take a shortcut to perform tasks in the absence of best operational standards (Mearns et al., 2013, Johnson and Shea, 2007).

3.3.3 Bridge Ergonomics and Automation

After discussing the role of the human in maritime operation and their influential factors in most of the accidents, it is important to establish a structure or identify a proven approach that can enhance human performance has become more evident. The ergonomic design, which concerns about the study of human and their working place in a manner that enhance human reliability and task performance, offers a possible solution for reducing human errors in the maritime industry (Stranks, 2007, Mallam et al., 2015).

If human needs to adapt to the way that the task is designed, then the operator is not able to perform to the optimum level, which then increases the probabilities of making human errors. Therefore, first, the ergonomic principle and its aspects will be explained to give a better understanding of the ergonomic design techniques. Then, how ergonomic is beneficial in designing a ship’s bridge so that the operational procedures can be designed to enhance human performance, rather than the other way around.

Ergonomic definition

Ergonomic is the design or layout of a working place to comply with the capabilities and limitations of human performance (Javaux et al., 2015). Designing ergonomically helps in reducing human over-stress and enhancing the performance by more comfortable working place (van de Merwe et al., 2016). Moreover, the automated systems' ergonomic display, which is designed to reach the optimum operational level obtained by operators (IMO, 2000, Mallam et al., 2015). Ergonomics can be applied in physical designs or as cognitive ergonomics (Stranks, 2007):

- Physical designs are about the physical capabilities of human in performing any tasks or operation, the allocation of a human within the surrounding environment (Stranks, 2007). This includes the lifting operation, movement in working place, reaching and handling devices, controller of systems and safety and health issues.

- Cognitive ergonomics are more focused on the relationship between human, machines and automation in a way that ensures optimum human perception and interaction with systems (man-machine interaction) (Stranks, 2007). That will help the operator with the decision-making loop, better situational awareness, less stressful situation and optimum tasks performance.

3.3.3.1 Ergonomics and Layout of Classical Navigational Bridge

With regard to the ergonomics and layout of the traditional navigational bridge, it is apparent how the navigational equipment is placed in various locations around the bridge (Figure 6). Moreover, in the maritime industry, the adoption of new regulation about allowing new technology or system in ships takes a minimum of five years to be enforced. Additionally, it is the nature of developing the navigational equipment, where every system has been developed individually in a different timeframe. As a result, the systems and equipment have been located in the available spaces on the bridge without consideration to the applicability of the locations for conducting the navigational duties (Bole et al., 2014d). Consequently, the OOW needs to be mobilised in the bridge to observe and monitor the navigational equipment and to collect the necessary information. Although, in newly constructed ships, the issue of systems integration and bridge ergonomic have been considered (Bole et al., 2014d). Still, the OOW needs to monitor several navigational systems to ensure the safe operation is obtained from all of the equipment. In this case, cross-checking in various equipment is essential, such as; GPSs with ARPA and ECDIS, AIS with ARPA and ECDIS, weather monitoring devices and magnetic and gyrocompasses.

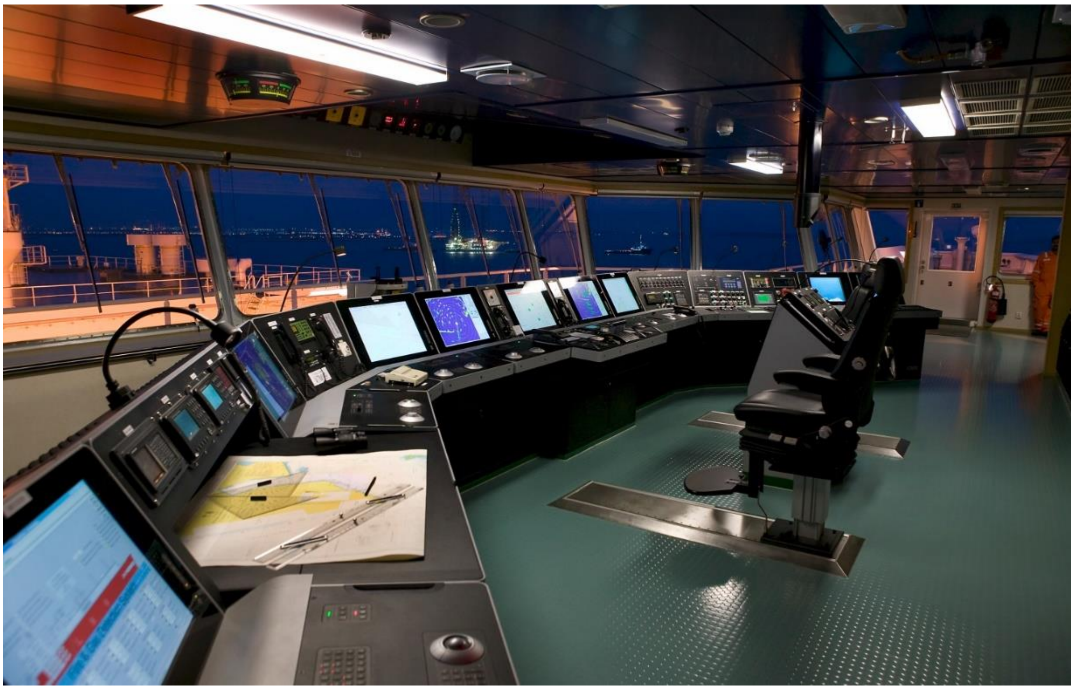


Figure 6 Ship's bridge (NOIA, 2017)

3.3.3.2 Enhancing navigational safety by implementing an ergonomic design in the ship's bridge

Generally, in maritime industry the naval architects, who design and build ships, are disengaged or incoherent with the end-users in ships' operators (Montewka et al., 2017, Österman et al., 2016). Therefore, without a complete awareness about the needs of the end-users to perform a task or duty, it would be difficult for naval architects to design an ergonomic and productive working place. In order to solve this challenge, attention shall be given to the needs of end-users (crew, OOW and engineers) (Costa et al., 2017). Accordingly, human-centred design of a navigational bridge can be achieved if full attention is given to the crew's and OOW's feedback to meet their needs in performing tasks (Costa et al., 2017). Also, consultations and discussions with experts from the industry will provide useful input about how better to design the ship's bridge to encourage an enhanced working environment to OOWs. Another solution is to assign a number of naval architects to spend some time on-board ships to fully understand the nature of life on ships, then assign them to redesign the navigational bridge to fulfil the seafarers desires (Norros, 2014). Additionally, move from the mind-set of developing the best and latest technologies, to human-driven technologies, which support and aligned with human needs, in order to have improved resources to perform tasks (Norros, 2014). With all these in consideration and better developed and ergonomically designed ships' bridge, an enhanced navigational safety will be achieved (Javaux et al., 2015, van de Merwe et al., 2016). This achievement will be targeted by better situational awareness, through a clearer perception of the OOW about the surrounding situation in an improved working environment (Costa et al., 2017). Due to this, the OOW will be more confident and able to make correct decisions in critical situations and this will lead to improved control over the entire ship.

However, this research will focus on the area of cognitive ergonomics, which study the relationship between human and machines, to improve the man-machine interaction and performance. In general, more focus is given to the man-machine interaction and the enhancement of human reliability in operations. By applying the cognitive ergonomic designs and man-machine interaction principles, human performance will be enhanced, and this will reduce human errors (Stranks, 2007). Thus, a great focus shall be given to the man-machine interaction and control of the system (the automatic collision avoidance system). Great attention is given to the information exchange between the navigational system and the user (OOW), which is the main source that OOWs depend on to maintain a safe navigational watch. However, a well-designed display unit (man-machine interaction) is able to minimise operational stresses, human errors and improve the overall human performance (Parasuraman and Riley, 1997, Stranks, 2007). For systems' control, one should consider the physical capabilities and strength of human for convenient operation (Stranks, 2007). Inefficient design of control station can be difficult to operate, and it could be a source of physical injuries, frequent mistakes and difficulty in operation and accidents in working place.

3.3.4 Educational psychology and human learning behaviour

After the discussion about the factors that have an impact on human performance during the navigational watch, which have a negative effect on the OOW, an action must be taken to support the OOW and enhance the navigational safety. Thus, investigating the characters of human learning and processing information will play an essential role to improve human performance. Moreover, to find a comprehensive solution that can support the OOW and the overall navigational safety, considering the human psychology in human-machine integration can play a major role to enhance the navigational process. Also, this will improve the working environment on the navigational bridge to achieve optimum performance. This can be attained by understanding the process in the human brain that helps to learn new skills and retrieving prior knowledge for problem-solving. This is covered in the educational psychology field, under The Cognitive Load Theory (Leppink, 2017).

Cognitive Load Theory

In general, the human utilises two different storage location, in the brain, that help in solving any problem or situation. The long-term memory and short-term memory (Sweller, 2016, Paas et al., 2003a). The long-term memory is where the previously learned knowledge and skills are located, where they can be retrieved when needed (Sweller, 1988). The long-term memory has unlimited capacity, where human is learning new skills and problem-solving techniques on everyday bases. In an effort to utilise the knowledge from the long-term memory, this information must be retrieved and allocated upon the required task (problem), based on the problem-solving experience of the person (Paas et al., 2003b).

The short-term memory is the working memory and it can hold a very limited amount of information, about two to three elements at the same time (Paas et al., 2003a). In this short-term memory, the person holds the required information (elements) to solve a problem in hand. This is the most related and important process in problem-solving that has an influence on the OOW in navigational duties and decision making. Therefore, here where the limitation in human performance and capabilities come into the picture as the very limited number of elements restrict the human from handling large amount of information at the same time. Additionally, the learning process of any new topic or skills starts with receiving the information in short-term memory. Then, retrieving the required pre-learned skills or knowledge, from long-term memory. After that, analyse the new information (inputs) based on prior learned experiences, to solve a problem in hand (Chandler and Sweller, 1991). With practice and experience, new knowledge and information move from short-term memory to long-term memory, which improves the performance of the person in his own field (Leppink, 2017).

However, the limited capacity in the short-term memory makes it difficult for a human to handle a complex situation. Likewise, in the navigational duties, where the OOW is required to monitor and perform a large amount of information and tasks, this is usually how human errors occurred. Where the human has a limited capacity to hold a tremendous amount of information, process them and then make the decisions, the potential to forget or miss an important part or task is becoming higher.

Based on the cognitive load theory, full consideration has been given to the human capabilities in handling navigational information. This has the motivation of finding a solution that allows the OOW to perform better and enhance the overall situational awareness on ships. In this manner, the proposed solution in this research aims to reduce the amount of information that required to be processed by the OOW, to reduce the load on the short-term memory. This will be achieved by the utilisation of the computer. In which computers have great mathematical and computational capabilities, this will be used to perform the complicated calculations, then provide it to the OOW. The responsibilities of the OOW will move from collecting information, do the analysis and make the decisions, to utilise the prior knowledge (from the long-term memory) to judge the system's decision and apply it. Figure 7 shows the operational process triangle, this triangle illustrates the interaction between human and machine, where certain procedures need to be implemented for the best application of the available system.

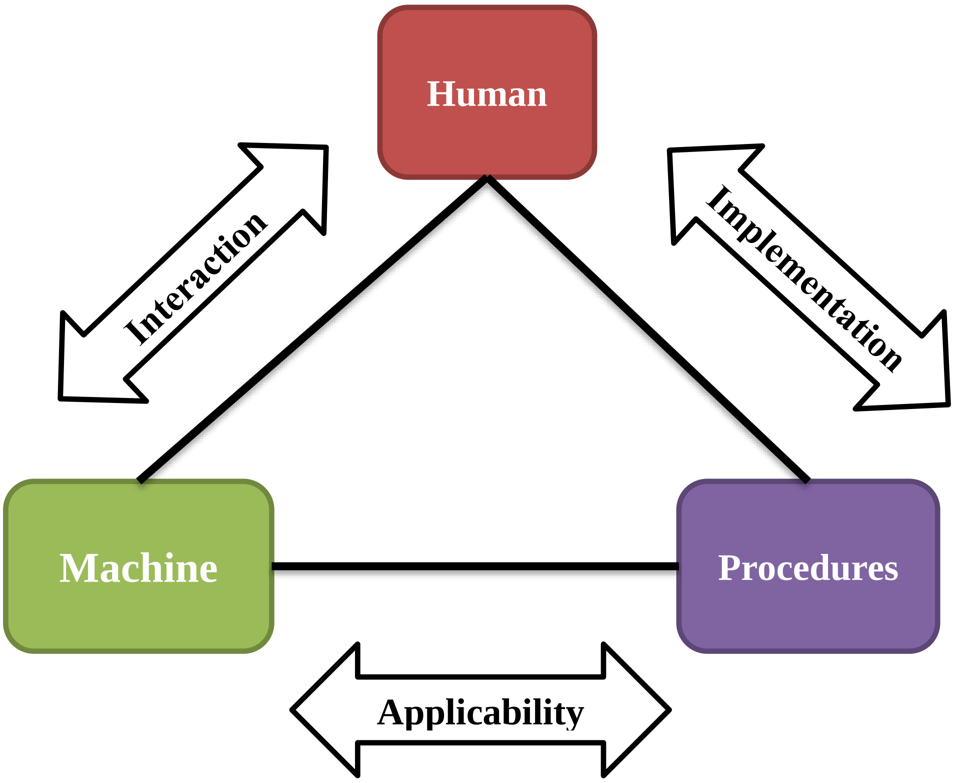


Figure 7 Operational process triangle

3.4 The International Regulation for Preventing Collision at Sea 1972

In fact, The first Rules of the Road (ROR), which also known as the COLREG, was introduced in 1840 by the London Trinity House, then entered into force in 1846 by the parliament (Cockcroft and Lameijer, 2012a). Eventually, the last major review and rewrite of the collision regulation were in 1972, after the deliberation of London conference by the Inter-Governmental Maritime Consultative IMOC (which is now known as the International Maritime Organisation IMO). As a result, the Convention of the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) brought up to the light (Cockcroft and Lameijer, 2012a). This convention entered into force in 1977 and followed by some minor amendments heretofore (COLREG, 2017, Belcher, 2002). The COLREGs are basically a set of rules that provided to the OOWs in order to help them with regards to the encountered situation, such as; crossing, head-on or overtaking (Wang et al., 2010).

Nevertheless, this requires full understanding and interpretation of the whole situation around the ship (Mohovic et al., 2016). However, the OOW will be able to appoint the responsibilities between vessels in encounter situation and how to avoid collision situation (Wylie, 1962). Finally, the rules guide the OOW about the suggested course of actions to avoid collision with other vessels and give some prohibited actions that shall not be taken under any circumstances. COLREG consists of 38 rules in which they are categorised in five parts as follows; Part A, is a general information and comments, Part B, Steering and Sailing Rules, Part C, the Lights and Day Shapes of vessels, Part D, the Sound and Light signals and Part E, Exemptions of some vessels from following some rules (IMO, 2005, COLREG, 2017). Furthermore, are four annexes for technical details and specifications of the navigational lights, shapes, sounds and distress signals (COLREG, 2017). However, these rules and its interpretation need to be well understood by the OOW to avoid any conflict situations at seas.

3.4.1 Explanation of Collision Situations and Actions in COLREG

With the consideration of COLREG, three conditions of vessel conflicts have been identified that covers all possible collision situation at sea (IMO, 2005). Identifying the conflict situation takes priority in order to assign the legal responsibilities between vessels as well as knowing the action to be taken and by which vessel it should be taken (Cockcroft and Lameijer, 2012d). Part B, Section II of COLREG regulation is the related section of vessels in sight of one another, which mentions the collision situations and the actions to be taken by the vessels in these conditions (IMO, 2005). The collision situations are Overtaking, Head-on and Crossing; but, it is crucial to correctly interpret the conflict situation in order to take the correct actions (Mohovic et al., 2016). Moreover, the legal responsibilities to allocate which vessel should take action and which one should continue in her route (the Give-way vessel and the Stand-on vessel) should be clearly spelt out. Thus, it is worth mentioning the definitions of these situations and actions with some of the essential points of COLREG in relation to collision situations.

Overtaking situation / Rule 13

Any vessel approaches the other from the stern is an overtaking vessel, and she shall keep clear of the vessel being overtaken (Figure 8) (IMO, 2005, COLREG, 2017). However, the stern sector is 22.5° abaft the beam of the ship, or at night it could be recognised by the stern lights, 135° (IMO, 2005, Cockcroft and Lameijer, 2012d).

Head-on situation / Rule 14

Any vessel meets the other on a reciprocal or near reciprocal course in a head-on situation, and both vessels shall alter course to starboard side, so they pass port to port (Figure 9) (IMO, 2005, COLREG, 2017). In such case, both vessels see the other ahead, and they can see the masthead light on a line or nearly on a line with both sidelights (IMO, 2005, Cockcroft and Lameijer, 2012d).

Crossing situation / Rule 15

Any vessel on a crossing course with another, where the risk of collision exists, is in crossing situation (IMO, 2005, COLREG, 2017). The vessel sees the other on her starboard side shall keep clear, as well as avoid to pass ahead of the other vessel if the circumstances admit it (Figure 10) (IMO, 2005, Cockcroft and Lameijer, 2012d).

Give-way vessel / Rule 16

The vessel that required keeping clear of another by this regulation is the Give-way vessel (IMO, 2005, COLREG, 2017). She shall do so in an early time with enough actions to be recognised by other vessels to keep well clear (IMO, 2005, Cockcroft and Lameijer, 2012d).

Stand-on vessel / Rule 17

The vessel that is not the Give-way is the Stand-on vessel, and she shall maintain her course and speed (IMO, 2005, COLREG, 2017). However, if the Give-way vessel is not taking action or her action alone is not enough to void the collision, then the Stand-on one shall take the best action to avoid the collision (IMO, 2005, Cockcroft and Lameijer, 2012d). Moreover, the Stand-on vessel, when she has to take action, should avoid altering course to the port side if she has a vessel on her port side. Also, the Give-way vessel is not relieved from her obligation to keep clear of the Stand-on one (IMO, 2005).

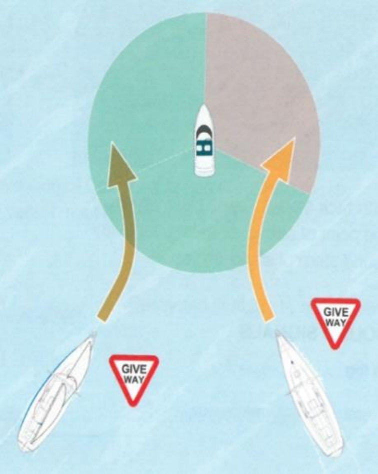


Figure 8 Overtaking situation (RYA, 2014)

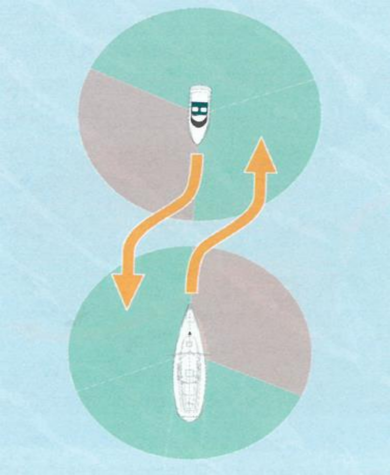


Figure 9 Head-on situation (RYA, 2014)

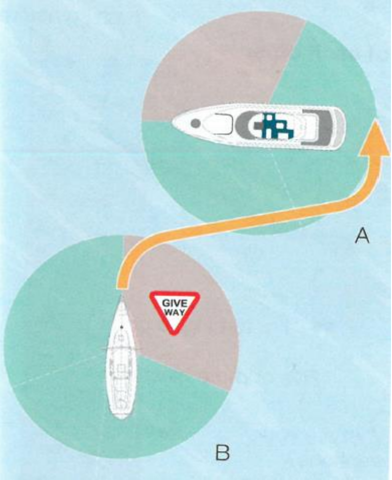


Figure 10 Crossing situation (A) Stan-on, (B) Give-way (RYA, 2014)

3.4.2 The Subjectivity and uncertainty of COLREG regulation

In maritime navigation, all collision avoidance manoeuvres are made based on the Collision Regulations COLREG (the Rules of the Road). Although these rules have helped in managing the maritime traffic and also advised every vessel about the collision avoidance manoeuvres that need to be taken in every situation, it did not stop accidents from happening (Lušić and Erceg, 2008, Demirel and Bayer, 2015). Especially nowadays, traffic density and ships' speed have increased significantly. After an in-depth study of the COLREG, we found a number of issues that can cause problem and confusion for the OOW (Demirel and Bayer, 2015, Belcher, 2002, Wylie, 1962, Szlapczynski and Szlapczynska, 2015). First of all, the subjective nature of the rules, where it does not inform the OOW about the specific action to take, instead it leaves the decision to OOW to decide (Belcher, 2002, Szlapczynski and Szlapczynska, 2015). That is clear in some phrases such as; "If the circumstances of the case admit" "In ample time" and "If there is sufficient sea room" all these cases are subject to the interpretation of the situation (Cockcroft and Lameijer, 2012d, Wylie, 1962). Moreover, COLREG does not inform the OOW with the magnitude, nor the time to take the avoidance action (Wang et al., 2010, Belcher, 2002). However, the judgement is left to the experience of the OOW and the good seamanship practices, which makes it dangerously subjective decisions (Cockcroft and Lameijer, 2012c, Belcher, 2002, Wang et al., 2010). Nevertheless, if we look at rule 15 Crossing Situation, it is clear that the ship sees the other one on her starboard side is the Give-way vessel, and she should avoid the Stand-on vessel (Cockcroft and Lameijer, 2012d). Whereas in rule 17 it says *"the Stand-on vessel may take action to avoid collision by her manoeuvre alone as soon as it became apparent to her that the vessel required to keep out of the way is not taking appropriate action"* (Cockcroft and Lameijer, 2012d). Again it is left to the OOW on the Stand-on vessel to decide when to take action then again they are subjective decisions (Belcher, 2002, Wang et al., 2010, Kunieda et al., 2015). On the other hand, looking at the risk of collision, and the collision avoidance regulation, it is highly dependent on the OOW interpretation of the situation; however, people perceive risk levels differently (Stranks, 2007, Mohovic et al., 2016, Szlapczynski and Szlapczynska, 2015). As a result, OOWs' risk perception is varying, thus, this impact on the time where the OOW decides to start the avoidance action, as well as the magnitude of the actions (Belcher, 2002, Wang et al., 2010, Hadnett, 2008). In this case, COLREG appears as ambiguous, with a high level of subjective and uncertain rules that left the OOW to decide the magnitude and time of actions based on his interpretation of the situations (Mohovic et al., 2016, Wylie, 1962).

Moreover, there is an ambiguity with the regulation in case of more than two vessels involved in a collision situation. All the scenarios of encounter in COLREG regulations assume two vessels in a collision course and no instructions are given if more than two vessels are approaching a collision point. However, in real life, when a ship is in a collision situation with more than one target, the OOW needs to analyse the whole situation to assign a priority of avoiding the most dangerous target, and then consider the less dangerous targets. In crowded navigational areas, the task of keeping clear of a high number of targets become exhausting and the chances of missing of forgetting to take an avoidance action can be of great danger to the safety of navigation. That is when, automatic collision avoidance system can be a great assistance to OOW.

3.4.3 The Use of VHF communication in Collision Situation

These days, the OOWs are commonly using the VHF to communicate with other targets about the agreement or disagreement of the avoidance manoeuvre, yet, this has increased the chance of accidents by some misunderstanding of communications between OOWs (Acar et al., 2012). Neither, COLREG regulations, nor the IMO recommend the use of VHF communication to agree on the avoidance manoeuvres, as every ship must apply COLREG requirement in every encountered situation. However, the VHF can be a useful device in order to remove the uncertainty of the situation by agreeing on or determining the actions to be taken. On the other hand, it is still not recommended to rely on VHF, as it can be the reason for many accidents. The collision between the MINERAL DAMPIER and the HANJIN MADRAS is an example where MINERAL DAMPIER was the give-way vessel, but as per the VHF agreement she decided to Stand-on and let the HANJIN MADRAS take the avoidance action. HANJIN MADRAS did not take any action and they collided leading to 423 fatalities (Cockcroft, 2003). (Harding, 2002) had claimed that the IMO has endorsed the use of VHF as a bridge-to-bridge mean of communication in collision situation to remove the uncertainty and agree on actions. He supported his claim by the United States of America’s act in 2001, which enforced the use of bridge-to-bridge radio communication to agree on the avoidance action for all vessels navigating in the American waters (Cockcroft, 2003, Harding, 2002, Stitt, 2003). (Stitt, 2003, Cockcroft, 2003) argued his claims by supporting the US act for the local waters in America only, as that rules will be enforced in harbours, channels and confined waters wherein most of the cases pilots are on-board. The VHF communications are conducted between the pilots (they receive the same level of training, all speak English as the first language and they are expert about the areas of their operation), where the criticality of the cases required the use of the VHF (Stitt, 2003). Nevertheless, those circumstances do not apply in open seas, with an extreme concern about the language issues, as it has been reported to be the reason of misunderstanding the VHF communication between ships (Stitt, 2003). In this regard (Cockcroft, 2003, Stitt, 2003) had denied the endorsement of VHF communication by the rules in collision avoidance manoeuvres, which had been claimed by (Harding, 2002) to avoid the misunderstanding between ships. In conclusion, the introduction of new technologies does not affect the obligation to follow COLREG at all times. In international shipping, there are differences in the cultures between OOWs, different levels of experience and languages difficulties, which is the case in the maritime industry. Therefore, it is safer to follow the international regulation at all times rather than individual agreements, based on the VHF communications, which can be easily misunderstood and leads to accidents.

3.5 The utilisation of navigational aids and equipment within the navigational duties

Sailing started a long time ago, where there were no electronic communication methods, nor navigational systems. However, sailors depend heavily on traditional methods and experiences inherited from previous navigators and sailors. Moreover, the toughness of sailors' life on board and the long times they used to spend in seas generated a proudness and glory of themselves. These attitudes, over time, turned out to be an arrogance where it became the most known character about sailors to date. Indeed, this created resistance from a large number of navigators to the development of new navigational technologies and techniques, claiming that they are inefficient, and it is impossible to dispense traditional techniques. In addition, the long processes and time required for adopting new technologies and systems in the maritime industry by the International Maritime Organisation IMO lead to individual equipment introduction over long periods (Bole et al., 2014d). This develops a poor bridge layout and systems' integration (Bole et al., 2014d, Brigham, 1972).

Consequently, the OOW is exposed to a high level of information flow from navigational equipment located in different areas on the bridge (Pietrzykowski et al., 2016). Whereas all these navigational aids are information systems only, yet no decision support system has been developed to help the OOW in decision making (Pietrzykowski et al., 2016). Explanations of ordinary bridge navigational equipment in the manner of information provided to support the OOW to interpret and understand the navigational situational around the ship are given below. In this section, the utilisation and interaction with the navigational systems are discussed together with the shortages of each system. In chapter 5, the technical specifications of each system are discussed in more details with the features and IMO requirement of systems, which will be mentioned.

- Ship’s conning display unit
- Weather monitoring unit
- Automatic Identification System (AIS)
- Radar, X and S bands / Automatic Radar Plotting Aid (ARPA)
- Electronic Chart Display and Information System (ECDIS)
- Global Positioning System (GPS)
- VHF for external communication
- Echosounder

3.5.1 Ship’s conning display unit

This system is a display unit where most of the navigational information is displayed for performance monitoring (Figure 11). The data is collected from different sources and sensors and displayed and grouped in a logical way for easy monitoring (Kongsberg, 2017). The conning display unit shows information related to the ship status and route (Kongsberg, 2017). In addition, an alarm system display can be integrated for alarms messages and acknowledgement purposes (Kongsberg, 2017). Yet, this system has most of the required navigational information that related to the own ship performance; still, the OOW cannot rely on this system solely. This is because of the need for monitoring the other navigational system (APRA, ECDIS, AIS) for full interpretation of the situation with regard to targets in the vicinity. However, this creates a dilemma of various systems monitoring and cross-checking of navigational information.

Status information (Kongsberg, 2017) includes:

- Heading
- Rudder angle
- Ship’s speeds (forward, astern and side speeds)

- Engine RPM
- Water depth
- Wind’s speed and direction (relative and true)

Route information (Kongsberg, 2017) includes:

- Distance and time to next waypoint
- Off-track distance and alarm
- The status of position receiver
- Autopilot modes
- Estimated time of arrival ETA

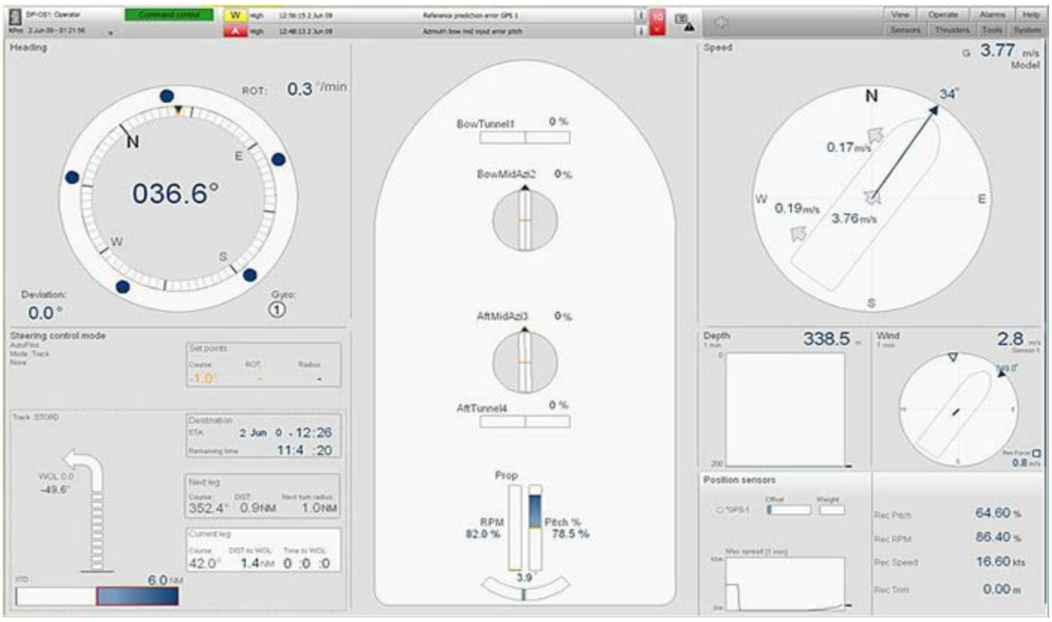


Figure 11 Conning display (Kongsberg, 2017)

3.5.2 Weather Monitoring Unit

This provides wind’s speed and direction measurement and the water current inductions, relative and true information. Also, the relative humidity and atmospheric pressure, which are important factors for future weather forecasting. The weather information is important to support the OOW in the navigational duties to predict the ship’s behaviour. Where wind and water current have a significant influence on the ship manoeuvrability and movement. Moreover, this information allows the ship crew to predict the weather condition and plan their voyage to avoid entering in bad weather condition.

3.5.3 Automatic Identification System (AIS)

The Automatic Identification System AIS is an automatic system for ships' information exchange with other ships and shore bases (Vessel Traffic Services VTS) (Tetreault, 2005). The main aim of the system is to enhance the situational awareness by automatically providing the OOW with other ships' information, such as; ship's identity and tracking information (IMO, 2002a). The AIS system operates on VHF frequency, and it exchanges data automatically and continually without OOW intervention (IALA, 2002). However, any AIS-equipped ship and VTS can receive the AIS information within the VHF range (20-30 NM), with updating rate vary from 3 minutes for ships at anchor to every 2 seconds for ship's speed over 23 knots and turning (IMO, 2002a, IALA, 2002). Thus, the AIS became a vital system for the safety of the navigation for the usefulness of its information, which feeds other navigational aids with essential navigational information, for example, ARPA and ECDIS (Bao, 2004, Bole et al., 2014b). The AIS categorise the information in four groups depending on the types of information and the data sources (IMO, 2002a, Harati-Mokhtari et al., 2007). The next table (Table 2) shows the information provided by the AIS system.

Table 2 AIS Information and input source (IMO, 2002a)

Static Information (On Installation)	**Dynamic Information (From Ship's Sensors)**	**Voyage Information (Manually Entered)**	**Short Safety Messages (Manually Entered)**
MMSI (Maritime Mobile Service Identity)	Ship's Position	Ship's Draught	Short text messages which manually entered about safety
Call Sign and Name	Time (UTC)	Hazardous Cargo Type	
IMO Number	Course Over Ground COG	Destination and ETA	
Length and Beam	Speed Over Ground SOG	Route plan (Waypoints)	

Type of Ship	Heading		
Location of Position Fixing Antenna	Navigational Status (Entered Manually)		
	Rate of Turn (If Available)		

Although the AIS enhanced the situational awareness by better information exchanges between ships, it still has some limitations which need to be well addressed by the OOWs (Harati-Mokhtari et al., 2007). First, the ability to switch the device manually; however, it is beneficial for security reasons (piracy area, for example) (IMO, 2002a). Also, it means the system could be switched off at any time, and it would stop broadcasting the navigational information. Second, the high chances of human error when entering the voyage information manually, then it would broadcast the wrong information (Harati-Mokhtari et al., 2007).

3.5.4 Radar, X and S bands / Automatic Radar Plotting Aid (ARPA)

The radar is the target detection device on board. It is also known as ARPA, where the system automatically plots the targets and provides the information to the OOW (Figure 12). However, the radar should be integrated with other sensors and data sources to be fully functional (IMO, 2004, Bole et al., 2014c, Bole et al., 2014d). The input data required are (IMO, 2004);

- Gyro Compass, for ship’s heading
- Ship’s speed
- GPS, for ship’s position
- AIS

Basically, the OOW monitors the radar to detect any target in the vicinity. Once a target is detected, the OOW acquire it to be able to see the target information and for target tracking (Figure 13). However, target acquisition can be made manually or automatically, wherein automatic targets acquisition, the OOW should define the boundary of automatic targets acquisition (IMO, 2004, Furuno, 2004). In addition, target detection has two options, it could be either, the target is detected by radar only, or the target is detected by the radar with AIS information (IMO, 2004, Bole et al., 2014c). In case of only radar detection, the target acquisition provides the range, bearing, Closest Point of Approach (CPA), Distance to CPA (DCPA), Time to CPA (TCPA), target's true course and target's true speed, also it should indicate the data source, whether radar or AIS (IMO, 2004, Furuno, 2004). Where in AIS targets acquisition, it provides navigational status, target's position, range, bearing, Course Over Ground (COG), Speed Over Ground (SOG), CPA, DCPA, TCPA and rate of turn, with the source of the data (IMO, 2004, Furuno, 2004).

Moreover, every ship is required to be fitted with X and S-band radars (IMO, 2004). X-band for high and sensitive targets detection. And S-band for better detection on different weather condition, like rain and fog (IMO, 2004). When a target is acquired, the ARPA system takes up to one minute to calculate and present the target's track (relative motion) (Bole et al., 2014a). Whereas, the ARPA system takes up to three minutes to calculate the predicted motion of the target, which provides full information about the target's movement and tracking (relative and true motions) for reliable information (Bole et al., 2014a). Basically, after the first detection of the target, the ARPA system needs to plot the target for a number of times to be able to calculate the targets information (Bole et al., 2014a). However, this is the reason for the relatively long time of calculation, where this process used to carry on manually by the OOW before the introduction of the ARPA system (Bole et al., 2014a).

APRA system gives alarms and warnings (IMO, 2004) if;

- CPA and TCPA are less than the value set by the OOW
- Alarm about new targets enters the guard zone and automatic target acquisition. The target must enter through the boundary of the guard zone, which is determined by the OOW. Otherwise, the system does not warn about it.
- Alert about lost targets, which already been tracked.

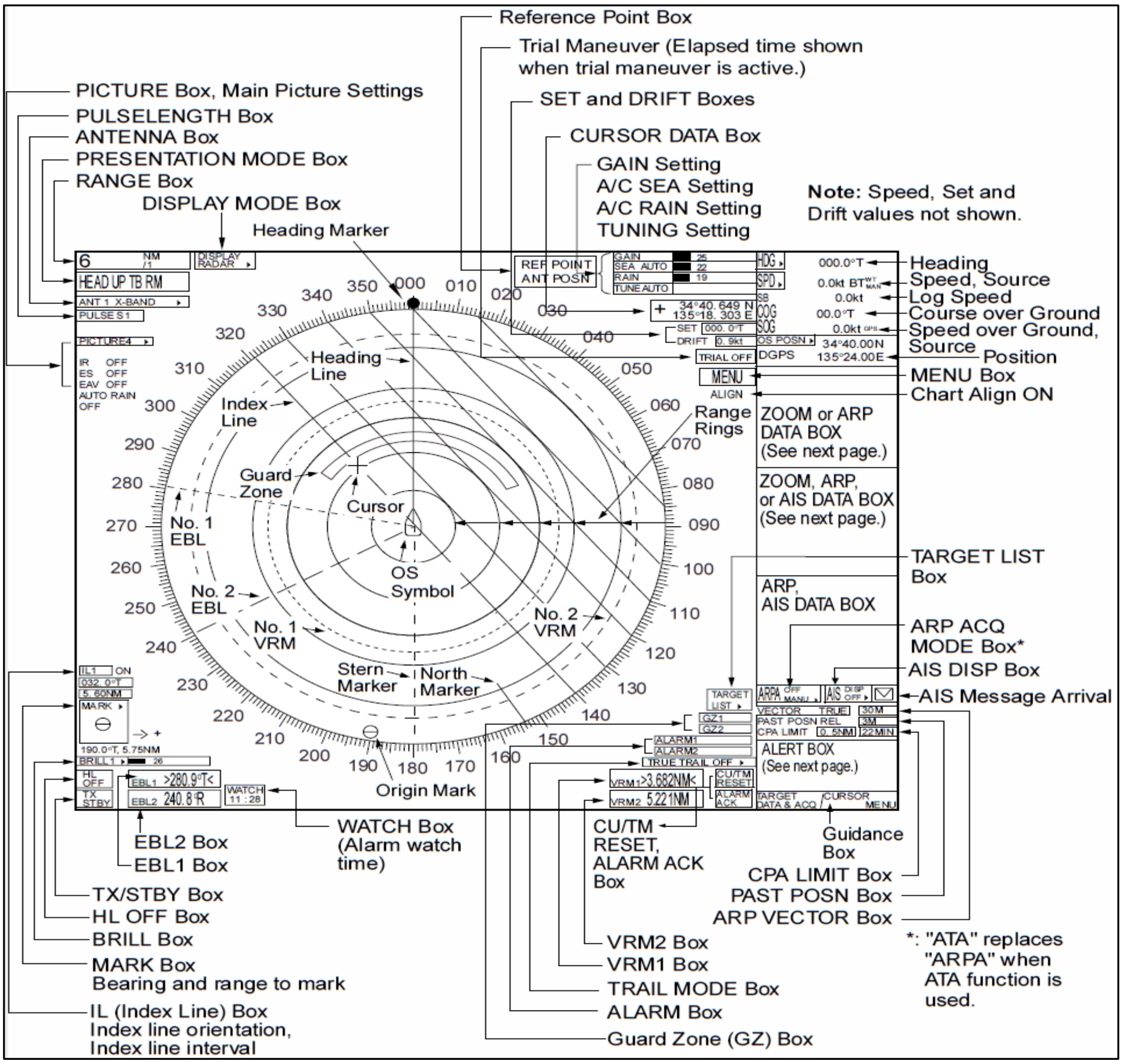


Figure 12 ARPA display and information (Furuno, 2004)

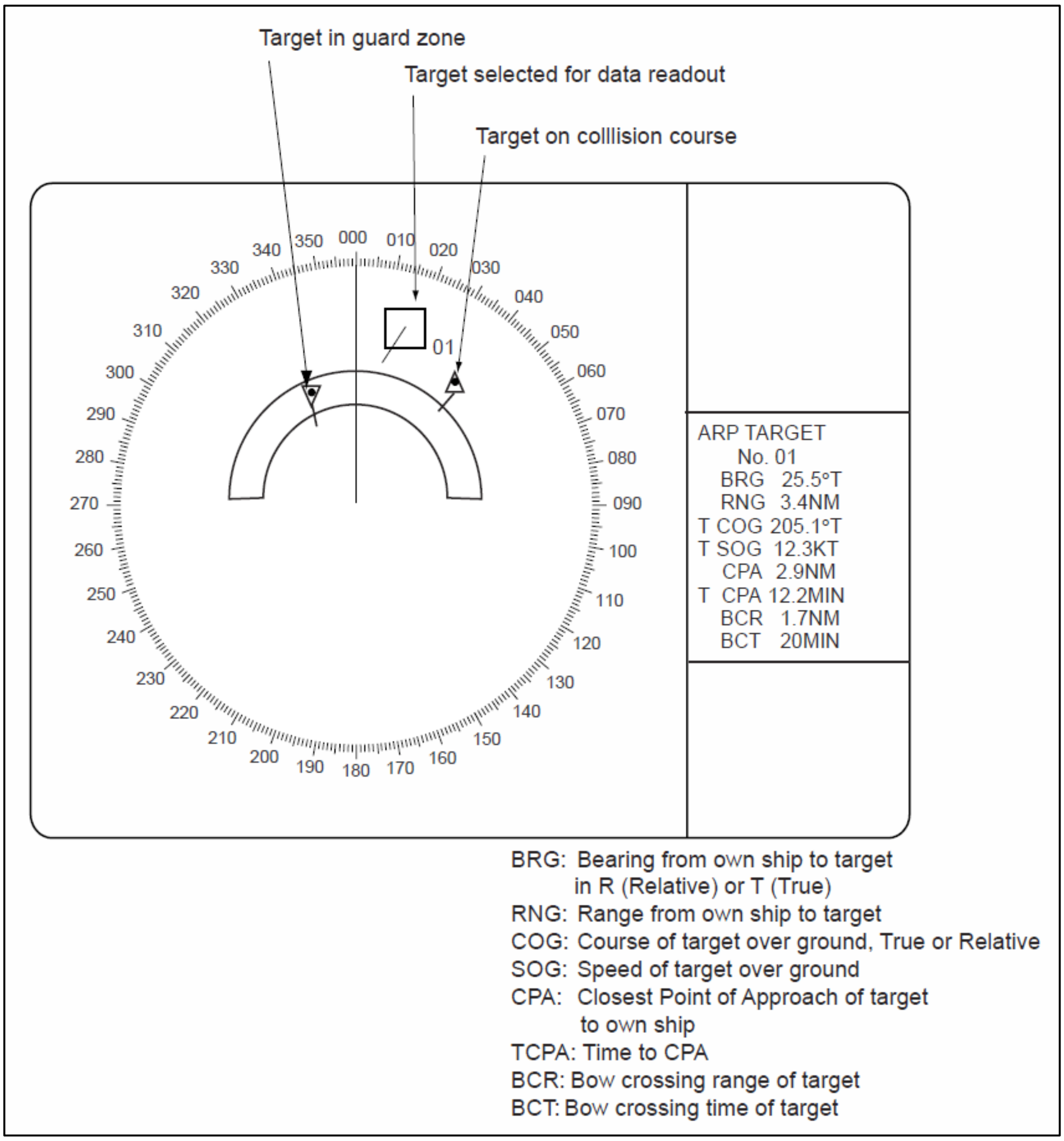


Figure 13 ARPA display, Guard Zone and Target's information (Furuno, 2004)

Yet ARPA system has reduced the workload of the manual plotting, and thus, allows the OOW to accurately predicts the developed scenario of conflict situations with other targets. However, this is still not enough to prevent maritime accidents. This is due to the lack of experience for optimally adjust the ARPA display system (layout of the screen, gain, clutter and tune) by the OOW, which lead to even misperception of the situation or misdetection of all targets. Moreover, the over-reliance on the system and the ignorance of the alarms and alerts or acknowledgement without investigating about the cause of the alarm. Additionally, the overconfidence behaviour of the OOW in the ability to manoeuvre the ship leads to either: critical situation (misjudgement of the situation) or the violation of the regulation (COLREGs).

With regard to the weaknesses of using the ARPA system, it is related to the accuracy of the information and the alerting techniques of the system. For information accuracy, the system mainly depends on the echo that transmitted and then received back if it hits targets, and these echoes affected by weather and climate elements that can sometimes impede the reception of the signals, such as; rain, sea condition and humidity. Also, the detection range can affect the accuracy of the ARPA system in targets detection.

For alerting related weaknesses, it is required by the user to enter the desired parameters in order to get the necessary alerts that are related to collision situation with other targets, such as; the minimum CPA and detection range, moreover, the inefficiency of target monitoring, where targets can be lost due to the weak echo or the above-mentioned weather conditions. Thus, if a target is lost, the ARPA system stops providing alerts about it even if it has appeared again on the screen until the OOW manually acquire the target. Although the ARPA system gives an alarm if a target is lost, that alarm is usually ignored by the OOW for the boredom of the frequent unnecessary alarms from the system.

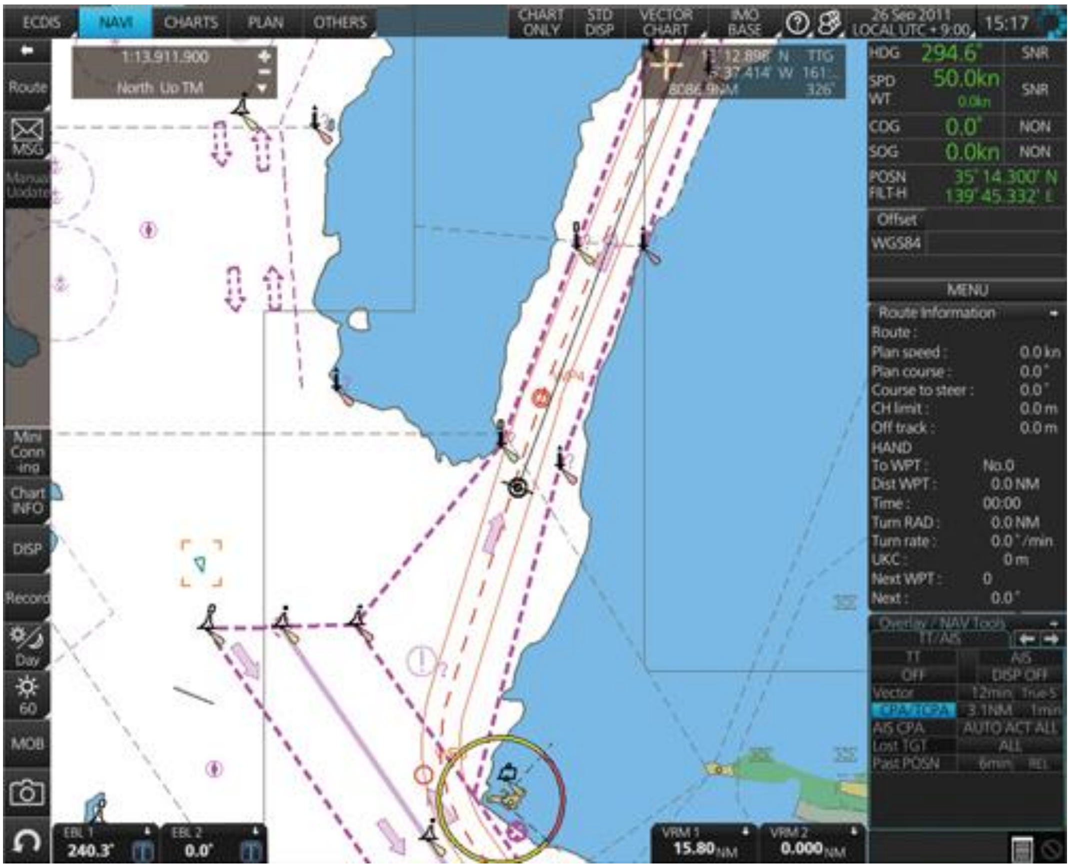
3.5.5 Electronic Chart Display and Information System (ECDIS)

The primary purpose of the ECDIS is to enhance the navigational safety, by displaying all the essential information on paper charts in an appropriate way to support the OOW in conducting safe and efficient navigational duties (Figure 14) (IMO, 2006, IHO, 2010). Moreover, ECDIS should reduce the navigational workload by replacing the traditional paperwork of; route planning, route monitoring and position plotting, to an electronic method performed on ECDIS (Pillich and Buttgenbach, 2001, Jie and Xian-Zhong, 2008). Also, it should have the ability to be connected and integrated to all navigational equipment on the bridge (ARPA, AIS, Position-fixing system, Gyro compass, Speed log and Echo sounder) (Bole et al., 2014d, IMO, 2006). Moreover, ECDIS should provide a clear presentation of all the information that the OOW needs to maintain a safe navigational watch (IMO, 2006). In case of a connection failure, the ECDIS system must raise the alarm or indication about the failure to alert the OOW (Jie and Xian-Zhong, 2008). The displayed information should have the same quality of information and presentation on the paper charts, with the ability to update the electronic charts up to the standards of the Hydrographic Office (IMO, 2006).

The ECDIS system provides the main features of route planning, monitoring and voyage recording to assist the OOW in maintaining safe navigational watch (IHO, 2010). For route planning purposes, the system must be able to add delete and change waypoints in an effortless manner to plan the whole voyage with an indication of dangers objects and prohibited areas (IMO, 2006). Additionally, ECDIS can display the whole planned route for monitoring purposes to plan ahead or check the ship performance on the planned route, with a single action to go back to own ship position on the display (IHO, 2010, IMO, 2006). Finally, the ECDIS system records the whole voyage information (Positions, heading, time and speed), and these records are protected from any changes for investigation reasons (IMO, 2006).

ECDIS alarms and alerts, (IMO, 2006);

- Alarm if approaching depth contour line and prohibited areas.
- Alarm if any connection or navigational information are lost.
- Alarm for a specific time or distance set by the OOW.



HDG 294.6° SNR
SPD 50.0kn SNR
WT 0.0kn
COG 0.0° NON
SOG 0.0kn NON
POSN 35°14.300' N
FILT-H 139°45.332' E
Offset
WGS84

Route :
Plan speed : 0.0 kn
Plan course : 0.0°
Course to steer : 0.0°
CH limit : 0.0 m
Off track : 0.0 m
HAND
To WPT : No.0
Dist WPT : 0.0 NM
Time : 00:00
Turn RAD : 0.0 NM
Turn rate : 0.0°/min
UKC : 0 m
Next WPT : 0
Next : 0.0°

TT OFF
AIS DISP OFF
Vector 12min True-S
CPA/TCPA 3.1NM 1min
AIS CPA AUTO ACT ALL
Lost TGT ALL
Past POSN 6min REL

EBL 1 240.3°
EBL 2 0.0°
VRM 1 15.80NM
VRM 2 0.000NM

Figure 14 ECDIS display (Furuno, 2017)

The main weakness of the ECDIS system is the requirement of manual input of the parameters to enable the system from raising alarms. These alarms are selected by the OOW with its features of distance, depth and time. Moreover, if the OOW acknowledge the alarm and takes no action to avoid a dangerous situation, the ECDIS system does not raise the alarm again and it does not provide any alternative actions to prevent accidents from happening.

3.5.6 Global Positioning System (GPS)

A satellite means to determine own ship's position accurately. Usually, there are two separated GPS antennas and display units on ships, and it feeds all navigational equipment with the ship's position.

3.5.7 VHF for external communication

The VHF is the external radio communication method with other ships and shore bases. All ships are required to keep monitoring channel 16 all the time, which is used for initial communication and distress calls. Yet, VHF communication is not an ideal solution for accident prevention in critical emergency situations for the high risk of misunderstanding and wrong addressing of conversations.

3.5.8 Echo sounder and ship's draught

The Echo sounder is the depth measurement device under the ship's keel. This is the source where the OOW get to know the available water depth under his ship. The main weakness of the echo sounder is the lack of proper integration with other navigational systems to operate as an accidents prevention method, mainly for anti-grounding alerts. Where the proper integration of the echo sounder this could be of great benefits to alert the OOW about the risk of grounding.

3.6 Comparison of Collision avoidance procedures between the aviation industry and the shipping industry

This section provides a comparison between the aviation and maritime industries in the context of collision avoidance. Thus, it focuses on the regulations, operational practices, techniques and procedures in both aeroplanes and ships for collision avoidance. Due to safety and technology advancements in the aviation industry, advancements in aviation to prevent collision avoidance can be implemented to ships to develop better situational awareness and improved navigational watch. This study reveals the shortages in the maritime industry and helps to adopt new safety-related enhancement to reduce the risk of collision.

Generally, the (OOW) on-board ships are responsible for all the decisions that need to be taken in the navigational bridge. Consequently, this requires an immense amount of data analysis; moreover, this data is located in various locations on the bridge. Yet this can cause a work overload for the OOW that may lead to human errors and lack of situational awareness.

Conversely, aeroplanes have the Traffic Alert Collision Avoidance System (TCAS), which alert the pilot about intruders in the vicinity and provides the best action to avoid collisions. The TCAS system is an independent system from any other navigational system or ground station, and it is the last measure for mid-air collision prevention. In this section, the operational procedures of the TCAS system will be discussed briefly and later on in chapter 5 the technical details of the system will be explained in more details. On the other hand, marine navigational aids are available and utilised on ships, but they are all information systems where the OOW needs to process and decide the actions. As a result of this, and to enhance the situational awareness as well as the navigational safety, it is foremost to regulate the information flow in ships' bridge, especially in critical conditions, such as; traffic density, collision and grounding situation.

In addition, it is essential to develop the automation of tasks and decision support systems to reduce the navigational workload. Accordingly, this comparison exposes significant deficiencies in marine navigational procedures. Nevertheless, it provides solutions to improve maritime safety by implementing some of the applicable aviation procedures and technologies.

3.6.1 Collision Avoidance Procedures on Ships

In marine navigation, the OOW is the only responsible navigator for the safety and manoeuvrability of the ship (Demirel and Bayer, 2015, Cockcroft and Lameijer, 2012b). Additionally, is the availability of Look-out person, who only provides assistance in external watch-keeping for targets and danger detection (Cockcroft and Lameijer, 2012b). Accordingly, the OOW is the only person responsible for monitoring all navigational aids and decision making on the bridge. Nevertheless, the number of navigational equipment needs to be monitored for data extraction is excessive (Pietrzykowski et al., 2016). Moreover, they are all information systems that only provide data, which needs more processes and interpretation to ensure the usefulness of it to conduct a safe navigational watch (Pietrzykowski et al., 2016, Jie and Xian-Zhong, 2008). In general, for regular navigational duty, the OOW should be aware of the weather condition and what weather to expect for better awareness about the ship performance. Then proper monitoring of the execution of the passage planning, which usually happens by monitoring the ECDIS system, compare ship's position with paper charts (if available), and cross-checking ship's position by any available means (landmarks, GPS, bearings and ranges). Also, the ship's performance (engine speed, speed over ground, side speeds) needs to be monitored to ensure excellent engine conditions, and the weather impact on the ship's movement. During all of this, continues listening of VHF radio communication is required to communicate with other ships and shore bases. After this the look-out and targets monitoring to detect any object or targets around the ship. This task requires a visual look-out with the support of the look-out person, plus the ARPA and AIS systems (AIS integrated with ARPA) for targets detection (IMO, 2004). Once a target is detected on ARPA, the OOW needs to acquire it to get its navigational information, and based on this he can assess the collision situation (Furuno, 2004). In general, the OOW first look at the CPA to assess the risk of collision, if it exists, then evaluation to COLREG is essential to define the collision situation and the Give-way and Stand-on vessels (Wang et al., 2010). Then the DCPA and TCPA are used to decide the best time to manoeuvre. Further discussion about the automatic collision avoidance models will take place in section 3.7 below.

3.6.2 Similarity and Differences between Aviation and Maritime in the Context of Collision Avoidance

3.6.2.1 Collision Avoidance Regulations

In general, all transport modes have developed technologically over the years. The advancement in technologies allowed the rapid growth of sizes, capacities, numbers and speed of fleets, whether they are aeroplanes or ships. In this manner, it becomes vital to have reliable means of traffic management in order to avoid any kind of accidents. It is worth mentioning that the maritime industry is the oldest mode of transport which started long before any method of electronic communications. Obviously, the common seamanship practices were acting as a regulation to control the navigational duties and responsibilities.

On the other hand, the first aeroplane was invented in 1903 by the Wright brothers, and the first commercial aeroplane in 1914, which had been in operation for just four months

(Frommelt, 2016). Commercial airlines started to flourish in the 1950s, just over a hundred years after the first maritime collision avoidance regulation entered into force. That allowed the aviation industry to become more advanced and better equipped electronically. Yet, the aviation sector does not have any manoeuvring regulations or rules to advise the pilot how best to avoid other aeroplanes; they rely on the concept of "See and Avoid" to avoid any collision, as the pilot decides the best action to take (FAA, 2011). Additionally, they have the Air Traffic Control (ATC), who manage air traffic all the time, for the duration of the flight (EUROCONTROL, 2016).

In maritime navigation, all collision avoidance manoeuvres are made based on the Collision Regulations COLREG (the Rules of the Road). The COLREG consists of 38 rules and divided into five sections (COLREG, 2017). Section B is the one related to steering and sailing from rule 4 to 19 (COLREG, 2017). Although these rules help to manage the maritime traffic and to advise every vessel about the collision avoidance manoeuvres that need to be taken in every situation, it did not stop accidents from happening (Lušić and Erceg, 2008). Especially nowadays, the traffic density and ships' speed has increased significantly. After an in-depth study of the COLREG, we found a number of issues that can cause a struggle and confusion for the OOW. For example, the subjective nature of the rules, where it does not inform the OOW of the specific action to take, instead, it leaves the decision to OOW to decide (Belcher, 2002). Stranks has mentioned the issue of risk perception, where some people may see a situation as very risky, and some others see the same situation as safe (Stranks, 2007). However, this leads to a hesitation in decision making, especially in applying rules 16 and 17 '*the Give-way and Stand-on vessels*'. In rule 17, the Stand-on vessel is required to maintain her course and speed, and rule 15 states the Give-way vessel should take the avoidance action. Though, if the Give-way is not taking action or her action alone is insufficient to avoid a collision, then the Stand-on should take the best action to avoid the collision. In this case and based on the risk perception principle, the OOW will face difficulties in deciding the best time to take actions. Yet, COLREG state that the actions should be taken in ample time, again it does not specify the best time to manoeuvre.

In aviation, where they do not have manoeuvring regulations, the decision is left to the pilot to avoid collisions. In addition, there are two collision avoidance barriers, the ATC and TCAS, plus the "see and avoid" technique. Thus, the air is being controlled by the ATC ground station, and the pilot is visually monitoring the traffic to avoid any conflict situation. Finally, as a last measure, the TCAS system, which alerts the pilot about intruders in the vicinity and provides the best avoidance action in conflict situations.

3.6.2.2 Collision Avoidance Systems; Operation and Techniques

The aviation industry has succeeded to develop an automatic collision avoidance system which helped enhancing the flight safety significantly by reducing the risk of a mid-air collision. The TCAS system is the last barrier of mitigating the risk of the mid-air collision, and it works independently without interference from ATC (Honeywell, 2004). In essence, the TCAS system alerts the pilot of any potential mid-air collision in two consequence steps: firstly, the Traffic Advisories (TA) to alert the pilot about any intruder in the vicinity and to be ready for the avoidance manoeuvres. The TA is generated 20-48 second before the Closest Point of Approach CPA (EUROCONTROL, 2016). Secondly, the TCAS generates the Resolution Advisories (RA) to provide the pilot with the best avoidance action. The RA is generated 15-35 second before the CPA, and the pilot must respond to the RA order immediately (EUROCONTROL, 2016). The RA advises the pilot to adjusts the vertical speed to avoid the collision, whether to climb up, descend or maintain the vertical level (EUROCONTROL, 2016). One of the most robust techniques of the TCAS system is the coordinated decisions (EUROCONTROL, 2016). Briefly, the TCAS keeps sending interrogation signals, when a TCAS fitted intruder receives this interrogation, it sends a reply message back (this message has information about the intruder, such as altitude) (EUROCONTROL, 2016). After they exchange messages containing information between aeroplanes, the TCAS computer unit (which is responsible for the surveillance, tracking intruders, avoidance manoeuvres and issuing the advisories) coordinate the avoidance manoeuvre with the intruder and come out with complementary decisions for both aeroplanes (EUROCONTROL, 2016). In addition, the system keeps monitoring the execution of the manoeuvres every one second, in case the first RA is not enough to avoid the collision, it issues another RA, or it can issue a reversal RA if the other aeroplane is not responding (EUROCONTROL, 2016).

In the maritime industry, there are no such systems which support the OOW in collision avoidance decision making. Hence it is all information systems, which means the OOW needs to collect all the navigational information, from various sources, to build up an adequate level of situational awareness (Pietrzykowski et al., 2016). As a result, OOW should monitor various systems in different screens and locations, no matter what the level of integration on the bridge is. For collision risk assessment, the OOW needs to extract information from ARPA and ECDIS (two separate screens) (Hadnett, 2008, Pietrzykowski, 2010). However, he still needs to be fully aware of other vital aspects, such as Anemometer for weather conditions, Echo-sounder for depth, Paper charts, GPS and GMDSS (Communication system). Constant monitoring of all this equipment is an exhausting task, mainly when the devices are located away from each other (Hetherington et al., 2006). On top of that, he still needs to assess the situation and decide the best avoidance manoeuvre, based on the COLREG rules (Belcher, 2002). This high information flow in such critical situations is hazardous. In addition to this, the possibility of equipment failure and human factors such as stress, fatigue, mental health and misinterpretation of the situation will adversely affect the avoidance manoeuvres. It is evident that a combination of all these factors is increasing the number of elements need to be processed by the OOW, which increase the chance of human errors that lead to accidents (Chauvin, 2011, Hetherington et al., 2006, Hadnett, 2008). Moreover, the limited coverage of the Vessel Traffic Management Services VTMS and its limited authority on controlling the ships' navigation and manoeuvrability (Pietrzykowski, 2010), will not provide the much-required interventions to avoid collisions.

3.6.2.3 Collision Avoidance Procedures, Actions and Responses

The most significant benefit of the TCAS system is the enhancement in situational awareness by alerting about the conflicting traffic in the vicinity and the collision avoidance manoeuvres (ICAO, 2006). Hereunder are scenarios of collision situations in air and sea to make a comparison between safety levels of navigation in both industries.

3.6.2.4 Scenario 1, Air collision Situation

Looking at the principle rules of separation in aviation, firstly the ATC is responsible for aeroplane control on the ground and in the controlled airspaces and as advice in non-controlled areas (EUROCONTROL, 2016). Its responsibility is to prevent collision and ensure separation between aeroplanes (EUROCONTROL, 2016). Then is the "See and Avoid" principle, where the pilot sees the other as a threat, have to avoid it in the best manoeuvre to avoid a collision. Finally, as the last resource of collision avoidance is the TCAS system (EUROCONTROL, 2016).

The essential operation of the TCAS system starts when the TCAS issues the TA to alert the pilot about an intruder (CÎRCIU and Luchian, 2014). The TA helps the pilot in the visual acquisition of intruders, preparing him to respond to RA if the risk of collision exists (FAA, 2011). Once the RA is issued, the pilot needs to respond immediately, if the given manoeuvre does not endanger the safety of the aeroplane (EUROCONTROL, 2016). The pilot needs to respond to the TCAS decisions, even if he cannot visually see the intruder, and he should not manoeuvre in the opposite direction of the RA (EUROCONTROL, 2016). It could be the case that the pilot is unaware of the intruder in general or it could be another intruder that the TCAS is providing an avoidance action than the one the pilot sees (EUROCONTROL, 2016). The RA provides the pilot with the required vertical speed to avoid the collision, whether to climb or descend (EUROCONTROL, 2016). In addition, the TCAS keeps monitoring the situation, to ensure safe manoeuvres are conducted and if the situation arises, to provide a change in the vertical speed or to reverse the manoeuvre (EUROCONTROL, 2016).

3.6.2.5 Scenario 2, Marine collision situation

In Maritime, the primary and first method of collision risk assessment is by taking a frequent visual compass bearing; if the bearing is not changing, that means the target ship is on a collision course. The next method is the radar, helping especially in restricted visibility. Finally, the ARPA system makes it much easier to assess the collision situation by calculating the Closest Point of Approach CPA ant the Time to CPA (TCPA).

In typical operation, the OOW needs to monitor the ARPA system to detect any target in the vicinity, in addition to the constant visual lookout (with the support of the Look Out watchman if needed). When a target is detected, the OOW gets the target's information and parameters on ARPA (which is integrated with the AIS system), and based on the CPA he decides if a risk of collision exists. If the target ship is on a collision course, the OOW needs to evaluate the situation, based on the COLREG rules, to know which ship is the one to give way. If it is the own ship, then he needs to keep clear of the Stand-on vessel. A change in course is more favourable than speed in collision avoidance situations, as it is more effective in close quarters situations, has a rapid effect on the ship and more noticeable to other ships (Cockcroft and Lameijer, 2012d). However, the OOW needs to follow the COLREG rules in every case of collision situation, Crossing, Head-on or Over Taking situations to pass in a safe distance from the target ship.

On the other hand, if the other ship is to give way, the Stand-on vessel should keep her course and speed. If the stand-on vessel finds that the one giving way is not taking an appropriate action to avoid the collision or her action alone is not enough, then the stand-on the vessel should take the best action to avoid the collision (Cockcroft and Lameijer, 2012d).

Additionally, the water depth is an essential factor in marine accidents, causing grounding. In general, the passage planning is created before the departure, and all the routes are checked to ensure a safe passage for the ship, with ship's draught in consideration all the way to the arrival point. However, in the case of avoidance manoeuvres which need an alteration from the original route, the OOW must check the availability of sea room around the ship to avoid shallow water and grounding accidents.

Table 3 provides a comparison summary between the aviation and maritime collision avoidance procedures.

Table 3 Table of comparison between TCAS system and the Ships Collision Avoidance

TCAS	Ships
Collision Avoidance Regulation	
No regulations or rules for manoeuvres and action to avoid a collision	Avoidance manoeuvres are regulated by the Rules of the Road, COLREG
Collision Avoidance Systems; Operation and Techniques	
Decision support system	Information systems only
Automatic coordination between aeroplanes for complementary decisions	No coordination between ships
The system keeps monitoring the situation to ensure clarity of conflict passage	No means of checking the situation and the correctness of the OOW decisions. All left to the OOW.
The system provides the pilot with the exact action to do with the magnitude of it for collision avoidance	The systems provide the OOW with information only; then he needs to take actions
The decisions made based on the real and correct interpretation of the situation	Decisions made based on the interpretation of the situation by the OOW
One source of information in case of collision	Too much information flow and sources all the time, the OOW needs to observe what he needs
Automatic acquiring of targets and alerts	Manual targets acquisition, visual lookout, no automatic alerts
The interrogation and responding technique for target acquisition	Rada and visual lookout for target detection
Collision Avoidance Procedures, Actions and Responses	
The pilot receives the collision avoidance decision from the system	The OOW collect information and make the decision based on COLREG
ATC managing and controlling the airspace	The OOW the only responsible person about the safe navigation
If the system issues an RA, the pilot needs to follow immediately, even if an intruder is not acquired visually	Visual lookout is essential all the time; ARPA and AIS are not enough for targets detection.

Objective decisions based on the system detections and calculations	Subjective decisions based on the OOW physical capabilities, experiences and interpretations

After the above-mentioned discussion about the collision avoidance procedures in both the maritime and aviation industries, which has shown a significant amount of information processing and the lack of decision support mechanism in the ship, it is worth studying the topic of developing an automatic collision avoidance system to support the OOW in decision making. This study should focus on the reduction of the amount of information processing and the development of a system that is capable of helping the OOW in taking the best avoidance manoeuvre to prevent the collision at sea. Moreover, the aviation techniques that are utilised to prevent the mid-air collision will provide important and valuable examples that can help to improve the navigational safety and the development of such an automatic decision support system for shipping.

3.6.3 Procedural Diagrams for Collision Avoidance in Aviation and Maritime Sectors

The comparison between the collision avoidance procedures in aviation and maritime has revealed several concerns in the maritime sector. Still, the diagrams help to spot the most critical issues in the maritime procedures. However, by comparing maritime procedures with aviation procedures, a significant improvement can be made to enhance situational awareness and navigational safety as well. These diagrams represent the author’s interpretation of the procedures in both the aviation and maritime industries from the following references (Belcher, 2002, Acar et al., 2012, Cockcroft and Lameijer, 2012d, EUROCONTROL, 2016, FAA, 2011, Honeywell, 2004)

Starting with the diagram for the aviation procedures, there are three independent collision avoidance measures available to stop mid-air collision from happening (Figure 15). The ATC is to control the overall aerospace and to provide separation between aeroplanes. Then the “See and Avoid” technique by the pilots to monitor the traffic in the vicinity and to avoid any intruder by best actions. If these two barriers failed to prevent the collisions, then the TCAS system is in place, which is an independent system and act as the last mean of mid-air collision avoidance.

On the other hand, in ships, there are no barriers for collision avoidance, it all depends on the OOW to conduct an efficient look-out to maintain a safe navigational watch with the support of the navigational aids, and the implementation of the COLREG regulation if the risk of collision exists (Figure 16). Also, careful monitoring of all the equipment on the bridge is required (Figure 17). Moreover, ARPA is the system, which is used for targets detection and to extract targets' information. Nevertheless, all the navigational aids, including the ARPA, provide the OOW with information that needs a farther process to build a decent situational awareness level. Consequently, the OOW utilise this information to realise the encounter situation, based on COLREG, then to decide the avoidance manoeuvre and responsibilities. Yet, the navigational aids do not either; warn the OOW about threats in the vicinity, nor the best avoidance actions.

The TCAS system, as the last mean of collision avoidance, works independently and automatically process all the encounter situation and information. As a result, the system warns the pilot about threatening intruders in the vicinity to help in visual acquisition, and then provide the pilot with the avoidance manoeuvre. However, the pilot only needs to immediately respond to the system's alert to avoid mid-air collisions. Where in maritime procedures, the navigational aids provide the navigational information and left the processes to the OOW, which lead to subjective decisions. Due to this, all maritime decisions are based on the perception and understanding of the OOW about the situation, which is highly susceptible to human errors. Thus, human performance can be affected by many factors such as; stress, fatigue, tiredness, lack of experience, information flow, misinterpretation, etc. However, all these lead to human errors. In addition, for the case of more than one target, then the OOW needs to consider all targets and decide the best avoidance manoeuvre for all the targets. Whereas in aviation, the TCAS system takes into consideration all the intruders in the vicinity, then provides a complementary manoeuvre to avoid them all. The colours in the diagrams (Figures 15 and 16) show the collision avoidance barriers and the level of automation in the collision avoidance process in aviation and maritime industries. The red colour boxes represent the collision avoidance barriers, which are unavailable for ships. Then, the green boxes that mark the automatic process for collision avoidance procedures. Finally, the orange boxes which are processes that require the OOW/pilot responses to avoid the collisions.

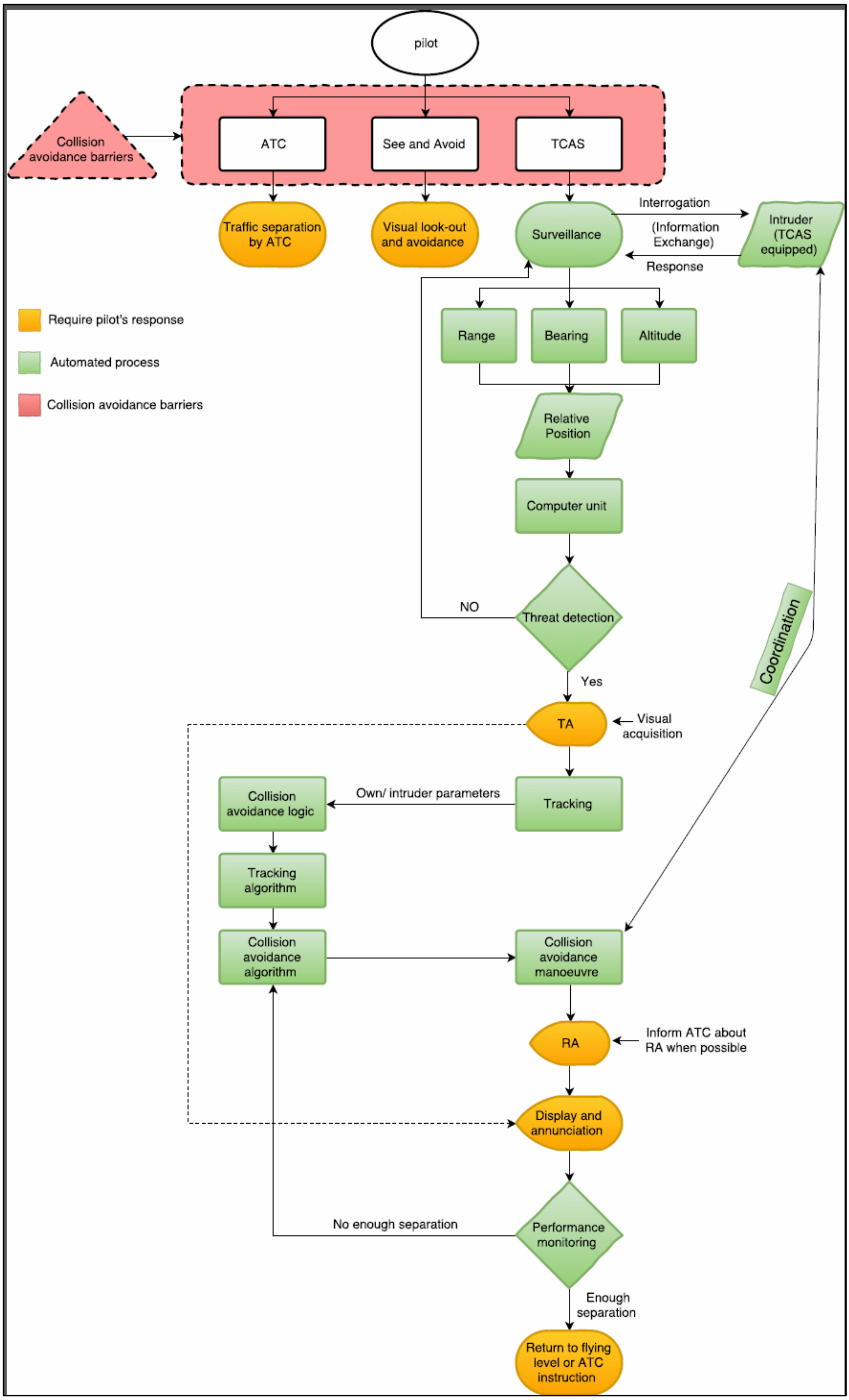


Figure 15 Collision avoidance procedures in aviation

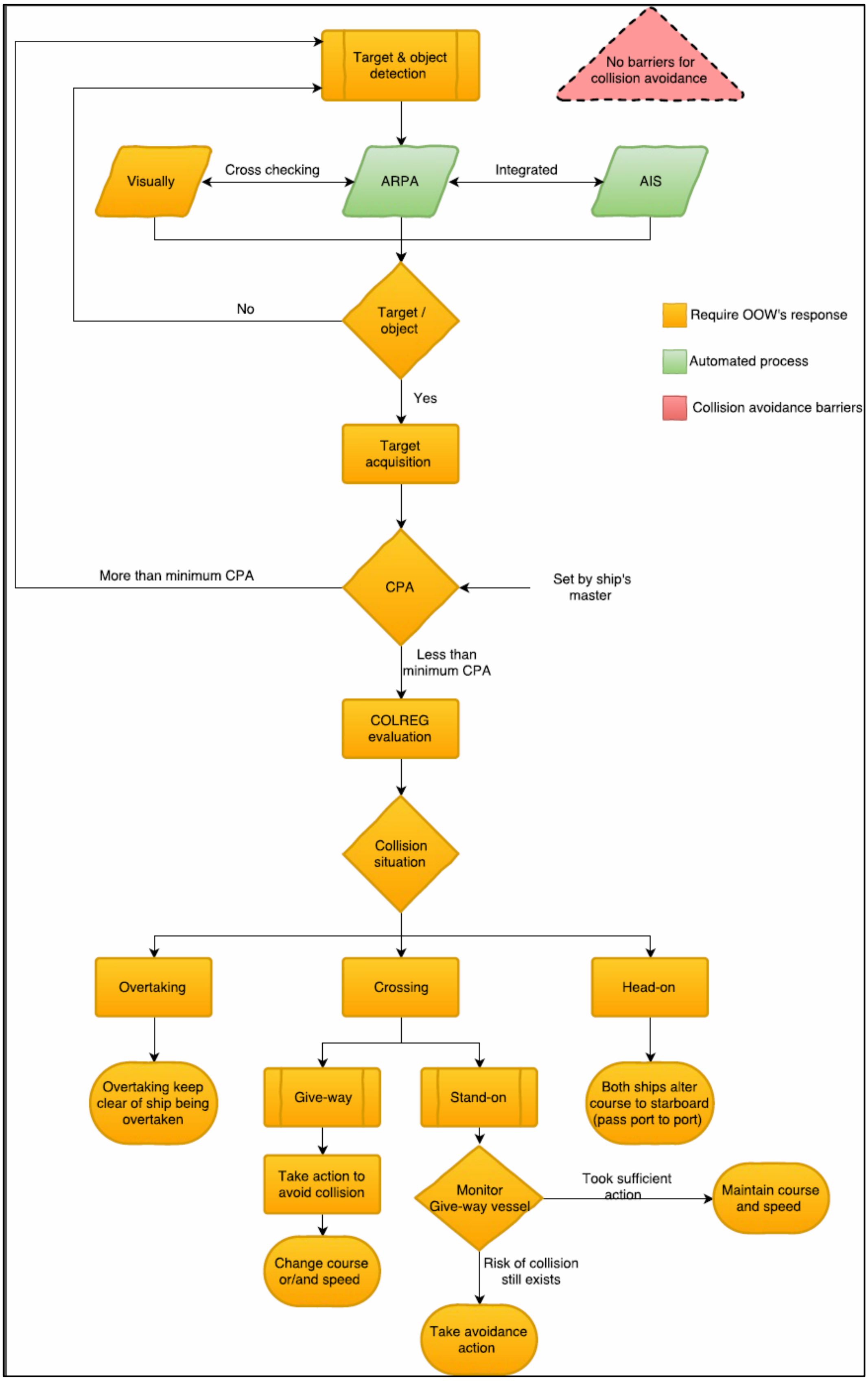


Figure 16 Maritime collision avoidance procedures, based on the maritime regulations

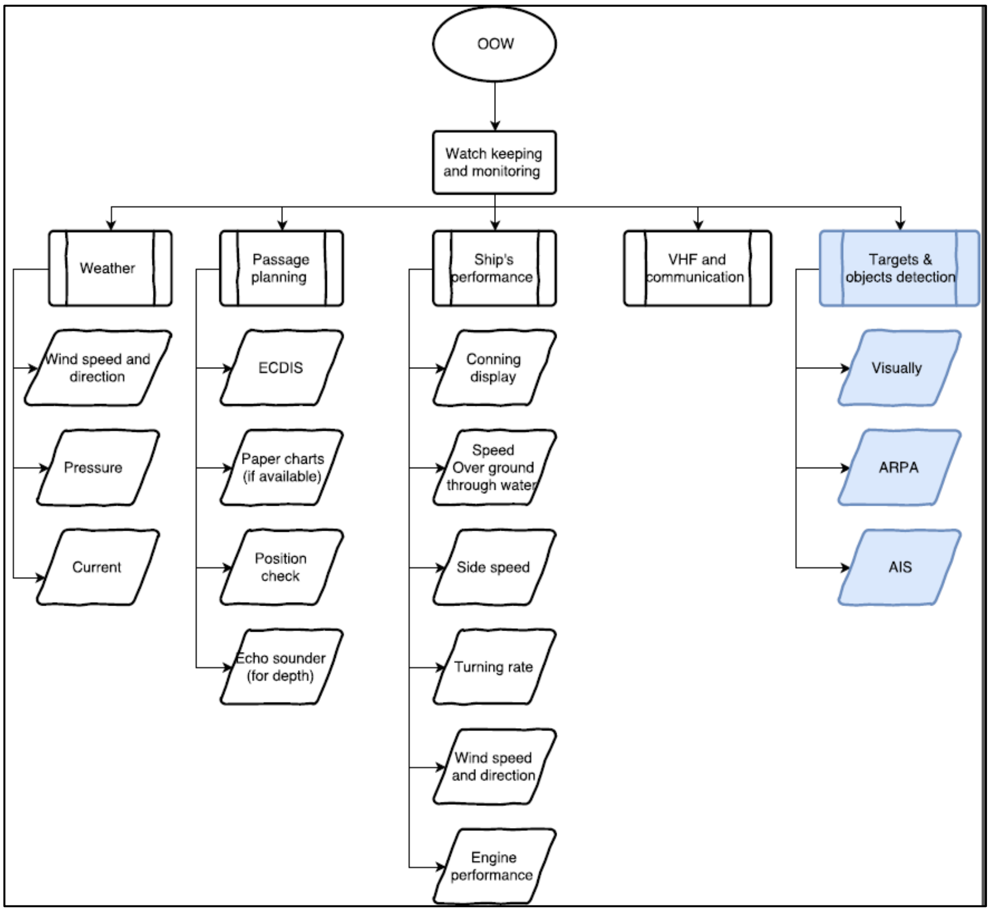


Figure 17 Maritime watch-keeping and monitoring

3.7 Maritime Automatic Collision Avoidance Models

The growth in marine traffic density and ships' speeds has increased the demand to find a solution to support the OOW in the process of decision making for collision avoidance manoeuvre. The most basic technique for risk of collision assessment was to plot several compass bearings in consecutive periods. If the plotted bearings do not change relative to the target, then these two vessels are on a collision course. This requires an avoidance manoeuvre, by one or both of the vessels on the collision course, to avoid the collision situation.

It is after World War II when the radar system became available and affordable for merchant ships to be installed on-board. The primary purpose was to assist the OOW in target detection around the ship. However, at that time, the radar was only providing echoes (dots on a screen represents targets) without any information about these targets. Thus, the OOW needs to manually plot every target to obtain some information about the target. This was a time-consuming process, especially in congested marine traffic. Nevertheless, to assist the OOW in collision avoidance decision making, which will enhance maritime safety, it is significantly worthy of developing an automatic collision avoidance system for ships. In this section, a critical review has been carried out about the state-of-the-art automatic collision avoidance studies and models. This helps in developing a novel system that surmounts the gaps in previous studies and enhances the collision avoidance procedures on-board ships. The structure of this section is as follows; first, it will discuss the research that has been done on the ship domain and collision. Then, the topic of automatic collision avoidance system will be studied under two main parts; the automatic collision avoidance models and the path planning models, and each one will be discussed in more detail below.

3.7.1 Ship’s Domain and Collision Assessment

It is essential to have a safety zone around every ship to determine the risk of collision. This safety zone is called the ship domain, which is defined as the area around the ship that the OOW should keep clear and free of all the other ships and obstacles (Goodwin, 1975, Coldwell, 1983, Fujii and Tanaka, 1971, Tam et al., 2009). There are many factors on which the captain decides the diameter of the ship domain as following; ship’s speed, length, manoeuvrability, traffic density and the navigational area (Fujii and Tanaka, 1971). The diameter is varying from 0.5 NM in a narrow area to 2 NM in open sea areas, depending on the captain’s assessment of the navigational situation.

(Fujii and Tanaka, 1971) is the first author that proposed to reshape the ship’s domain from being a circle around the ship to an ellipse shape, with consideration of the previous factors. Since then, Fujii ship domain has been the most important approach of risk of collision assessment (Tam et al., 2009).

In 1975 Goodwin proposed another shape for ship domain to be more favourable to COLREG, she divided the ship domain into three sectors with the headline of the ship to be the baseline, as following(Goodwin, 1975):

- The starboard sector from 0° to 112.5°.
- The astern sector from 112.5° to 247.5°.
- The port sector from 247.5° to 360°.

The main concept of this work is to mathematically calculate the distance of each sector of the ship domain. With this in mind, the starboard side of the ship has a preference of a larger safety area, where the OOW is responsible for the avoidance action to ships on his starboard side (Tam et al., 2009). Moreover, in the stern sector, the OOW is no more responsible for the avoidance action to any targets behind the ship, then this sector has the smallest area (Goodwin, 1975). The final sector, the port side has a small area as well, where the targets on this side are responsible for taking the avoidance action (Goodwin, 1975).

In 1983 Coldwell considered the ship domain in restricted areas. The proposed domain is similar to Fujii shape domain. However, he suggested that in the head-on situation, the astern sector to be removed, as it does not have any importance in such a situation. Moreover, in over-taking situation, Coldwell used the full shape of the ellipse to offer safety zone all over the ship (Coldwell, 1983). The proposal of this work is unacceptable, due to the fact that in the real situation, the OOW should be aware of all the areas around his ship. Encounter with more than one target at the same time requires a full situational awareness about all targets in the vicinity.

Pietrzykowski in 2008, introduced the fuzzy logic to determine the shape and size of ship domain for open and restricted waters (Pietrzykowski, 2008, Pietrzykowski and Uriasz, 2009). The main feature of his model is the ability to learn from expert methods and artificial intelligence tool. This will help in deciding the optimum domain shape and size with consideration of all the factors that have an influence on the decision, such as; the weather condition, visibility, ship's speed, length, etc. (Pietrzykowski, 2008, Pietrzykowski and Uriasz, 2009). This study has a significant limitation with regards to the implementation of the model which is the time required to assess if collision risk exists or not. This assessment time is considerably long and is insufficient for the purpose of collision avoidance due to the shape of the safety domain (ellipse shape). Because of this limitation, most of the other studies prefer to use the DCPA and TCPA approach to assess the collision risk due to the simplicity of the mathematical calculations.

Finally, the Closest Point of Approach CPA appears to be the most utilised method to assess the risk of collision. Also, based on the CPA and TCPA, the OOW evaluate the collision situation and decide the avoidance action and time (Tam et al., 2009). In this process two parameters are required in order to assess the collision situation accurately, the Time to Closest Point of Approach (TCPA) and the Distance to Closest Point of Approach (DCPA) (Pietrzykowski et al., 2010, Tam et al., 2009). In the past, these parameters were calculated manually using the radar to locate the targets then manually plot it on the plotting sheet, which used to be a time-consuming process, until the decision is reached. Nowadays, the ARPA system automatically provides the necessary information, where the OOW needs to collect it and make the avoidance decision based on it. Full consideration is given to the to ship domain, where no targets or obstacles are allowed to breach the domain distance, which is decided by the captain or the OOW (Pietrzykowski et al., 2010).

3.7.2 Autonomous Navigational methods

The research for automatic collision avoidance systems started in the 1960s with the introduction of new technologies on-board ships (radar and GPS). At that time, the focus was about finding the potential position of the collision, in an encounter situation between ships (Tam et al., 2009). However, avoidance decisions used to be made by the OOW, based on basic information obtained from the radar. Since the 1960s until today, many navigational aids have been introduced on-board ship (AIS, ECDIS, ARPA and GPS). Yet, they are information systems only and the OOW needs to make the avoidance decision to avoid a collision at sea, where the main function of the navigational aids is to computerise the calculations and provide the information to the OOW to make the decisions (Pietrzykowski et al., 2014).

Nevertheless, the issue of automatic collision avoidance is remaining unsolved, where many theoretical solutions are available as concepts, but not yet tested and implemented as a reliable model. Moreover, due to legal issues of defining the responsibilities between vessels in case of collision between autonomous ships (financial issues; as insurance companies cannot blame automatic systems for accidents), it became unfeasible to apply fully automatic collision avoidance systems on-board ships yet (Tam et al., 2009). Therefore, the topic of autonomous vessels is actively under discussion on IMO agenda under the maritime safety committee. However, until the IMO provides clear guideline and regulation about the implementation and operation of the autonomous vessels, it is more professional to call it a decision support system for collision avoidance. In this case, the OOW receives the collision avoidance decisions from the system, then apply it to the ship control.

Considering the previous models of automatic collision avoidance, it appears that nearly all of them were using the principle of safe ship domain for own ship and target ship to assess the risk of collision (Tam et al., 2009, Szlapczynski, 2006b, Pietrzykowski and Uriasz, 2009). Moreover, the research on automatic collision avoidance models can be categorised in two groups, either (Tam et al., 2009, Statheros et al., 2008);

- Collision avoidance models (solve conflicts between vessels only).
- Path planning models (optimum solution to avoid collision and return to the original track).

The collision avoidance models were widespread before the 1990s. These were more about solving collision problem between two vessels or avoiding the most dangerous targets in the vicinity (Statheros et al., 2008). After the 1990s, the path planning models became more recognised due to the development in the technologies and the wide use of computer systems. Moreover, this approach was divided into two footpaths; a deterministic approach or a heuristic approach (mainly after 2000s) (Tam et al., 2009).

In general, the collision avoidance models were more about providing information to solve the collision situation (Statheros et al., 2008). Based on the COLREG regulations, the ships were involved in collision situation as stand-on vessel (maintain course and speed) and a give-way vessel (take avoidance action) (Tam et al., 2009). The category of collision avoidance models usually provides the following decision for collision avoidance manoeuvres:

- Course alteration (Port or starboard).
- Degrees of course alteration.
- When to alter the course.
- When to come back to the original track.

In the path planning models, more complex situations were solved. These models provide more critical suggestion, such as (Xue et al., 2009):

- The level of dangerous collision situation based on the ship domain.
- Provide the optimum solution to avoid collision situation (shortest track for example).
- The minimum avoidance action to pass clear from the target ship.
- Provide manoeuvres that comply with COLREG.

3.7.2.1 The automatic collision avoidance models

Rafal Szlapczynski has introduced a number of research papers related to the topic of automatic collision avoidance models, which are discussed below. His work is of interest as it shows a variety of methods and different area of application (Ships, Vessels Traffic Serveries VTS, Traffic Separation Scheme TTS and restricted visibility), as well as the development of his methods concerning the available literature. However, in these studies, the author was focusing on solving the collision problem, how to calculate the avoidance decisions, without great attention to the human capabilities and the implementation of the developed system on real navigational bridge. Thus, no methods for data-sharing and decision-acknowledgement where introduced in these studies to enhance the situational awareness and sharing the same mental model were proposed. Additionally, the developed systems have not been tested on navigational simulator or real ships to evaluate the implementation procedures and testing the human performance when such new system is utilised.

(Szlapczynski, 2006a) proposed a new method for ship trajectories and collision avoidance on raster grids with extra safety margins and turning penalties to minimise the number of turns and time spending for trajectories. In general, the raster grids are used to provide the best route from the starting point to the destination without colliding with any obstacles at the sea. The principle of raster grids based on an algorithm used to provide the ship's route on the free cells, where no other ships are allowed to be in the same cell at the same time. Moreover, to increase the safety margin, no ships are allowed to be in the cells around the own ship for a distance defined by the user (safety ship domain). However, if another ship is located in a collision cell, the system assesses the situation to decide which the give-way ship is. If the own ship is the give-way, the system recalculates the avoidance manoeuvre to avoid the target in a safe distance. Also, Szlapczynski added penalties on turns for route calculation to avoid unnecessary distance and time in the provided new route.

(Szlapczynski, 2011) introduced another method of ships' path planning and collision avoidance manoeuvres by utilising a technique called *"Evolutionary Sets of Safe Trajectories"*. The new approach is combining the concept of game theory with the evolutionary programming technique. The main advantages of this approach are to overcome the long-time of computational calculation in the game theory to determine the avoidance trajectory. This is to allow the model to deal with changeable targets parameters, as the evolutionary method (which uses genetic algorithm) is always assumes unchangeable parameters of targets. This method is able to calculate a set of trajectories for all targets involving in an encounter situation, instead of own ship only avoiding all targets. Moreover, it does not allow any ship domain violation, with full consideration of COLREGs regulation for the provided trajectories. This method provides optimum route planning for all ships in an encounter situation. From the time the system detects a risk of collision between ships until all ships pass clear from each other. Furthermore, if one of the ships changes its parameters, the system will recalculate the trajectories and provide new solutions for all ships. In regard to the low computational time, it is applicable for ships and VTS as well. After additional investigation and farther studies on the evolutionary mechanisms, it appears that it needs more improvement to support the optimisation technique and shorten the calculation time for a faster solution (Szlapczynski and Szlapczynska, 2012).

For the extension of the above-mentioned method, which is suitable for open water and restricted areas. The authors have introduced rule 10 of the COLREGs (Traffic Separation Scheme) to the previous model (Szlapczynski, 2013). Basically that allows the model to provide safe ship trajectories to proceed in the TSS with compliance to COLREG rule 10 (Szlapczynski, 2013).

As a continuation of the ***Rafal Szlapczynski*** research, the criteria of rule 19 (restricted visibility) of COLREGs has been applied in his previous model (Szlapczynski, 2015). This rule states that any course alteration to the port side for all targets spotted ahead of the ship’s beam must be prevented, unless in an overtaking situation. Also, it restricts any course alteration toward targets spotted abeam or behind abeam (Szlapczynski, 2015). However, all these considerations are modified in the *“Evolutionary Sets of Safe Trajectories*” to calculate the optimum trajectories in restricted visibility.

(Szlapczynski, 2008) reported a new method to solve the problem of multi-targets avoidance manoeuvres. The normal approach of these kinds of manoeuvres is usually to avoid the most dangerous target first, then the less dangerous ships come after. As a result, the normal approach has many course alterations, which is unsafe, unfeasible and longer in time and distance. The new method utilises optimisation algorithms to calculate the best course alteration to avoid all targets (Szlapczynski, 2008).

(Szlapczynski, 2009) provided two methods of emergency planning of avoidance manoeuvres. The first one is for monitoring the give-way vessel if it does not start to take avoidance action before it is a critical situation. The system calculates the probability of give-way vessel not taking action, then provides a new trajectory for the stand-on to avoid the target. However, the OOW does not have sufficient time to evaluate the new trajectory, which introduces the role of the second method. This method provides a visual display of the dangerous zones of other ship’s domain, and allow the OOW to easily select the safe area to manoeuvre (Szlapczynski, 2009). The second method uses the Collision Threat Parameters Area CTPA approach to calculate the forbidden areas. This allows the OOW to choose the best course and speed to avoid the risk of collision. (Figure 18) shows the suggested display for this model, where the white areas are the safe destination for manoeuvre. However, in real-life scenarios, when navigating in a congested traffic area, the model’s display will be filled with dangerous areas (black) and this will introduce more complication to the OOW to find the safe area to manoeuvre. Moreover, this model has been suggested for emergency manoeuvring decision support system; thus, in critical situations, the OOW will be overwhelmed to recognise the situation and select the best action to avoid the collision situation.

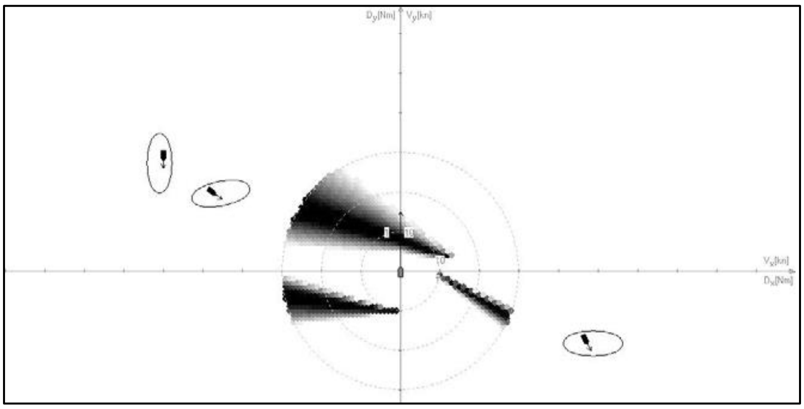


Figure 18 Emergency planning avoidance manoeuvre (Szlapczynski, 2009)

(Szlapczynski and Szlapczynska, 2015) introduced a new technique for visualising collision avoidance manoeuvres, which based on the CTPA principle by (Lenart, 1983) to find the collision threat areas with other ships. The new technique complies with COLREGs regulations (Szlapczynski and Szlapczynska, 2015). As a result of this technique, it became straightforward for the OOW to decide the avoidance manoeuvres, which are COLREGs compliant manoeuvres. Basically, it depends on colours to define the navigational areas. Whereas, the light blue is for the COLREG’s forbidden area. The red is a dangerous area where the collision will take place. The pink area is the ship’s domain violation area or close passing distance. Finally, the white area where is the safe area to navigate (Szlapczynski and Szlapczynska, 2015). This helps the OOW to find a safe manoeuvring area without violating COLRGEs rules. Moreover, in order to help in deciding the value of new course, speed or both, every pixel on the display unit is assigned with a course and speed values, then all that it needs is to move the pointer to the desired area and read out the new course and speed, which allow safe collision avoidance (the white area) (Szlapczynski and Szlapczynska, 2015). This new method will help the OOW in decision making and obeying the COLREGs rules in an easy manner. Figure 19 is an illustration of the visualising display method for collision avoidance.

Although, Rafal Szlapczynski has developed models that have covered a variety of navigational situation and they have been illustrated thoroughly, yet, they have not been tested in ship’s navigational simulators or in real ship to validate its operation in navigational situations. All the suggested models have been tested in computer-based simulator software where they have shown satisfying results, but the computer-based simulator cannot test the capabilities of the models in real-scenarios when operating by OOWs. Moreover, the computer-based simulation is capable of validating the accuracy of the models’ calculation and outcomes, but this does not test the operational capabilities in navigational situations. However, these tests did not provide a complete result that test the improvement in the OOW performance when utilising such models.

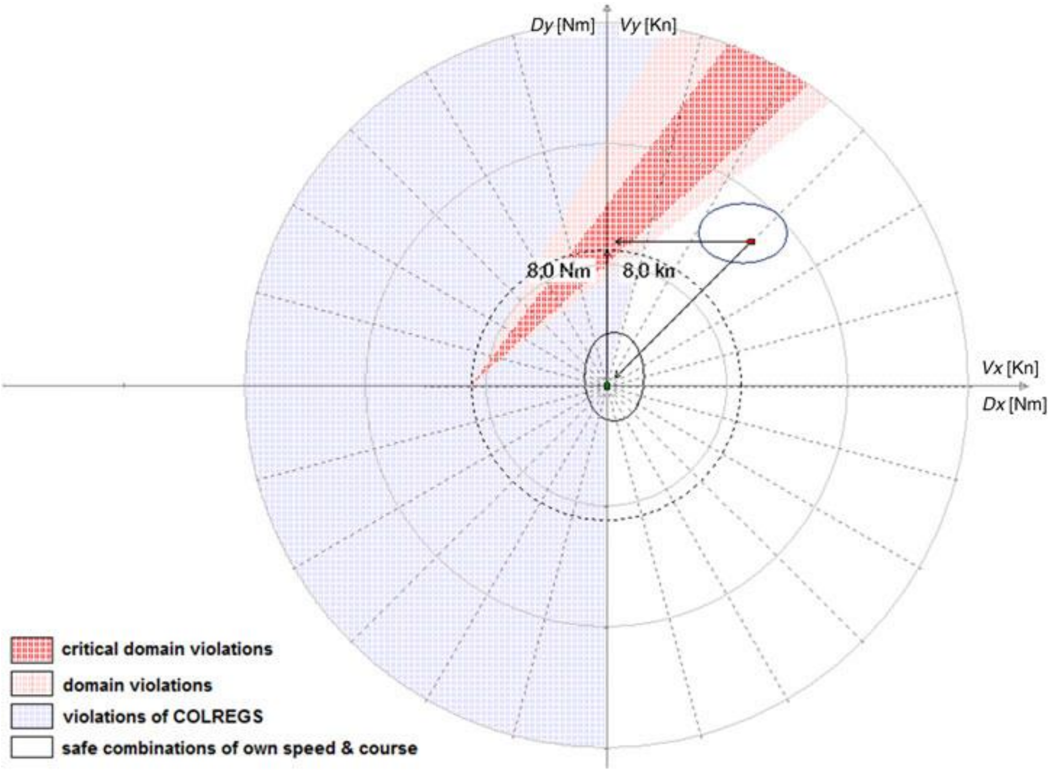


Figure 19 Visualising display method for collision avoidance, (Szlapczynski and Szlapczynska, 2015)

(Perera et al., 2009) proposed a decision-making system for collision avoidance in ocean navigational areas. The system applies fuzzy logic to analyse the navigational information of both own and target ships. After the collision risk assessment of the conflict situation, the system evaluates the COLREG regulations to define the responsibility between the vessels in a collision situation. Then, if own vessel is the give-way one, the system provides the avoidance manoeuvre by either, course and/or speed change with respect to COLREGs regulation (Perera et al., 2009). However, the decision-making system still needs more studies and experiments to be able to assess the more critical situation in other navigational areas.

(Perera and Soares, 2012b, Perera and Soares, 2012a) introduced a method to identify the risk of collision and near-collision situation, by measuring targets and own ships' relative motions (Parameters; course, speed and track). In order to calculate the relative motion, this method uses the Kalman filter algorithm, which is an algorithm used for the calculation of estimations (Perera and Soares, 2012b). Whereas the normal Kalman filter is only able to deal with linear systems. However, the Extended Kalman filter is used to overcome this limitation and be able to work with the non-linear systems (Perera and Soares, 2012a). This method is part of an

Intelligent Navigation System (INS), which is designed by the same authors to have a complete e-navigational system. This system is able to provide collision avoidance manoeuvres for multi-targets in conflict situations. The INS system is designed in three sub-systems; Vessel Monitoring and Information System, Collision Avoidance System and Vessel Control System (Perera and Soares, 2012b). The first system is responsible for target detection, monitoring the vessels in vicinity and provides the navigational information (speed, course, position, and ext.), where the detection of the risk of collision method is part of this sub-system. Then, the second system is responsible for the decisions and actions that need to be taken to avoid collisions with multiple targets. Finally, the third system is responsible for autonomous control of the own ship, where it receives the avoidance decision from the second system. The avoidance manoeuvres are changing in the course and/or speed. Then the system connects to the control unit of the ship to give the rudder and propeller order to execute the avoidance manoeuvres. The INS system basically applies the fuzzy logic navigational decision support system, which, as explained earlier, provide an autonomous vessel concept. This system is able to avoid collisions with multi-targets in more complicated situations with full compliance to COLREGs regulation. However, this model has not been tested for collision avoidance situation with multiple targets and no validation results available to ensure its capabilities to detect and avoid more than one targets.

(Perera et al., 2015) applied the above-mentioned mathematical formulation of automatic navigation and collision avoidance system in a real vessel model. This has been experimented in a testing tank to find the effectiveness of the model in real-life situations. The experimental model consists of the mathematical formulation (Fuzzy logic) and a physical system. In more detail, this combines the previous explained work of the authors as the mathematical formulations with the physical system. This model is divided into; the vessel model and a Navigational and Control Platform. Moreover, the Navigational and Control Model is the key part of controlling the vessel and executing the manoeuvres. Furthermore, the Navigational and Control Model is divided into; Hard Structure, which has the Command and Monitoring Unit and the Communication and Control Unit, and then the Soft Architecture, which has the Human Machine Interface and the Control system of steering and speed sub-systems (Perera et al., 2012). The experiment was conducted in the testing tank between two vessels, in many navigational and collision situations. However, the system was not able to complete the provided avoidance manoeuvre due to a sudden change in own and target ships course and speed because of wind and wave condition in the testing tank. To solve this problem a further modification had to be made on the computational algorithm to simulate the target’s manoeuvre. Although the results were promising, the system still needs more development to be capable of manoeuvring and avoiding multi-targets in a conflict situation. Additionally, this experiment was conducted between two vessels only and no results were obtained for multiple targets avoidance. Finally, the OOW response to such a system could not be measured, as the tests were conducted in the tank. Thus, this experiment is acceptable to examine the operation of the developed model, but it does not test the full implementation of such system on-board ships to measure the OOW performance on navigational situations. The next diagram (Figure 20) has been developed by the author (researcher) to summarise the work of (Perera et al., 2015) in the decision-making system for collision avoidance and the experimental model using the following literature; (Perera et al., 2009, Perera et al., 2011, Perera and Soares, 2012a, Perera et al., 2010b, Perera et al., 2010a, Perera et al., 2015).

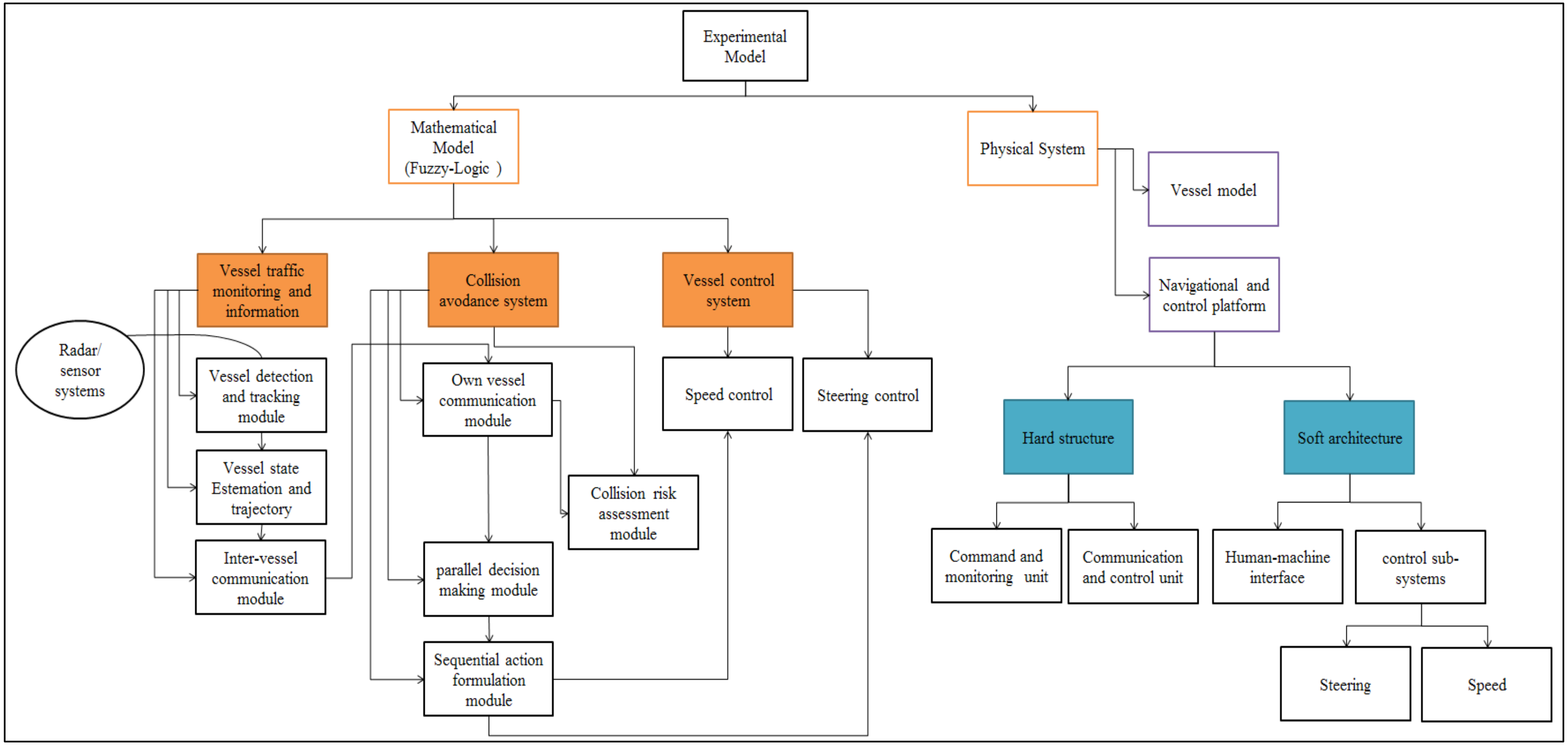


Figure 20 a structure summary for Perera et al works in the decision-making system for collision avoidance and the experimental model

(Wang et al., 2010) proposed a collision-avoidance model that helps in the decision-making process to reduce the workload and stress level on the navigational watch. This claims that it has the potential to eliminate or minimise the occurrence of human errors in navigational decisions. Moreover, the model reduces the events of misinterpretation of COLREGs between vessels in a complicated situation. In addition, where COLREGs regulation provides qualitative information only, then the OOW must decide what collision avoidance manoeuvres are needed. This is directly related to the OOW perspective of the situation and the evaluation of the required quantitative decision. The proposed model develops a mathematical formulation to solve three stages of collision avoidance process. The first stage is to decide if the situation requires own ship to take action or not, based on COLREGs regulation. This decision is considered by calculating the Distance to Closest Point of Approach DCPA then compare it to the desired passing distance set by the OOW. If the DCPA is greater than the desired passing distance, no manoeuvre is required, if it is less, then the own ship must take action based on COLREGs guidance. The second stage is to decide when to take the actions, this is calculated using the Time to Last Minute Action formula to give the OOW the best time to take actions. After this time the avoidance actions by own ship alone will not be enough to avoid a collision. Also, the Time to Last Minute Action is useful for the stand-on ship to be aware when to take avoidance action, in case of no action is taken by the give-way ship, or if her action is not enough to avoid a collision. Finally, this the part of the collision avoidance decisions, it is either; change in course (preferable) or/and speed. The model suggests the avoidance manoeuvres quantitatively by giving the amount of course and speed changes to pass the target ship in the desired passing distance.

(Liu and Shi, 2005) introduced a fuzzy-neural collision avoidance model for ship encounter situations that are applying COLREGs regulation on its decision output. The model is combining the fuzzy logic technique with the neural network method. The fuzzy logic is the right approach for describing the knowledge and analysing the information. Also, it is useful in transferring qualitative information to quantitative ones for computations. The main shortage of the fuzzy logic approach is the difficulties in modifying some of the functions and fuzzy rules. Nevertheless, the Neural Network method is useful in learning and mimicking nonlinear functions techniques. Yet, it is difficult to explain and read the information stored in the network. These reasons make it feasible to combine both methods to have an intelligent collision avoidance system, which is able to provide useful decisions with the ability to be trained to solve problems. The outputs of the collision avoidance system are; the actions, the rate of turn and the time to conduct a successful avoidance manoeuvre with respect to COLREG regulation.

3.7.2.2 Path Planning Models

(Tam and Bucknall, 2010) has introduced an algorithm which can provide an optimum navigational trajectory to avoid multi-targets in close range conflict situations. This trajectory is compliant with COLREGs regulations. The Evolutionary Algorithm has been applied in this model for its flexibility in the sense of changeable parameters for vessels involved in the avoidance situation. This allows the algorithm to reassess the situation, if any parameter change, and find an optimum solution that takes into consideration the previous scenarios (Tam and Bucknall, 2010). The main idea behind this model is to find a safe area around the target ship, which the own ship is allowed to pass from. However, the model is capable of providing a noncompliant to COLREGs trajectories if the circumstances of the situation require. On the other hand, it provides and executes the trajectories in early time to avoid such a situation. Also, to reduce the magnitude of the turning angle. The Evolutionary Algorithm basically analyses multi solutions until it finds the most suitable one for the available traffic situation. The algorithm's structure consists of two parts; assessment of the risk of collision with other targets using its relative position and heading. Then it provides the best trajectory for the traffic situation. In a computer simulation, the model comes out with impressive results, as it can calculate feasible and optimum solutions for almost all traffic cases, while complying with COLREGs and the general seamanship practises.

(Lee et al., 2004) proposed a fuzzy logic-based collision and path planning model for autonomous ships under COLREGs regulation satisfaction. The algorithm applied the Virtual Force Field VFF method, which has been used broadly in the area of navigation and obstacle avoidance by robots. The general principle of the VFF is to define the wanted destination (waypoint), and that waypoint keeps attracting the own ship towards it. The model detects the obstacle, then surround it by pushing force function to prohibit the own ship from moving towards it. This allows it to pass in a safe distance (Lee et al., 2004). However, the traditional VFF method is inefficient for moving targets. Due to this, the authors used a Modified Virtual Force Field to have flexibility in providing track keeping and collision avoidance manoeuvres with compliance to COLREGs regulations. The results of the computer simulation show good capabilities in performing avoidance manoeuvres that satisfy COLREGs regulations.

(Tsou and Hsueh, 2010) introduced a collision-avoidance route planning model that uses an Ant Colony algorithm to calculate the shortest and safest avoiding manoeuvre. Then it provides the best returning decision to move back to the original track. The model considers the best seamanship practices, COLREGs and AIS information to calculate the avoidance manoeuvres in real-time. Also, the model displays the manoeuvre on Geographical Information System GIS with other navigational information. The principle of the Ant Colony Algorithm is the same as the real ants when they try to find the shortest route from the food source to their nest. To solve this, the ants depend on pheromones to lead them to the way (Tsou and Hsueh, 2010). In this model, it uses evolutionary computations to solve real-time collision avoidance problems. The model is able to calculate the avoidance manoeuvres based on the following criteria;

- Minimum distance for the total manoeuvre.
- Minimum risk of collision.
- No breach of the safety domain by any targets.
- Provides avoidance decisions that include the returning routs to the original track without other conflict situations.
- Minimum turning angles for avoidance and return decisions with respect to the safety aspect.

The proposed model is capable of providing the following decisions for collision avoidance manoeuvres, in which it can reduce the workload in bridge operation and helps the OOWs in decision making;

- Collision risk assessment.
- The best avoidance actions.
- The last moment before critical situations.
- The avoidance decisions (turning angles).
- The time required to return to the original track.
- The actions to return to the original track.

Finally, the computer simulation results show some useful planning to avoid critical situations. This is helpful for understanding the scenario of collision avoidance in advance and the safety criteria. Also, this allows the OOW to ensure the safety of the ship without performing unnecessary tasks, which reduce the situational awareness on the bridge.

Some other research studies about the topic of collision avoidance topic found very similar results to the explained work above. However, to avoid the repetition of discussing similar approaches and topic, also, to be able to cover all the available studies, the following table (Table 4) has briefly summarised the studies that are related to this research area.

Table 4 Summary table for other avoidance models

Authors	Models or Techniques	Model reasoning	Collision assessment	Avoidance decisions
(Xu, 2014)	Danger Immune Algorithm	The capability to solve single and multiple problems (multi-targets situations).	DCPA, TCPA, COLREGs and ships' static and dynamic data.	Course Change, Course and speed change, Course change and revers engine.
(Perera et al., 2011)	Fuzzy logic	Its formulation based on human thinking techniques, which make it a human friendly model	Speed and course of each vessel, distance, DCPA, TCPA, other targets, environmental conditions and COLREGs.	Avoiding action for Stand-on vessel if Give-way vessel does not take appropriate action, by course and/or speed change only (no crash stopping).
(Tsou et al., 2010)	Genetic Algorithm of Artificial Intelligent	The ability to search for the optimum route to be followed from many routes.	DCPA, TCPA and COLREGs	Find the shortest route to avoid collision and pass safely until getting back to the original track.
(Xue et al., 2009)	Artificial Potential Field for ship route planning	Its simplicity and smartness in mathematical applications and route planning.	Safe distance to pass, COLREGs and ships' static and dynamic data	Optimum route for collision avoidance by course change (speed change for emergency situations)
(Zhuo and Hearn, 2008)	Adaptive Neuro-Fuzzy Inference System	Fuzzy used to analyse imprecise data to come out with actions. And	DCPA, TCPA, Ships' static information and COLREGs.	Course change and Time to take action

		neural network for training purposes.		
(Smierzchalski and Michalewicz, 1998)	Evolutionary Algorithm (Evolutionary Planner/ Navigation)	The optimisation factor in selecting trajectories.	DCPA, TCPA, Static and Dynamic data.	Optimum trajectory (route) to avoid collision and reach the destination

3.8 Discussion

The existence of navigational aids and systems has improved the navigational safety and situational awareness dramatically. However, it introduced other drawbacks about the aspect of best seakeeping practices, which attract the attention of researchers and organisational bodies. The issue of over-reliance on systems may lead to deterioration of navigational skills as a result of the poor performance of navigational tasks where all the information is available on the equipment. Nevertheless, the reliance on erroneous information from systems (loss of signals, damage in equipment or systems malfunction), without checking the raised alarms, until critical situation exists which put the ship in a dangerous situation and can lead to accidents. Although all the essential elements in the bridge are designed with alarms and alerting functions, still officers are acknowledging these alarms without investigating its reason. This is because of either; the workload or overconfidence of the OOW. After the intensive research on all the navigational aids, the result comes as following; all the navigational aids, equipment and systems on the bridge, are information systems only. However, the OOW is the responsible person for collecting, analysing and decisions making to ensure the safety of the navigational watch. Therefore, these bring the importance of developing an automatic collision avoidance system that supports the OOW in decision-making processes. This system must support the OOW in the following processes and tasks;

- Information flow in the bridge.
- Man-machine interaction.
- Automatic Coordination and Connection between ships.
- Remove the subjectivity and uncertainty of the decisions and help in decision-making objectivity based on the COLREG.

For ships manoeuvrability and performance, the manoeuvring characteristics standards have been introduced by the IMO to provide ship designers and builders with guidelines about the minimum requirement of ships manoeuvrability and performance standards to ensure safe handling of ships. However, the information in the manoeuvring booklet considered being an essential source of the ship's capabilities, where this will determine the manoeuvring capability of every ship. For the development of an automatic collision avoidance system, this information should be considered carefully; in this case, the system will provide feasible manoeuvres that the ship can perform. In addition, as the coordination feature of manoeuvres in the automatic collision avoidance system searches for the optimum manoeuvre for collision avoidance for all ships in the vicinity. Thus, this information will be of great benefit to allow the system to consider the manoeuvring capacities of every ship in order to provide the most optimum manoeuvre for all ships.

At first glance into the navigational watch duties and collision avoidance procedures, it appears like an easy and logical task. However, when all these processes are carried on at the same time, in an area with traffic density, they become very stressful and tiredness tasks. Additionally, the amount of information flow at the same time is colossal to be handled by a human in such a stressful situation. Moreover, the navigational situation must be well interpreted, and the navigational information should be perceived correctly to allow the OOW to make the most appropriate decision. Indeed, the presence of the human element in almost every marine collision is not surprising when this tremendous amount of data processing is required. Especially as the data sources are located in different locations and screens on the bridge.

On the other hand, the alarms and alerts in the systems are not efficient to act as a barrier to stop the accidents. Firstly, some of the alerts on ARPA and ECDIS system do not function automatically, where the OOW needs to enter values and set alarms. Thus, all these alarms are to remind the OOW about crossing areas or pre-determined locations. Secondly, some alarms about the loss of single or multiple targets, where they go off very frequently even for the unimportant warning, are ignored by the OOW. In general, no alarms are intended to alert the OOW about dangerous or collision situations. However, the OOW should process all the information from the navigational aids systems to assess the situation.

The above comparison between the aviation and maritime industries has shown that technological advancement, collision avoidance procedures and safety level are superior in the aviation industry. Hereafter are the critical elements found in the aviation industry, which can be adopted by the maritime to enhance navigational safety, especially in critical collision situations.

Firstly, the amount of information flow in ships' bridge is immense. In such critical situations, the OOW becomes distracted by all equipment that needs to be monitored and the manoeuvrability of his ship. In order to enhance the OOW's performance, it would be better if a standardised display on one screen, presenting all the vital information for the critical collision decision-making procedure is available on bridge. In this case, the OOW will be able to focus on decision-making without missing any other relevant information or tasks.

Secondly, the man-machine interaction; this concept of designing navigational systems will enhance the level of situational awareness on the bridge. The conventional navigational systems are information systems only, which present all the information and the OOW utilises what is needed. In this case, the chances of missing a key element are high, and there is no method of ensuring that the OOW is fully aware of the situation. By applying the man-machine interaction technique, the system will automatically ensure the awareness of the OOW and the full utilisation of the information. Also, an alert must be issued if the OOW it not utilising the vital information on the system to ensure the awareness of the OOW.

Thirdly, the technique of automatic coordination and connection between maritime collision avoidance systems to remove the uncertainty: by adding such a technique, the OOW will be able to monitor the target ship more accurately. Moreover, it will allow the OOW and the systems to deal with the changeable parameters of target ships as well. Additionally, the feature of acknowledging the manoeuvres of both target and own ships will enhance the level of situational awareness significantly. For example, the OOW can monitor the target ship's changes in course and/or speed in real-time. Plus, if the target ship can show a means of acknowledgement to indicate its awareness of the situation, this will remove the uncertainty of the whole situation, and it will indicate both ships' recognition of the situation. In such cases, the stand-on vessel in rule 17 will be sure about the give-way vessel's action. Whether the give-way vessel is aware of the situation and taking the avoidance action or she needs to avoid the collision by her own actions.

Finally, the possibility to change the subjectivity nature of the OOW's decisions, which are based on his own perception and interpretation of the situation to take objective decisions, ruled by real-time information, with a correct and full interpretation of the situation. This will enhance the level of situational awareness and navigational safety dramatically.

In conclusion, to improve maritime navigational safety, it is essential to introduce an Automatic Collision Avoidance System, which is similar to the TCAS system. The new system will enhance the collision avoidance procedures and utilisation of information on the bridge. Consequently, navigational safety will improve by using better interpretation and perception by the OOW. In addition, this will remove the uncertainty in the COLREG and the decision-making, as well as the subjectivity of the OOW decisions.

4 Approach Adopted

4.1 Introduction

Despite the entire enhancement in maritime regulations and the technological advancement in the maritime industry, maritime accidents are still happening at sea. According to the European Maritime Safety Agency (EMSA), a yearly average of 3315 accidents and incidents has been reported from 2014 to 2017 (EMSA, 2018). Thus, half of these occurrences are related the navigational activities, such as; grounding, contact and collision (EMSA, 2017). Generally, these accidents have happened for many reasons, like; human factors, equipment failure, commercial pressure, machinery failure, etc. However, the main contributing factors of accidents are human factor and equipment failure. Furthermore, the increases in traffic density have a tremendous impact on the number of maritime accidents, especially in inland waters. This increased the interest and the motivation of researchers to develop systems to enhance maritime safety as shipping carries more than 95% of the world trade (UNCTAD, 2019). In order to achieve this, it is essential to understand the main factors that lead to accidents at sea to help in addressing the problems and prevent accidents. It was highlighted that collisions, contact and grounding make up most of the maritime accidents. Accordingly, the maritime accident statistics have revealed that more than 80% of the accidents are due to human factors. However, it is extremely important to understand the factors behind human errors, which leads to a chain of wrong actions that lead to the accident. By conducting this research, we will be able to answer this question and find the best solution to mitigate the risk.

4.2 Methodology outline

This chapter presents the adopted approaches that will be followed to perform this research study. Figure 21 shows the steps as a road map to guide the author to conduct the proposed research. The first step is the literature review, which provides the main issues that are related to the maritime safety and accidents at sea. By identifying the problems of collision accidents, a review of concepts and procedures in other industries was carried out to adopt the best practices with regards to collision avoidance. This has facilitated the creation of the system framework (system architecture) for the new automatic collision avoidance system. The framework of the new system is the roadmap and operational principle of the automatic collision avoidance system. After the development of the system architecture, the required mathematical formulas and calculations to build the collision avoidance model were formulated. The model for the new automatic collision avoidance system is tested and validated in a ship navigational bridge simulator by using the past collision accident reports and measuring the improvement achieved in the OOW’s performance if such system is available on ships.

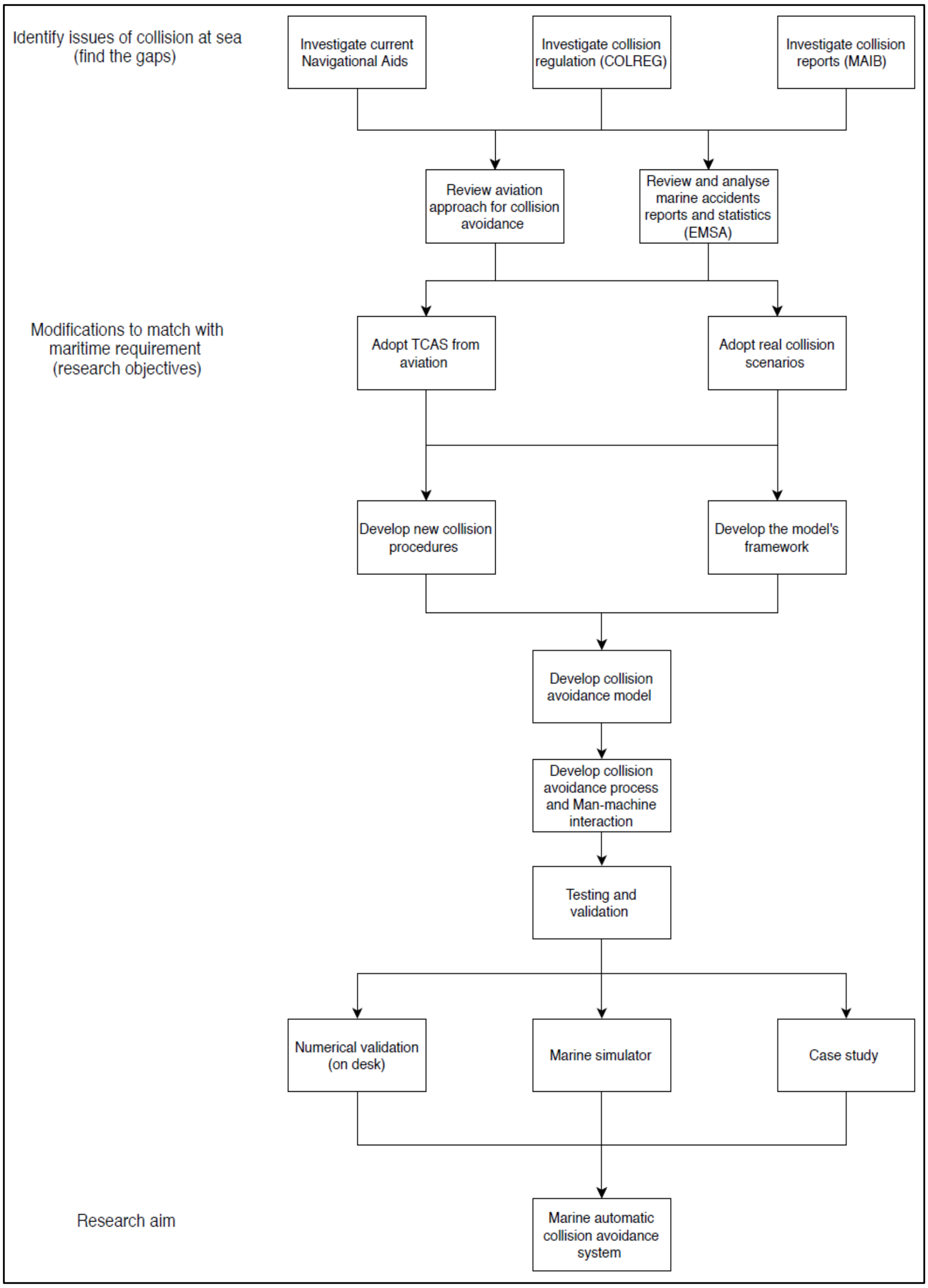


Figure 21 Methodology outline

4.3 Literature review

In this step, the literature about the related topics needs to be reviewed to identify the challenges and their causes and consequences. For this reason, the maritime accident statistics have to be looked at to justify the need for this research and to find the most contributing factors for the accidents in order to prevent them. Then, the human factors and how OOWs perform in the navigational duties have to be understood, including the human psychology in learning and decision making to support the proper design of a user-friendly system for collision avoidance. Moreover, the collision regulation COLREG, and the navigational procedures have been critically reviewed to identify the gaps and address them in the proposed system architecture. Ship navigational systems and equipment have been reviewed in chapter three with regards to their operation and utilisation to recognise the weaknesses of these systems. Furthermore, in chapter five, the maritime navigational system and the TCAS system have been reviewed intensively to deploy the best features and functions from both the aviation and maritime technologies and procedures in the new framework for the automatic collision avoidance system. At the end of chapter three, the research gaps in ship collision and the automatic collision avoidance system are summarised.

4.4 Procedural diagrams and system’s framework (architecture)

In order to develop the automatic collision avoidance system, the best procedures and practices have to be adopted in the new system. Accordingly, it is essential to develop procedural diagrams for the maritime and aviation collision avoidance processes to support in capturing the best practices and address the shortages of the navigational procedures. The development of the system’s framework (architecture) helps to create the conceptual model of the proposed system, which provides the structure and operational specifications of the system. This framework (architecture) provides the formal description of the new automatic collision avoidance system and its representation in an organised approach that supports the logic of the framework’s structure and the operation of the system. The system’s framework (architecture) and specifications are discussed in chapter six.

4.5 The mathematical formulas of the automatic collision avoidance model

The development of the automatic collision avoidance model requires the utilisation of mathematical formulas and calculations. These formulas are utilised for the vector calculations of the target ship's position, course and speed relative to the own ship. Thus, this will allow the calculation of the CPA and TCPA to assess the risk of collision, then, if a risk exists, they calculate the avoidance manoeuvre and provide the best action to avoid the collision by changing of speed, course and/or both of them. The mathematical formulas are discussed in chapter seven.

4.6 The validation experiment of the automatic collision avoidance system

After the development of the Automatic collision avoidance model, it is essential to examine the system and prove its capabilities to prevent maritime navigational collisions. The validation experiment will be performed in the ship's navigational bridge simulator. For the validation experiment, the seafarers will participate in the scenarios which will be developed from real maritime collision reports (from MAIB). These scenarios will be reconstructed in the simulator environment and the OOWs' performance will be monitored all the time. The main aim of the experiments is to measure the ship navigational performance of participants (OOW) against the Key Performance Indicators (KPIs) linked to the classical collision avoidance approach and the automatic collision avoidance approach. Then, the required analyses will be performed to quantify the enhancement in the safety of navigation when utilising the developed automatic collision avoidance system. The Fuzzy-TOPSIS Multiple-Criteria Decision Making (MCDM) tool will be used for the selection of the best action to avoid the collision. The validation experiments are discussed in chapter eight.

5 Technical specifications of navigation and collision avoidance systems in maritime and aviation industries

5.1 Introduction

This chapter illustrates the navigational systems in the maritime industry and collision avoidance systems in the aviation industry with its utilisation during the navigational duties. First, it will explain the technical details of all the important navigational equipment that are being used on ships to ensure safe watches. Moreover, this will include the ship's capability and manoeuvrability with regards to the IMO standards for ships' manoeuvrability and sea trials. The final section has a thorough explanation of the aviation automatic collision avoidance system, TCAS. This section provides a complete review of the TCAS system and its operational techniques which will help the author and the maritime sector to develop a similar system for ships.

5.2 Navigational Systems, Navigational Information and its Impact on Navigational Safety

In order to improve the navigational procedures on ships' bridge, it is crucial to understand the current condition and how the OOW is performing on the navigational duties. An extensive review was, therefore performed, and the impact of each factor was highlighted in this section. This includes a review of the navigational equipment, available information on ships' bridge and the ship's capabilities and manoeuvrability. The technical issues, utilisation and weakness of each navigational system are discussed in this section. Moreover, the ships performance and minimum manoeuvrability requirements, by IMO, are covered here.

5.2.1 Ships' Navigational Aids

As in every industry, technological advancements facilitate the duties of operators in different ways. Automation has been applied to replace humans in monotonous work and provide the necessary information to the operator (Parasuraman and Riley, 1997). For example, in the marine industry, most of the navigational aids systems have been introduced to release the OOW from the boredom of the repetitive tasks. This is to reduce the workload and to give more time for decision-making rather than processing the information. As a result, ships' bridge has been equipped with many devices and screens, which in order provide more information than what the OOW can handle. However, the maritime industry used automation to reduce the crew size while the amount of information flow increased significantly. This affected the situational awareness in a negative way, where the OOW is required to monitor more systems which provide a tremendous amount of information (Hetherington et al., 2006). Thus, the increase in the mental workload leads to higher chances of forgetting some information and wrongly interpreting the surrounding situation.

Moreover, the integration of the navigational systems seems like a solution to such a problem. Indeed, it improved the man-machine interface passionately, but then again, this did not solve the problem. After the integration of systems, the OOW still needs to monitor all screens and devices to ensure their operation and performance is at the optimum level, plus cross-checking the data to ensure systems are working properly. Another problem arises with the widespread of navigational equipment's makers, is the lack of standardisation of the information presentation, availability and accessibility. This introduced more confusion for the OOWs with the usage of this equipment, especially by the newly assigned officers. Following is a more detailed explanation for these navigational aids that the OOW needs to monitor and use to perform safe navigational duties.

5.2.1.1 Automatic Identification System (AIS)

The Automatic Identification System (AIS) has been adopted by the International Maritime Organisation IMO in 2000, as a new amendment to SOLAS chapter V (Carriage requirement) (Figure 22). This amendment is to be applicable for all ships of 300 Gross Tonnage and above, which are engaged in international voyages, and all ships of 500 Gross Tonnage and above in domestic operation (IMO, 2002a). The AIS intends to enhance maritime safety through better availability and exchange of information between ship-to-ship and ship-to-shore bases. The AIS information is categorised in four groups;

- Static.
- Dynamic.
- Voyage related information.
- Short safety messages.

(Table 5) contains the details of each group (IMO, 2002a). For each type of information, the entry into the device is done differently.

- First, the static information, which entered in the installation stage, and it cannot be changed manually.
- Second, the dynamic information, which is collected from the ship’s sensors and systems.
- Finally, the voyage information, which is entered manually at the beginning of each voyage, should be updated during the progress of the voyage (Ou and Zhu, 2008).

However, this information is to be exchanged between all ships and shore stations in the vicinity, which are equipped with AIS receiver, automatically (IMO, 2002a). The rate of sending dynamic information is changing depending on the navigational status of the ship. For an anchored ship it is every 3 minutes. For an average ship speed of 19 knots it is every 6 seconds and for ships’ speed over 23 knots and changing her course is every 2 seconds (IMO, 2002a) where the static and voyage information are updated every 6 minutes in the AIS system. (Table 6) shows the rate of data update in more detail. (Figure 22) shows an AIS display unit and the targets information on the system. Additionally, the AIS system is integrated with the ARPA and ECDIS systems to provide the targets information to the OOW.

Figure 22 Furuno AIS system (ThitonikMarine, 2019)

Table 5 The information categories in the AIS system

Static Information (On Installation)	**Dynamic Information (From Ship's Sensors)**	**Voyage Information (Manually Entered)**	**Short Safety Messages (Manually Entered)**
MMSI (Maritime Mobile Service Identity)	Ship's Position	Ship's Draught	Short text messages which is manually entered about safety
Call Sign and Name	Time (UTC)	Hazardous Cargo Type	
IMO Number	Course Over Ground COG	Destination and ETA	
Length and Beam	Speed Over Ground SOG	Route plan (Waypoints)	
Type of Ship	Heading		
Location of Position Fixing Antenna	Navigational Status (Entered Manually)		
	Rate of Turn (If Available)		

Table 6 Rate of data update in the AIS system

Ship's status	**Dynamic information**	**Static information**	**Voyage information**
Anchor	3 minutes	6 minutes	6 minutes
Speed 0 – 14 knots	12 seconds	6 minutes	6 minutes
Speed 0 – 14, with turn	4 seconds	6 minutes	6 minutes
Speed 14 – 23 knots	6 seconds	6 minutes	6 minutes
Speed 14 – 23 with turn	2 seconds	6 minutes	6 minutes
Speed > 23 knots	3 seconds	6 minutes	6 minutes
Speed > 23, with turn	2 seconds	6 minutes	6 minutes

The use of AIS system in a collision situation has been addressed in the COLREG regulation; indeed, it is recommended by the IMO. However, some precautions must be taken when utilising the AIS system. The AIS information is useful in collision avoidance situations for identification of targets' name and call sign. Moreover, it provides information about targets' navigational status and ships' type, which helps in building a general idea about the surrounding situation. Furthermore, the availability of manoeuvring information and parameters of nearby ships' will help significantly to make future predictions to support the collision avoidance decision making process by the OOW (IMO, 2002a). Although the AIS system has enhanced navigational situational awareness, the OOW must keep on his/her mind that the AIS is a support system only, and it does not substitute other navigational systems (ARPA and ECDIS) (IMO, 2002a).

Furthermore, using of AIS, the OOW must follow COLREGs at all the time. The AIS system is a supporting system, and the OOW should use all the available information at all the time. The IMO in its guideline for the AIS operation on-board mentioned two cautionary points which should be followed by all the OOWs.

- First, it should be noted that not all vessels are equipped with AIS system, like leisure boats, fishing and warships.
- Second, some AIS-equipped ships may switch off their AIS system for many reasons (such as; security and piracy activity), which is decided by the master of the ship (IMO, 2002a).

Moreover, based on the author's experience and a study conducted in Liverpool John Moores University (Harati-Mokhtari et al., 2007), it is not unusual to find wrong information transmitted by the AIS system. In some cases, wrong status, wrong ship's name can be transmitted while in other cases unavailability of dynamic information can be encountered (Harati-Mokhtari et al., 2007). By examining different AIS information, it appears that in many cases incorrect or incomprehensive information related to ships in vicinity are broadcasted. This incorrect information usually confuses the OOW and can lead to misinterpretation of the situation (Harati-Mokhtari et al., 2007). Next is the AIS information that has been examined, and its effect on situational awareness. The Maritime Mobile Service Identity (MMSI), which is a unique identity for each vessel, has been reported that an incorrect MMIS address is broadcasting. This wrong address will mean the vessel will not be able to receive any messages or information that are sent to her by other vessels (Harati-Mokhtari et al., 2007). The MMIS number is entered manually in the installation stage, which can be either; forgotten or inadequate installation procedures that lead to incorrect addresses setting. In other cases, a wrongly transmitted static data (such as; vessel type, length, beam, etc.), can have a tremendous negative impact on the situational awareness, where misidentification and misinterpretation can take place (Harati-Mokhtari et al., 2007).

Additionally, inaccuracy or error with the ship's name or call sign makes it difficult to establish a VHF communication, where AIS can help greatly to identify target ships (Harati-Mokhtari et al., 2007). Inaccurate ships' name can be due to the limitation of the AIS to accommodate the long name of a ship; for instance, it has only 20 characters for the name field. Then the OOW needs to shorten his ship's name, and sometimes it becomes difficult to understand. For the navigational status, it is the confusing part, where a shortage of choices in the device promotes a selection of the nearest status to the real one (e.g. underway or sailing, underway for a power-driven vessel, and sailing is for sailing vessel). Another mistake is the vessel, which is at anchor, shows under-way status as the OOW forgot to change the status (Harati-Mokhtari et al., 2007). Also the draught, destination and Estimated Time of Arrival ETA, which needs to be entered manually by the OOW at the beginning of every voyage and updated when needed, which OOWs usually forgot to update this information (Harati-Mokhtari et al., 2007). Finally, ship's position, heading, course over ground (COG) and speed over ground (SOG) are essential information for risk of collision assessment. Thus, it is crucially important to have this manoeuvring information correct in order to take the appropriate avoidance action. Unfortunately, this information can be wrongly fed into the AIS devices by connection errors or a sensors fault (Harati-Mokhtari et al., 2007).

For the interest of this research, the AIS system has been studied to discover its usefulness as a collision-avoidance system. In general, the AIS system has enhanced navigational safety as it plays a vital role in collision avoidance decision-making process. This enhancement has been achieved by facilitating and providing easy access to other ships' information (identity and parameters). The availability of such information has increased the situational awareness level on the bridge due to the correct identification and interpretation of the situation around the ship. However, with all these benefits of the AIS system, it is still not reliable and not recommended to rely on the AIS alone. The AIS system may have inaccurate information on target ships, which can deteriorate the situation rather than improving it. Also, the fact that not all the vessels are equipped with AIS is another disadvantage. This makes the AIS just a supportive navigational system that concurs with the other navigational aids (ECDIS, ARPA and GPS).

Moreover, the lack of standardisation in the system manual entry, and the fact that human can forget to update the information when the situation changes make it a source of unwanted errors. Also, it is not practicable to allow such a vital source of navigational information to be switched off upon master's request. Although the AIS system's average coverage area of 40

NM, is acceptable for ship-to-ship manoeuvrability. However, this is an insufficient range for the Vessel Traffic Services (VTS) monitoring and traffic management.

The introduction of the satellite-based transmission has allowed long-range AIS services coverage. Since the AIS system has become mandatory in the navigational bridge, it has enhanced navigational safety and security positively. Likewise, the short operational range, of 20 NM between ships and 40 NM for ship-shore communication, has limited the utilisation of the system for the worldwide coverage (Li et al., 2017). However, many potential systems have been tried to develop long-range coverage, but several technical issues have been faced during its adoption (Cervera et al., 2011, Challamel et al., 2012, Zhao et al., 2014). The main issue was the detection ability of the AIS system; this is due to a large number of transmitting vessels in the satellite's coverage area, as the receiver gets conflict signals from the massive number of ships (Li et al., 2018, Challamel et al., 2012). In 2015, the IMO's proposal was accepted by the International Telecommunication Union (ITU) to allocate two extra channels for the long-range AIS transmission and reception (Li et al., 2018). This has improved the performance of the long-range satellite AIS to be utilised for long-range ships' monitoring. Thus, the satellite based AIS system has been developed to provide a coverage range of up to 1000 NM.

On the other hand, the primary intention of the newly developed technique is to monitor the ships, where it has an updating rate of 3 minutes for the related navigational information (Li et al., 2017). However, this updating rate is inefficient for automatic collision avoidance purposes, especially in critical and emergency situations, where this considered a long time for the calculation model to provide the required decisions to avoid such situations.

5.2.1.2 VHF Data Exchange System (VDES)

After the proven benefits of the AIS in improving the navigational safety, AIS system has been heavily utilised for safety, security and better situational awareness at sea. However, this increase in utilisations of the AIS as a data communication method, causes overloading of the Very High Frequency (VHF) channels (IALA, 2017). Additionally, the recognition of the need for advanced digital communication in the maritime sector has motivated the International Telecommunication Union (ITU) to consider and designate channels in the maritime band for digital data transmission. Thus, the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) has proposed a new enhanced version of the AIS to overcome the overloading problem and to introduce a digital data transmission in the system (IALA, 2017).

Moreover, this will serve the purposes of the e-navigation concept and implementation. Furthermore, the VDES is intended to enhance the satellite coverage of the current AIS services, with a real-time data transmission and data link (IALA, 2017, Lázaro et al., 2018). Although, the current AIS broadcasts in the satellite coverage transmitter, it is still not a real-time transmission, which is used for monitoring purposes only (Lázaro et al., 2018).

The main enhancements suggested in the VDES system are the higher rate of data transmission and the digital data exchange for the AIS information. Also, the capability of the system to transmit broadcast messages for all vessels in the vicinity, and addressed messages for a specific vessel or to group or fleet of vessels (Figure 23). The highest priority in the VDES system is given to the AIS functions, the safety information and ships position report. Thus, to increase the coverage of the VDES system, it utilises a satellite link between ships and shore centres. Moreover, The VDES must include three functions as follows;

- AIS data exchange available all the time.
- Digital data exchange feature between ships and shore, including satellite coverage. This is to enable the Application Specific Messages (ASM) and the VHF data exchange (VDE) techniques.
- Data exchange link other than the VDES usages. This technique is to enable any data exchange from separated systems on-board ship and shore centres.
- Application-Specific Messages (ASM) is direct messages to addressed vessels. Usually, this includes navigational safety information.

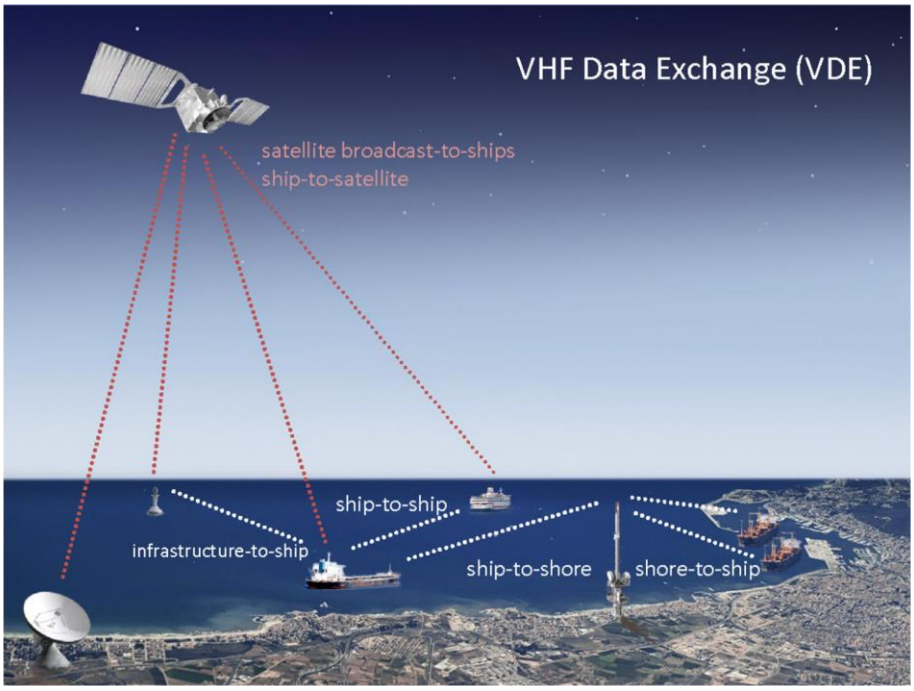


Figure 23 General concept of the VDES and the links of communication (Lázaro et al., 2018)

Generally, the development of the VDES system addresses the requirement of the e-navigation concept, which has been defined by the IMO (IMO, 2015) as; *"the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment"*. Moreover, the e-navigation Strategic Implementation Plan (SIP) and its Maritime Service Portfolios (MSP) has been fulfilled by the VDES system. This is mentioned in (Table 7)

Table 7 The Maritime Service Portfolios (MSP) for the E-navigation SIP, cited by (IALA, 2017) from the (NCSR1/28/Annex 7).

Number	**Identified Services**	**Identified Responsible Service Provider**
MSP 1	VTS information service	VTS authority
MSP 2	Navigational assistance service NSA	National competent VTS authority/coastal or port authority
MSP 3	Traffic organisation service	National competent VTS authority/coastal or port authority
MSP 4	Local port service	Local port /harbor operator

MSP 5	Maritime safety information service	National competent authority
MSP 6	Pilotage service	Pilot authority
MSP 7	Tugs service	Tug authority
MSP 8	Vessel shore reports	National competent authority, shipowner/operator, master
MSP 9	Telemedical assistance service	National health organisation
MSP 10	Maritime assistance service	Costal/ port authority
MSP 11	Nautical chart service	National hydrographic authority
MSP 12	Nautical publications service	National hydrographic authority
MSP 13	Ice navigation service	National competent authority
MSP 14	Meteorological information service	National meteorological authority
MSP 15	Rea-time hydrographic and environmental service	National hydrographic and meteorological authority
MSP 16	Search and Rescue Service	SAR authorities

The operational concept of the VDES system as follows:

1. Data exchange between ships and shore centres by terrestrial or satellite transmission.
2. Automatic and/or manual data exchanges.
3. Minimum involvement is required by the OOW for transmission and receiving data.
4. Support the current AIS applications.
5. Application Specific Messages (ASM) feature.
6. VHF Data Exchange (VDE) feature.
7. Cybersecurity and encryption consideration.
8. A long-range coverage ability due to the satellite link utilisation.
9. Machine-to-machine data exchange and communication (interface with another navigational system for information utilisation).

10. System operation all the time; underway, anchoring and moored condition.
11. Information sharing can be done in three methods; automatic transmission, assigned transmission to a specific user and pooled information by interrogation.

The VDES system has a promising enhancement for the safety of life at sea, navigational safety, property and environment protection and maritime security. This enhancement will be the result of better communication and data exchange between vessels and shore centres. Moreover, this will improve the level of OOW's situational awareness in the navigational bridge for better decision making in critical situations. Chapter 6 will discuss more on the utilisation of this device to facilitate the data connection and exchange within the proposed automatic collision avoidance system.

5.2.1.3 Electronic Charts Display and Information System (ECDIS)

The IMO has first adopted the performance standards for the Electronic Charts Display Information System ECDIS in 1995, by resolution A.817 (19) (IMO, 2006). This has been followed by other amendments to include the back-up arrangements in case of failure in 1996, and the other amendments, which allow the use of raster charts in ECDIS system when vector charts are not available. The 2009 amendments of SOLAS (chapter V, Safety of Navigation) have made it compulsory to all ships that built on the 1st of July 2012 onwards, to be fitted with ECDIS on their bridges (Figure 24) (SOLAS, 2010). The primary purpose of the ECDIS is to enhance the navigational safety; this will be achieved by the ability to display all the essential information on the paper charts in an appropriate way that helps the OOW to conduct safe and efficient navigational duties (IMO, 2006). Moreover, ECDIS has been designed to reduce the navigational workload by replacing traditional paper charts work to electronic charts. This should include route planning, route monitoring and position plotting as an electronic method performed on ECDIS (Pillich and Buttgenbach, 2001). In addition, it needs to be compatible to be connected and integrated with all the other navigational equipment on the bridge. This includes ARPA, AIS, Position-fixing system GPS, Gyro compass, Speed log and Echo sounder. This will provide a clear presentation of all navigational information that is required by the OOW to maintain a safe navigational watch. Sequentially, in case of any failure in the connections, the integrated systems and information, the ECDIS system must raise the alarm or indication about the failure (Jie and Xian-Zhong, 2008). Finally, it must have at least the same quality of information and presentation of paper charts, with the ability to update the electronic charts up to the standards of the Hydrographic Office (IMO, 2006).

Figure 24 Console of Transas ECDIS system (Transas, 2019)

For the ECDIS system features mentioned above of ECDIS system; route planning, monitoring and voyage recording, each one has to fulfil the main navigational requirement as follows;

- Route planning purposes, the system must be able to add, delete and easily change waypoints to plan the whole voyage. An indication for dangerous or prohibited areas or subjects must alert the OOW if the planned route is passing on, or near to these areas (IMO, 2006).
- Route monitoring purposes, EDCIS must have the possibility to display areas further away from the original ship position for advanced planning or to check the ship performance on the planned route. It also should allow the manual entry of coordinates easily, and thus, to go back the original ship position display. Additionally, the system

must be able to alert the OOW if the ship is approaching a pre-selected distance from contour lines, crossing track limits or arriving at waypoints, if the OOW has selected these alerting functions (Jie and Xian-Zhong, 2008).

- ECDIS system should be able to record the voyage progress and information (Positions, heading, time and speed), and these records must be protected from any changes for investigation reasons. (Figure 25) shows the display unit of the ECDIS system.

Figure 25 Transas ECDIS display (Transas, 2019)

In general, the ECDIS system has enhanced navigational safety and increases the situational awareness on the bridge by the capability of integrating all the navigational equipment in one platform. The system allows a single screen on the bridge to display most of the required information to the OOW to perform his navigational tasks.

On the other hand, the ECDIS system has many disadvantages which could threaten the safety of navigation. These disadvantages can be divided into three groups; Human Errors, System fault and Operational Error; thus, a chain of these errors can lead to an accident (Jie and Xian-Zhong, 2008). The human error can occur in many cases, such as; lack of knowledge or skills about ECDIS operation, human performance (fatigue, stress, health, etc.), lack of the situational awareness and inadequate management of navigational tasks (Jie and Xian-Zhong, 2008). Equipment failure is any malfunction that can affect ECDIS performance. Additionally, any failure to the integrated systems that connected to ECDIS can all affect the performance of ECDIS negatively (Jie and Xian-Zhong, 2008). These failures such as;

- Physical damage.
- The inconsistent geodetic datum for GPS.
- Lack of charts information (raster charts).
- Lack of latest updates for the charts.

Moreover, the operational errors mainly occur as an over-reliance on the system without checking the vital navigational information (e.g. Position) and tasks omission by the OOW. After studying the ECDIS system, it appears that it is an information system only. This provides all the information that necessary to perform a safe navigational watch to the hand of the OOW; then he/she needs to analyse this information for performing best actions and decisions. However, in a critical situation or collision avoidance decisions, the OOW must come out with the most appropriate solution from his own experience, knowledge and best seakeeping practices.

5.2.1.4 Position Fixing Systems (GPS and GLONASS)

The primary and most well-known position fixing system is the Global Positioning System GPS, an American System, which was used by the Department of Defence for military uses. Later it became available for civilian usages as well. Also, the Global Navigation Satellite System GLONASS position fixing system, the Russian version, which works similarly as the GPS. Moreover, some devices' antennas receive signals from both systems, GPS and GLONASS, for more precise positions (MCA, 2008). When it comes to navigation, the GPS provides a position (latitude and longitude), velocity and UTC time, which are essential information for monitoring ship's position in real-time (Misra et al., 1999). Regarding the accuracy of the GPS system, it gives position with 10 meters accuracy, depending on the number and angle of satellites, which the antenna receives signals from. this is an acceptable accuracy for ships navigation purposes (Misra et al., 1999). (Figure 23) shows the display unit and the antenna of the GPS system.

Figure 26 JRC GPS unit (communication&Radionavigation, 2018)

The GPS system has improved the navigational safety and reduced the navigational workload by providing a precise ship position at real-time. However, like any other system, some precautions need the attention and training of the OOW. First, the OOW must ensure that the GPS is providing the correct position at all the time (Lützhöft and Dekker, 2002). Because in some cases the antenna losses signals, and in this case, the system starts to shows Dead Reckoning DR position, which is an estimation of ship's position using the previous position, course and speed (Lützhöft and Dekker, 2002). This was the case in the grounding of the Royal Majesty passenger ship in 1995, where the GPS antenna was damaged, and the GPS altered to DR position. The GPS system has alerted the OOW, but he did not recognise that and was using the GPS position normally until the grounding of the ship (Lützhöft and Dekker, 2002). In addition, for the correct and accurate position, there should be a match between the GPS Datum (World Geodetic System 1984 Datum) and the charts datum in order to have the correct position for the exact chart (MCA, 2008). The chart datum is usually written on the corner of the chart and the GPS shows which datum is using as well (MCA, 2008). In general, the OOW should always check the navigational aids and ensure that they are functioning in good condition, and, according to the bridge standards, to have the correct information all the times. Also, he must check all the alarms that go off in the bridge and never acknowledge them without investigating the cause of the alarm to ensure the performance if the systems and equipment are at the optimum level.

5.2.1.5 Radar / Automatic Radar Plotting Aids (ARPA)

The first introduction of the radar equipment for merchant ships was after World War II, where it became affordable for civilian uses. At that period, the radar technology played a significant role in the safety of navigation, which helped with targets detection around ships, especially in low visibility and bad weather. In addition, the standard procedure used to be performed manually as lookout watches and compass bearing monitoring. This was performed to avoid the conflict in COLREGs as to whether radar plotting was required or not in collision avoidance situations (Flyntz, 1983). Basically, the use of radar was only to detect targets, and the OOW was manually plotting that target's position for three consecutive times. This is to calculate the true course and speed in order to calculate the Closest Point of Approach CPA (distance and time) (Wylie, 1972). However, with the growth in the merchant fleets, and the increase in ships speed, the maritime traffic became congested, and thus, this required the OOW to plot more targets in less time. This manual plotting technique became incredibly difficult, in some cases, which lead to ignorance of some less prioritised targets (Wylie, 1972). (Figure 27) shows the console of the ARPA/radar system.

Figure 27 ARPA/ Radar system (JRC, 2019)

Furthermore, the importance of automatic plotting aid arises to support the OOW managing the increased number of targets in the vicinity (Wylie, 1972). Therefore, the Automatic Radar Plotting Aids ARPA system brought about, leaving behind many older versions of plotting aids systems that did not succeed up to the required level (Wylie, 1972). Today, usage of ARPA by OOW is mandatory for ships over 300GT. In general, the prime aim of the ARPA system is to improve the collision avoidance procedures, by reducing the workload of manually plotting multi targets, to the possibility of having the needed information automatically available (IMO, 2004). (Figure 28) shows the display unit of the ARPA/radar system.

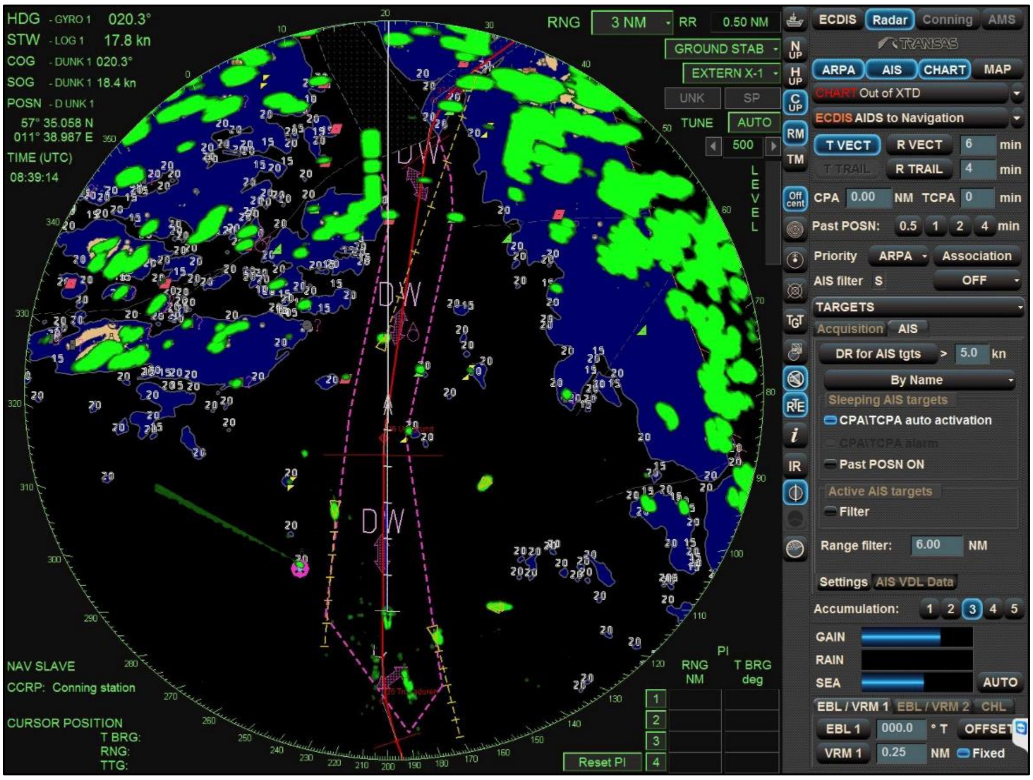

HDG - GYRO 1 020.3°
STW - LOG 1 17.8 kn
COG - DUNK 1 020.3°
SOG - DUNK 1 18.4 kn
POSN - D UNK 1
57° 35.058 N
011° 38.987 E
TIME (UTC)
08:39:14
RNG 3 NM
RR 0.50 NM
GROUND STAB
EXTERN X-1
TUNE AUTO 500
CHART Out of XTD
ECDIS AIDS to Navigation
T VECT 6 min
R TRAIL 4 min
CPA 0.00 NM TCPA 0 min
Past POSN: 0.5 1 2 4 min
Priority ARPA Association
AIS filter S OFF
DR for AIS tgts > 5.0 kn
By Name
CPA\TCPA auto activation
Past POSN ON
Range filter: 6.00 NM
Accumulation: 1 2 3 4 5
SEA AUTO
EBL 1 000.0 °T
VRM 1 0.25 NM Fixed
NAV SLAVE
CCRP: Conning station
CURSOR POSITION
T BRG:
RNG:
TTG:

Figure 28 Transas ARPA display (TRANSAS, 2018)

The capabilities of the ARPA system stand on the ability to detect targets such as; vessels, shorelines, navigational hazards and navigational aids (e.g. buoys). Nevertheless, ARPA system must provide the range, bearing, distance to CPA, time to CPA, course and speed of any radar tracked targets at all the times to assist the OOW in collision avoidance procedures

(IMO, 2004). Yet the accuracy of the system in measuring range and bearing are 30 meters and 1 degree, respectively (IMO, 2004). In order to get the optimum detection, the system must have an automatic and manual adjustment for gain, clutter and tune to eliminate unwanted echoes that caused by sea, rain and clouds (IMO, 2004). Moreover, the system has the following functions;

- Variable Range Markers VRM (measures the range from any point in the display to any object).
- Electronic Bearing Lines EBL (measures true and relative bearing from the ship position and from any point on display to any object).
- Parallel Index Lines PI (used for monitoring the ship track).

All these functions are to help the OOW to monitor and plan his navigational watch in an appropriate way and time (IMO, 2004). However, ARPA system is an integrated system with the other navigational aids on the bridge, to enhance the situational awareness. The systems that integrated with ARPA are; Gyro-compass, Speed log, GPS and AIS (IMO, 2004).

5.3 Ship parameters and manoeuvrability

The research in ship's parameters and manoeuvrability is an extensive area of investigation, with many aspects need to be considered in the scope of the research. However, this section will discuss the aspects that have a direct relation to the development of the Automatic Collision Avoidance System, which is the main aim of this research.

5.3.1 Ship Parameters

Ship parameters in the context of collision avoidance are the factors that need to be well-thought-out for the assessment of collision risk processes, which are mostly dynamic parameters. In other words, it is the controllability of the ship, the ability to control the manoeuvrability, with consideration to target ships in the vicinity (Landsburg, 1993, House, 2007, Kornev, 2013). In order to assess collision situations, the OOW must be aware of the behaviour of his own ship with real-time availability of its parameters (navigational information), as well as other targets parameters (Ward and Leighton, 2010). After the calculation and analysis of this information, the result will provide relative motion of the target ship in relation to own ship. If the risk of collision exists, the point where the collision will happen or the closest point of approach (CPA), distance to the Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA) will be calculated (Wilson et al., 2003). Based on this information, the OOW decides the best collision avoidance manoeuvre to avoid the collision. The following (Table 8) contains the ship parameters that are used in the risk of collision assessment, which must be available for both own and target ships.

Table 8 Ship's parameters for risk of collision assessment

Speed through water	The bearing of the target ship
Speed over ground	Range to the target ship
Course over ground	Ship’s navigational status
Heading	Relative motion
Position	The closest point of approach CPA
Rate of turn	Time to the closest point of approach TCPA
Stopping distance	Distance to the closest point of approach DCPA

After the discussion about ship parameters, it is essential to mention the factors that influence the manoeuvrability of ships, where they are strongly linked to ship characteristics, such as; the effect of the manoeuvring capability and the behaviour of the ship (House, 2007). Two main factors, which have an effect on the ship’s behaviours are listed below and illustrated in the flow diagram in detail (Figure 29);

- First, controlled factors, which can be adjusted by the operator, either during design stage or during the operational stage (Pérez and Clemente, 2007).
- Second, are non-controlled factors, like weather and environment (Kornev, 2013).

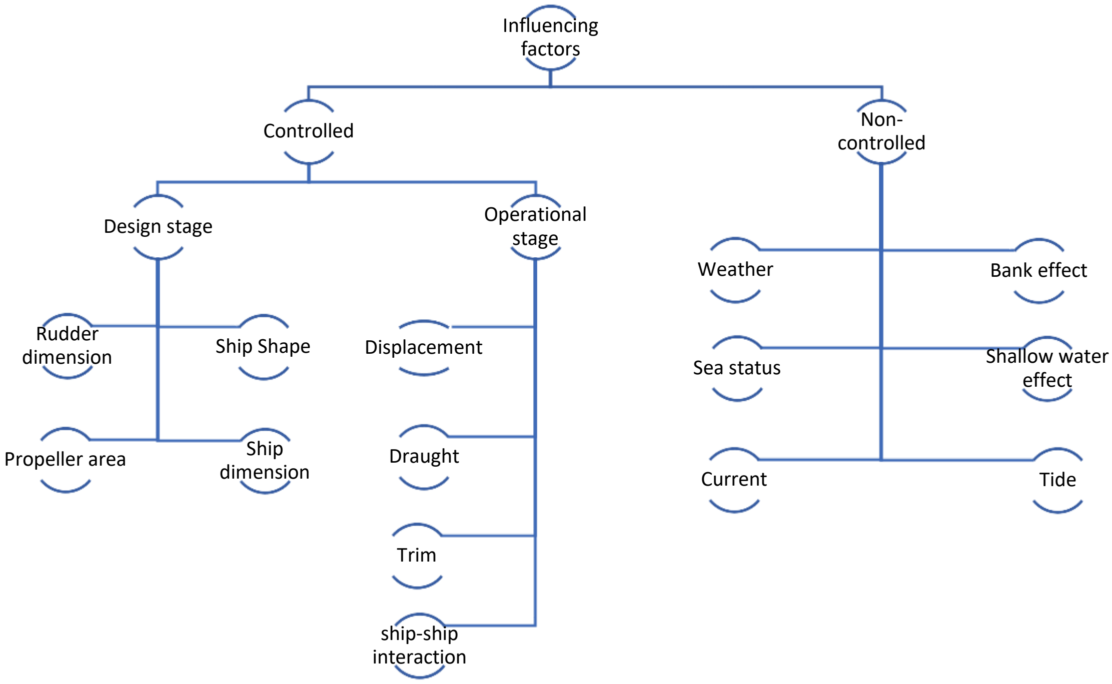


Figure 29 The influencing factors on ships manoeuvrability

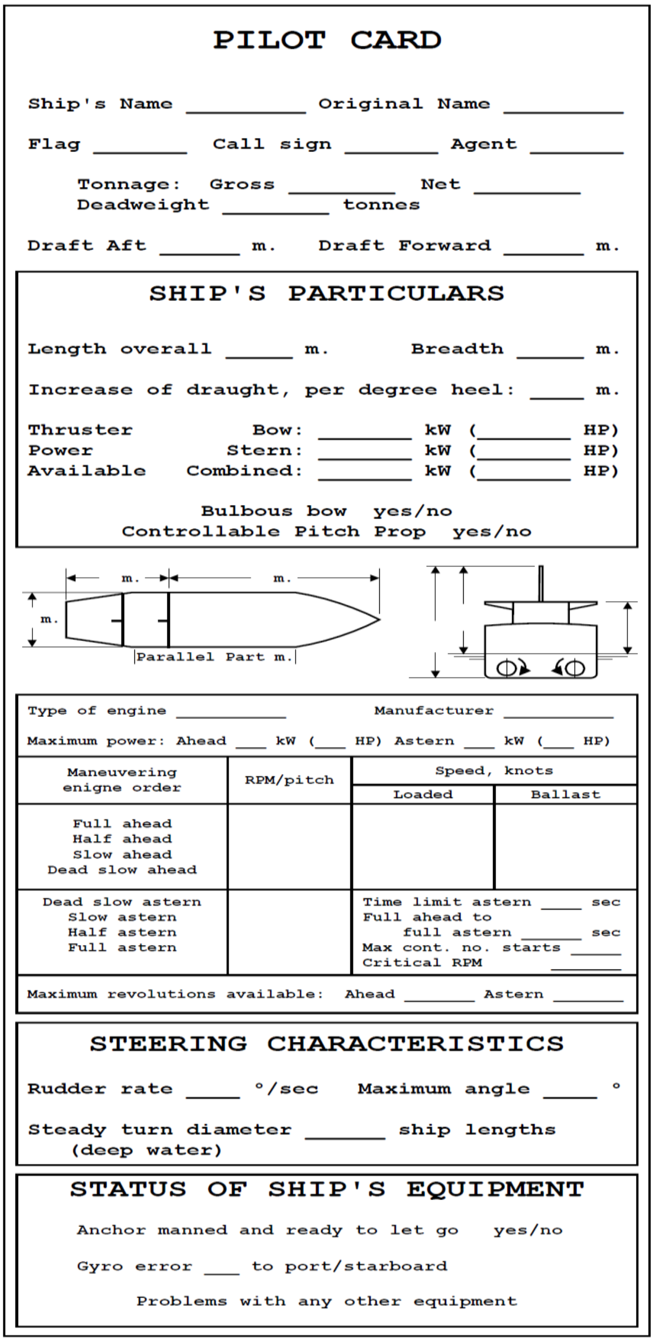
5.3.2 Display and availability of manoeuvring capabilities and information on the ship's bridge

As per the IMO Resolution A.601 (15) in 1987, it is recommended for all ships more than 100m in length and all chemical tankers and gas carriers of any size, to have and display its manoeuvring capabilities and information in three forms as follows; pilot card, wheelhouse poster and navigational booklet (IMO, 1987).

The Pilot Card is to provide the pilot with the necessary information about the condition of the ship, such as manoeuvring capability and equipment, loading condition and ships propulsion system and power, as well as any other related information regarding the navigational condition of the ship (Figure 30). The pilot card is to be filled by the master of the ship upon the arrival time (IMO, 1987, ABS, 2017).

Wheelhouse Poster is to provide general information about the ship's particulars and manoeuvring characteristics (Figures 31, 32 and 33). It should be of a size that can be seen from anywhere in the wheelhouse and navigational area (IMO, 1987, ABS, 2017).

Manoeuvring booklet is a full detailed booklet about the manoeuvring characteristics of the ship. The information on this booklet is based on the sea trial and estimation during the design stage. This booklet should be in the ship's bridge during the operational period of the ship, and amended as required (IMO, 1987, ABS, 2017).



PILOT CARD

Ship's Name __________ Original Name __________
Flag ________ Call sign ________ Agent ________
Tonnage: Gross _________ Net _________
Deadweight _________ tonnes
Draft Aft _______ m. Draft Forward _______ m.

SHIP'S PARTICULARS

Length overall _____ m. Breadth _____ m.
Increase of draught, per degree heel: _____ m.

Thruster Power Available	Bow:	________	kW	(________ HP)
	Stern:	________	kW	(________ HP)
	Combined:	________	kW	(________ HP)

Bulbous bow yes/no
Controllable Pitch Prop yes/no

m. m.
m.
Parallel Part m.

Type of engine ___________ Manufacturer ___________
Maximum power: Ahead ___ kW (___ HP) Astern ___ kW (___ HP)

Maneuvering enigne order	RPM/pitch	Speed, knots	
		Loaded	Ballast
Full ahead Half ahead Slow ahead Dead slow ahead			
Dead slow astern Slow astern Half astern Full astern		Time limit astern ____ sec Full ahead to full astern ______ sec Max cont. no. starts _____ Critical RPM _____	

Maximum revolutions available: Ahead _______ Astern _______

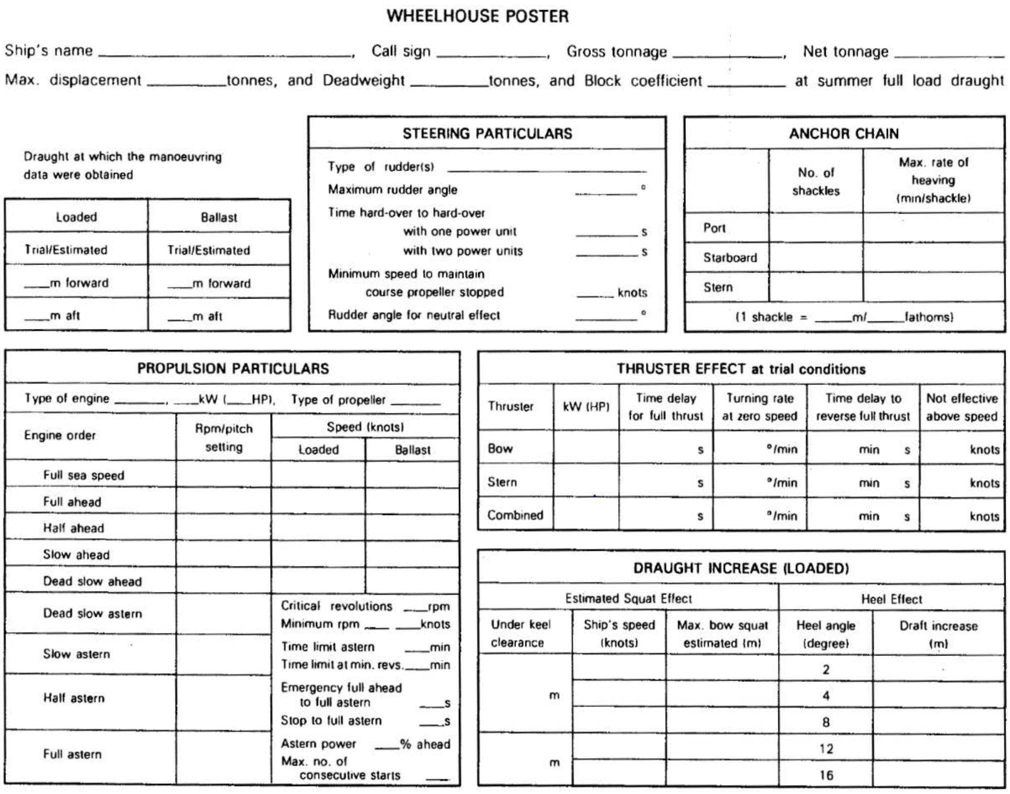
STEERING CHARACTERISTICS

Rudder rate _____ °/sec Maximum angle _____ °
Steady turn diameter _______ ship lengths
(deep water)

STATUS OF SHIP'S EQUIPMENT

Anchor manned and ready to let go yes/no
Gyro error ___ to port/starboard
Problems with any other equipment

Figure 30 Sample of pilot card, (ABS, 2017)



WHEELHOUSE POSTER

Ship's name ______________________________, Call sign _____________, Gross tonnage _____________, Net tonnage _____________

Max. displacement _________tonnes, and Deadweight _________tonnes, and Block coefficient _________ at summer full load draught

Draught at which the manoeuvring data were obtained

Loaded	Ballast
Trial/Estimated	Trial/Estimated
____m forward	____m forward
____m aft	____m aft

STEERING PARTICULARS

Type of rudder(s) ______________________

Maximum rudder angle ________ °

Time hard-over to hard-over

with one power unit ________ s

with two power units ________ s

Minimum speed to maintain course propeller stopped _____ knots

Rudder angle for neutral effect ________ °

ANCHOR CHAIN

	No. of shackles	Max. rate of heaving (min/shackle)
Port		
Starboard		
Stern		

(1 shackle = _____m/_____fathoms)

PROPULSION PARTICULARS

Type of engine _______, ___kW (___HP), Type of propeller _______

Engine order	Rpm/pitch setting	Speed (knots)	
		Loaded	Ballast
Full sea speed			
Full ahead			
Half ahead			
Slow ahead			
Dead slow ahead			
Dead slow astern		Critical revolutions ___rpm Minimum rpm ___ ___knots	
Slow astern		Time limit astern ___min Time limit at min. revs.___min	
Half astern		Emergency full ahead to full astern ___s Stop to full astern ___s	
Full astern		Astern power ___% ahead Max. no. of consecutive starts ___	

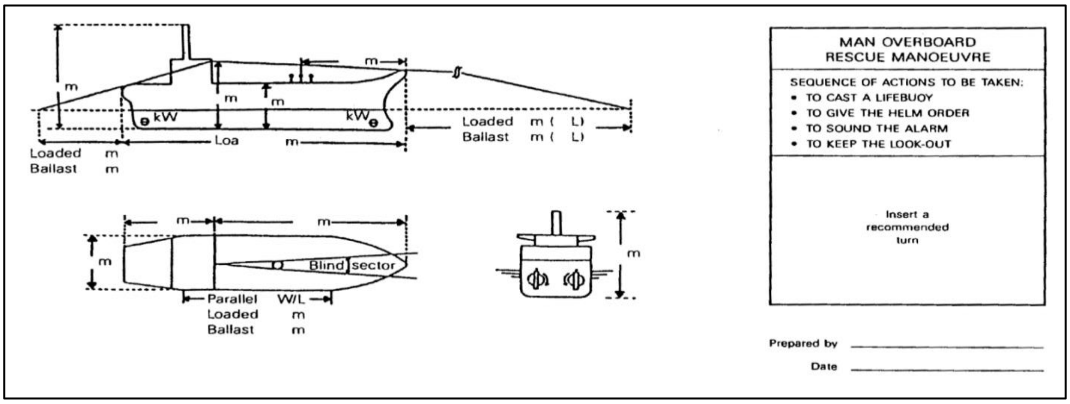
THRUSTER EFFECT at trial conditions

Thruster	kW (HP)	Time delay for full thrust	Turning rate at zero speed	Time delay to reverse full thrust	Not effective above speed
Bow		s	°/min	min s	knots
Stern		s	°/min	min s	knots
Combined		s	°/min	min s	knots

DRAUGHT INCREASE (LOADED)

Estimated Squat Effect			Heel Effect	
Under keel clearance	Ship's speed (knots)	Max. bow squat estimated (m)	Heel angle (degree)	Draft increase (m)
m			2	
			4	
			8	
m			12	
			16	

Figure 31 Sample of wheelhouse poster, (IMO, 1987)



MAN OVERBOARD RESCUE MANOEUVRE

SEQUENCE OF ACTIONS TO BE TAKEN:

- TO CAST A LIFEBUOY
- TO GIVE THE HELM ORDER
- TO SOUND THE ALARM
- TO KEEP THE LOOK-OUT

Insert a recommended turn

Prepared by ______________________

Date ______________________

Figure 32 Continue, sample of wheelhouse poster, (IMO, 1987)

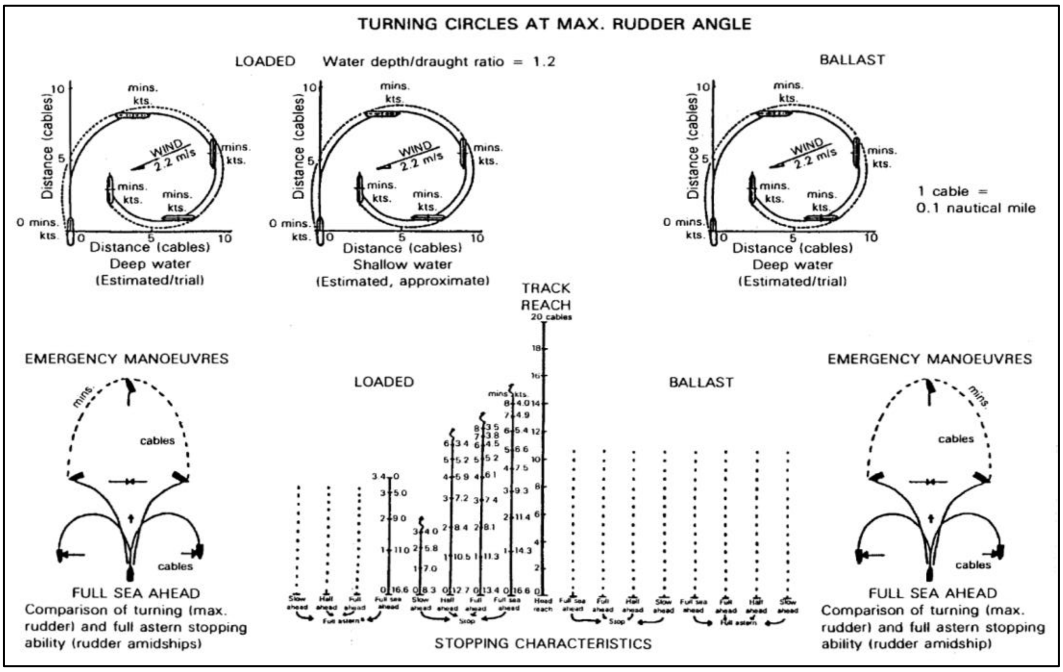


Figure 33 Continue, sample of wheelhouse poster, (IMO, 1987)

5.3.3 The standards and criteria for the manoeuvring characteristics tests

In the past, ship designers used to rely on the ability and performance of seamen to handle the deficiency in ship's manoeuvrability due to poor design (IMO, 2002c, Pérez and Clemente, 2007). Therefore, in 1968, the IMO has raised its concerns about this issue in the Sub-Committee meeting on Ship Design and Equipment, which led to the adoption of the MSC/Circ.389. This concerns the Interim Guidelines for Estimating Manoeuvring Performance in Ship Design, in January 1985, to support the idea of better manoeuvrability by better ships' designs (IMO, 2002c). The main aim of these standards is to provide the designers with guidelines to follow during the design stage of ships. Thus, ships must be built to comply with the standards as a minimum requirement for the manoeuvring capability to ensure safe ship handling operation (IMO, 2002c, ABS, 2017). The concern of the standards is to provide good quality and handling performance of ships, that can satisfy the nautical aspects (House, 2007). The performance of ships can be both calculated and simulated in the design stage, or scaled model tests could examine it. Finally, both results must be compared with the sea trial tests according to the following criteria (House, 2007, IMO, 2002c, IMO, 2002b, ABS, 2017).

- Turing ability test is performed by turning the ship hard over. It is considered as satisfactory results if, (Figure 34);

  - The side distance from the turning moment (turning point) until it reaches 90° is not more than 4.5 ship’s length (Advance),

  - The side distance from the turning moment (turning point), until it reaches 180°, is not more than five ship’s length (Tactical Diameter).

- Initial turning ability test is a 10° turn (on port and starboard sides), where the side distance should not be more than 2.5 ship’s length when the ship reaches 10° change in the heading.

- Yaw checking and course keeping ability tests, this is to be performed by the Zig-zag manoeuvres (10°/10° and 20°/20°), (Figure 35). A turning of 10° to port side until the ship’s heading is changed to reach 10° (first overshoot), then turn to the other side 10° until the ship’s heading is changed to reach 10° on the opposite side (second overshoot). To continue with the test, another turn of 10° to the opposite side is performed until the ship’s heading is changed to reach 10° on the opposite side. Furthermore, the same test is to be performed for the 20°/20° manoeuvre. The test results will be considered as satisfactory if;

  - The first overshoot’s change in heading is not more than (in 10° test);

    10°, if the ship’s length divided by the test speed (ship’s speed when performing the test) is less than10 second,

    20°, if the ship’s length divided by the test speed (ship’s speed when performing the test) is 30 second or more.

  - The second overshoot’s change in heading is not more than (in 10° turn);

    25°, if the ship’s length divided by the test speed (ship’s speed when performing the test) is less than10 second,

    40°, if the ship’s length divided by the test speed (ship’s speed when performing the test) is 30 second or more.

  - The first overshoot’s change in heading is not more than 25° (in 20° turn).

- Stopping distance test is performed by reversing the ship’s engine from full ahead to full astern, (Figure 36). The stopping distance is measured from the point that the engine is reversed until the point when the ship is totally stopped (the track distance that the ship moved on; track reach). That total distance should not be more than 15 ship’s length, and for large displacement ship not more than 20 ship’s length. (Head reach; is the distance from the engine reversed point until the is ship stopped, a straight-line distance)

All manoeuvrability tests should be conducted in the following conditions;

- Unconfined and deep water,
- Calm weather and sea condition,
- Ship in a fully loaded condition, to the summer load line and no trim,
- Ensure steady speed before starting the test.

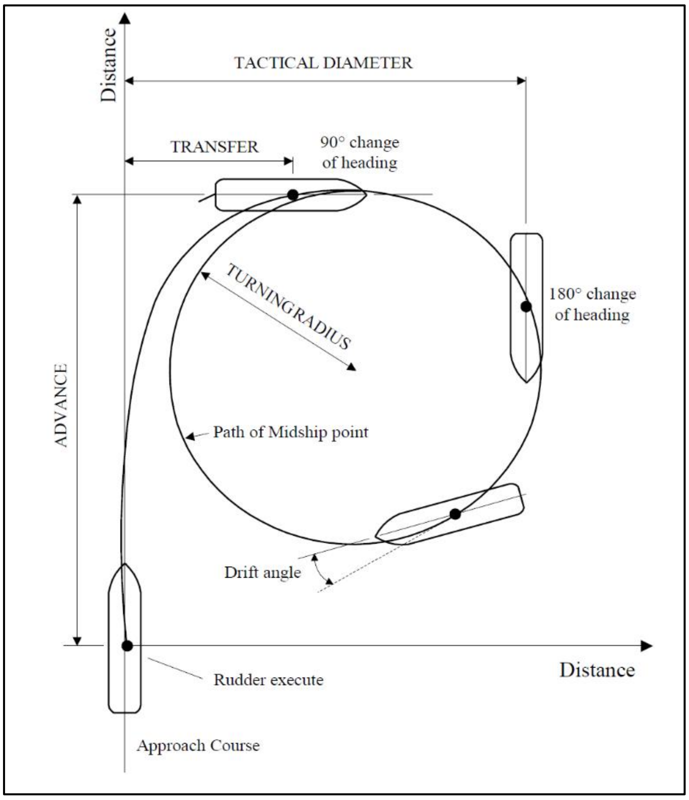


Figure 34 Turning circle test, (ABS, 2017)

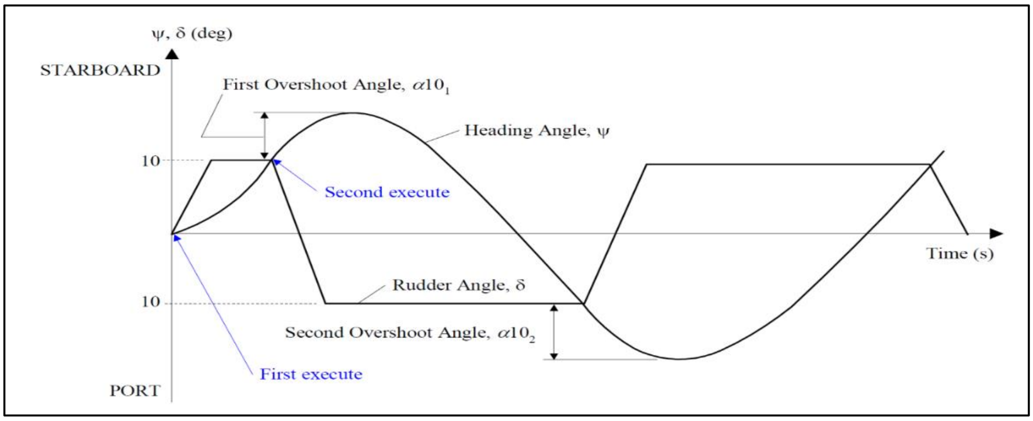


Figure 35 Zig zag test (10/10), (ABS, 2017)

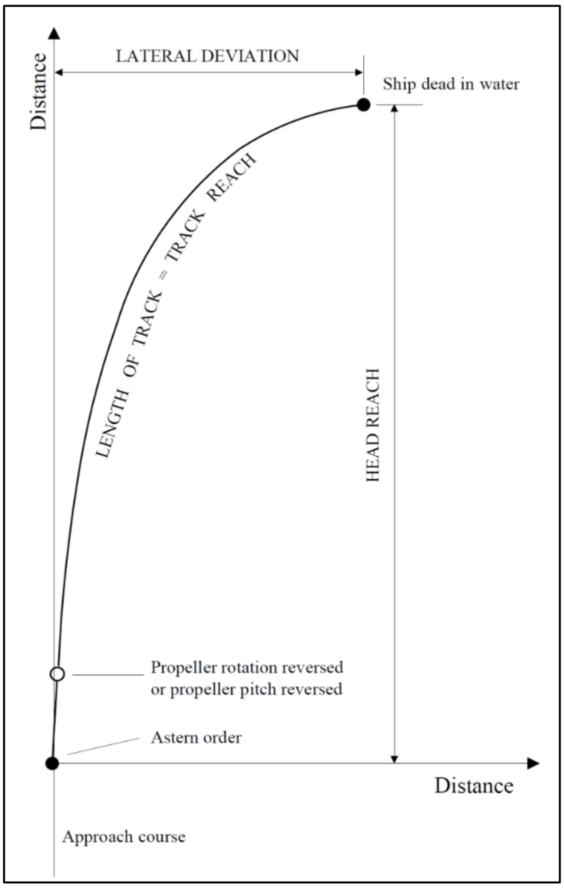


Figure 36 Crash stopping test, (ABS, 2017)

5.4 Collision Avoidance in Aviation

5.4.1 History and development of TCAS system

The first method of collision assessment for aeroplane was by the concept of “see and avoid” other targets, with advice from the ground stations “Air Traffic Control ATC”. In 1955, Dr John S. Morrel introduced a new method of collision assessment and avoidance. The new method is the Time to the Closest Point of Approach. This method is still the technique used in the new collision avoidance systems in both maritime and aviation industries (EUROCONTROL, 2016). After that came the Beacon Collision Avoidance System (BCAS) which established in 1975, it was the first system that is able to detect range and altitude data for other targets “or so-called intruder”, that information is received as a signal from the Air Traffic Control Radar Beacon System (ATCRBS) (EUROCONTROL, 2016, FAA, 2011, Williamson and Spencer, 1989). Later in 1981, the Traffic Alert Collision Avoidance System (TCAS) was developed, after a mid-air collision in California; under the umbrella of the Federal Aviation Administration (EUROCONTROL, 2016). The TCAS was based on the same concept of the BCAS system with some advancement (EUROCONTROL, 2016). Then in 1986, the US Congress, after another mid-air collision in California, has mandated the installation of TCAS system on some types of aeroplanes operating in its airspaces (EUROCONTROL, 2016). In addition to the development of the TCAS system, the International Civil Aviation Organisation ICAO was concerning the development of standards and guidelines for the use of TCAS. The implementation of TCAS was mandated in Europe in January 2000, for all fixed-wing turbine-engine aeroplane with maximum take-off mass of 15,000 kg, or carrying capacity of 30 passengers or more (EUROCONTROL, 2016). Then, in January 2005, it becomes mandatory for all fixed-wing turbine-engine aeroplane with a maximum take-off mass of 5700 kg, or carrying capacity of 19 passengers or more (EUROCONTROL, 2016).

In aviation, where they do not have manoeuvring regulations, the decision is left to the pilot to avoid collisions. In addition, they have the ATC role in allocating every aeroplane with a specific level (altitude) of flying then to ensure the separation of aeroplanes in general (Williams, 2004, Kuchar and Drumm, 2007). Also, the Traffic Alert and Collision Avoidance System TCAS come as the last measure of collision avoidance, by alerting the pilot of any intruders in the vicinity, which could be a potential conflicting aeroplane (Kuchar and Drumm, 2007, Burgess et al., 1994). If that intruder comes in a collision course, the TCAS provides the pilot with the best avoidance action. The TCAS system has proven its reliability as a collision avoidance system (Harman, 1989). However, that makes it mandatory to obey the system's decisions immediately, even if the pilot does not acquire the intruder visually, as mentioned in the International Civil Aviation Organisation ICAO (EUROCONTROL, 2016). It could be the case that the pilot is unaware of the intruder or cannot see it visually, and the TCAS system detects it and issue the avoidance decision (EUROCONTROL, 2016).

This research concerns about the latest version of TCAS (The TCAS II version 7.1) and all the specifications mentioned are related to this version and not the oldest one.

5.4.2 Surveillance and Target detection in TCAS System

The TCAS system works independently from other navigational systems in the aeroplane and ground traffic services (FAA, 2011). TCAS system keeps monitoring the surrounding area around the aeroplane, up to 30 NM, by the "interrogation and response technique" using a radio signal (Figure 37) (Xu, 2013). After that, the TCAS antenna keeps sending interrogation messages at 1030MHz and receives transponder replies at 1090MHz (Harman, 1989, Williams, 2004). Once another TCAS equipped aeroplane receives the interrogation message from the TCAS antenna at 1030 MHz, by mode S transponder, it replies at 1090 MHz, using mode S transponder, to the TCAS antenna (EUROCONTROL, 2016). The reply message from the mode S transponder has 24-bit address for every aeroplane to allow farther connection and coordination between them (FAA, 2011).

Moreover, this reply message allows the TCAS to determine the intruder's range, bearing and altitude to find the relative position (relative bearing and altitude), which keeps updating every one second (Williamson and Spencer, 1989). Then, the TCAS sent this information to the TCAS computer unit for processing and collision avoidance decisions. The mode S sends replies every one second, and the TCAS keep listening all the time (Kuchar and Drumm, 2007). If the transponder message does not contain altitude information, the TCAS system will detect the intruder, but it cannot issue an avoidance manoeuvre (EUROCONTROL, 2016, Kuchar and Drumm, 2007). Where the relative altitude is unavailable, so the system will assume that the intruder is in the same faying level as the worst-case scenario (EUROCONTROL, 2016). On other words, every TCAS equipped aeroplane has TCAS antenna and mode S transponder. The TCAS antenna sends the interrogation signals, and the mode S sends a response to it. This response has the address and information of the intruder to help the TCAS system to locate and issues the avoidance decisions.

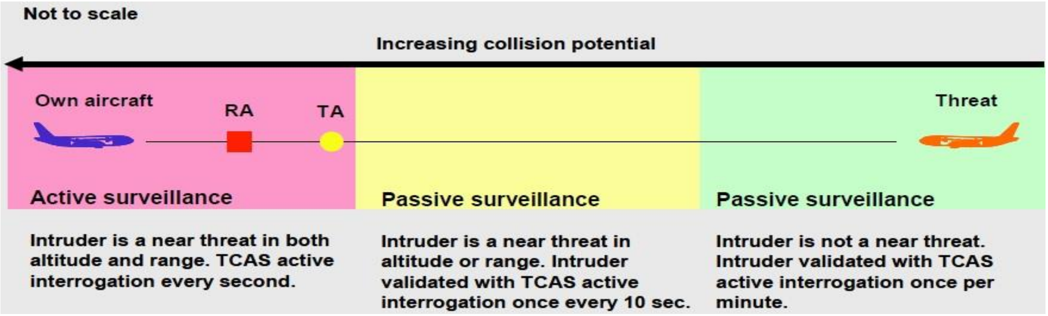


Figure 37 Surveillance technique (EUROCONTROL, 2016)

5.4.3 The Principle of Collision Detection, Tracking and Avoidance in TCAS System

The TCAS computer is the main part of the system, and it is the responsible unit for surveillance, threat recognition, tracking, avoidance manoeuvre, and issuing decisions (EUROCONTROL, 2016). However, the basic principle used in TCAS is the Time to Closest Point of Approach (TCPA) (Honeywell, 2004). The Closest Point of Approach (CPA) is the minimum passing distance between the intruder and the own aeroplane. In TCAS, it relies on the time remaining to collide or pass in the closest point from the aeroplane (Honeywell, 2006). Thus, if the intruder passing distance is less than 300-800 feet vertically (depending on the flying level), this means it is passing dangerously close, and an avoidance action shall be taken (Figure 38) (FAA, 2011). After detecting the dangerous passing situation, the TCAS keeps tracking the intruder to assessing the situation and issues the avoidance manoeuvre (Livadas et al., 2000).

Consequently, the Collision Avoidance Logic (CAS) uses the own aeroplane’s parameters (altitude, vertical rate and the relative altitude), and the intruder’s parameters, which received from the mode S transponder, in the tracking algorithm (Murugan and Oblah, 2010). The outputs of the tracking algorithm are the parameters for both aeroplanes (range, the horizontal range at CPA, approaching rate, relative altitude and relative altitude rate), which then passed to the collision avoidance algorithm to provide the best avoidance manoeuvre, using the TCPA principle (FAA, 2011). The aeroplanes should pass in the distance higher than 300-800 feet, and the TCAS system should advise the pilot with the best action to fulfil this (Williams, 2004).

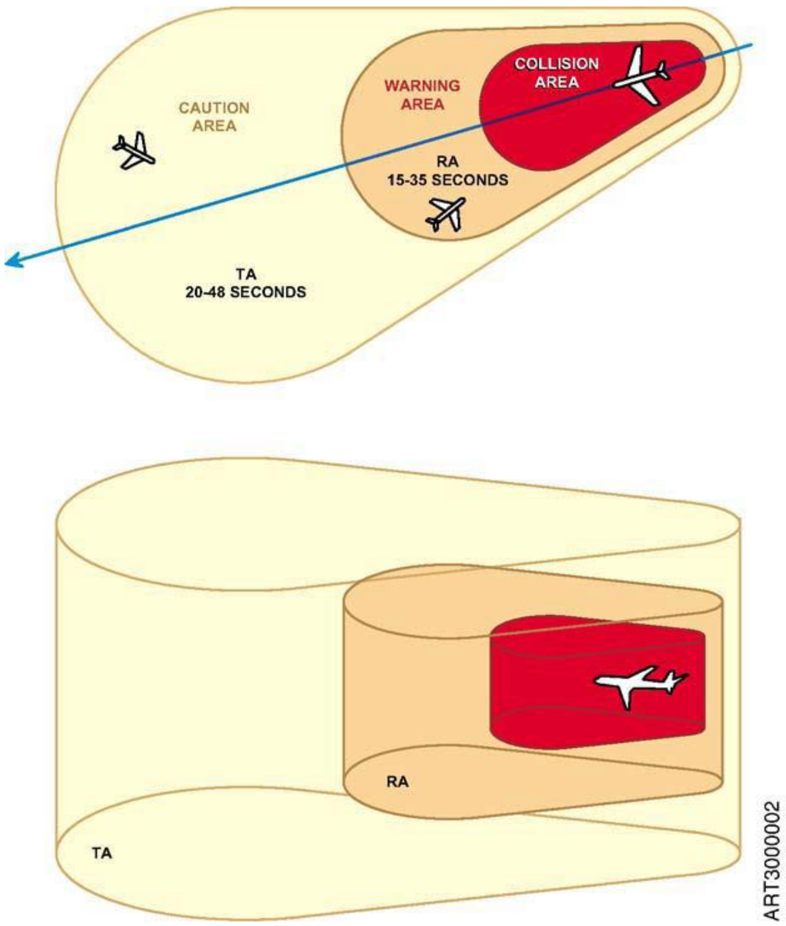


Figure 38 Alert zones and time (FAA, 2011)

5.4.4 TCAS Operation, Alerting and Avoidance Decisions

The enhancement in aviation safety and situational awareness that gained after the introduction of the TCAS system has been achieved by assessing the pilot in collision avoidance, intruders detection and visually acquiring conflict situations (ICAO, 2006). However, this does not exempt the pilot from applying the best practices and judgment to avoid conflict situation, in which no action shall be taken in the opposite direction of the TCAS decision (ICAO, 2006). Following are the operation and alerting of the TCAS system and how the pilot shall respond to each of them.

Traffic Advisories (TA)

TA aims to alert the pilot about potential traffic in the vicinity, which might cause a conflict situation, and to assess in visual acquisition of intruders(Murugan and Oblah, 2010). It also prepares the pilot for a potential collision situation and to perform the avoidance manoeuvre (ICAO, 2006). The vertical detection range of intruders is 850-1200 depending on the flying level (EUROCONTROL, 2016). In case that an intruder is not including the altitude information on the mode S transmuted message, the system will only issue TA alerts without avoidance manoeuvres (Honeywell, 2004). The TCAS system issues the TA 20-48 seconds before the CPA, depending on the flying level, and the pilot should be ready for the Resolution Advisory (RA, Figure 38) (FAA, 2011).

Any intruder located within 6NM and ±1200 feet will be detected even if it does not cause TA to be issued, and this intruder will be shown as proximate traffic (EUROCONTROL, 2016).

Resolution Advisory (RA)

The RA aims to provide the pilot with the avoidance manoeuvre to avoid collision (Figure 39) (ICAO, 2006, Livadas et al., 2000). After TA is arising, if the intruder is still approaching a collision point, the TCAS system will issue the RA. In order to issue RA, the system needs to assess the decision in two steps. First, it needs to choose the direction of the manoeuvre, whether to climb or descend. The direction which provides greater separation is the more favourable one (Figure 40), with the avoidance of crossing in front of the intruder as much as possible (Figure 41) (Kuchar and Drumm, 2007). However, if the uncrossing direction does not satisfy the needed separation, then the system will choose the crossing direction (EUROCONTROL, 2016). Secondly, is the rate of vertical speed which satisfies the separation in the least diversion from the original path (Kuchar and Drumm, 2007, Williams, 2004). As a result, the RA advises the pilot whether to climb, descend or maintain the flying level, with the rate of vertical speed to pass an intruder in the greatest distance, and without crossing if possible (Munoz et al., 2013). The TCAS system issues the RA 15-35 seconds before the CPA, depending on the flying level (Munoz et al., 2013). The pilot must respond to the RA within 5 seconds of the issuance (FAA, 2011, Honeywell, 2006).

Additionally, the TCAS system keeps monitoring the performance of the provided avoidance manoeuvre and the performance of the pilot every one second (EUROCONTROL, 2016, Williamson and Spencer, 1989). If the issued RA is not providing enough separation distance to pass the intruder, the system will strengthen or weaken the rate of vertical speed to pass safely (Livadas et al., 2000). Moreover, if it appears that the provided RA will not prevent the collision, or one of the aeroplanes are not obeying the RA, then the system will reverse the RA to the obeying aeroplane to prevent the collision (EUROCONTROL, 2016, FAA, 2011, Honeywell, 2004).

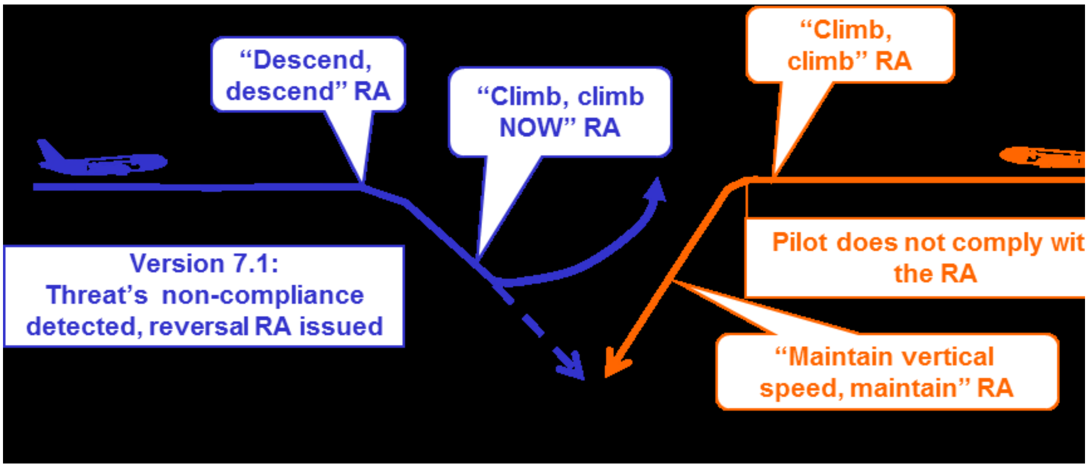


Figure 39 The principle of TCAS avoidance and the reversal action (EUROCONTROL, 2016)

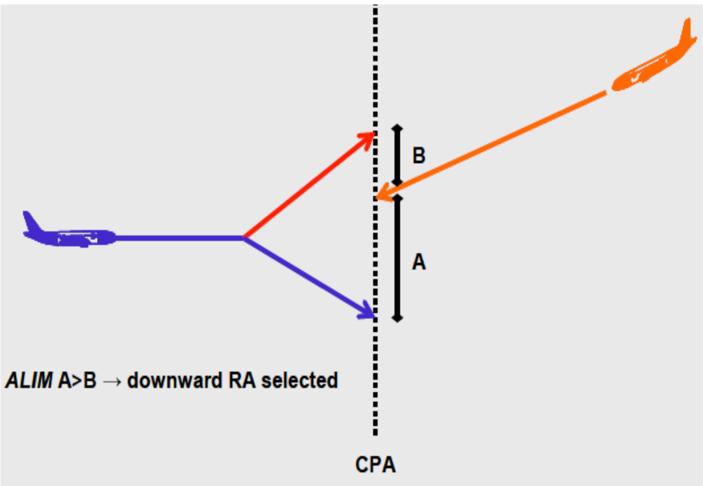


Figure 40 Manoeuvre's direction Selection (EUROCONTROL, 2016)

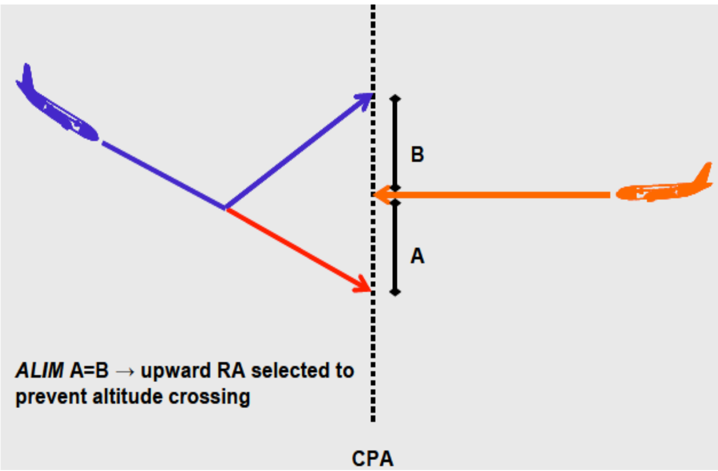


Figure 41 Uncrossing selection (EUROCONTROL, 2016)

5.4.5 The Traffic Display Symbols and the Annunciation of Advisories

The TCAS has standardised the symbol and colours of the traffic that displays to eliminate the human error and to facilitate the interpretation of the situation (Honeywell, 2006). (Figure 42) shows all the displayed symbols by the TCAS system with its colours (EUROCONTROL, 2016). The yellow circle is the intruder aeroplane, which issues the TA. The red square is the threat aeroplane, which issues the RA. If the intruders' altitude is available, it appears on display as relative altitude on top of the symbol for intruders in above, and bottom if the intruder is below. The number indicates (100 feet), in (Figure 42), the last symbol means 200 feet above the own aeroplane, and the arrow indicates if the intruder is climbing or descending.

The TCAS system verbally announces the alert in the cockpit (Williams, 2004). The TA alert is announced as "Traffic, Traffic", whereas, the RA is an avoidance decision that the TCAS system provides to the pilot, Table 9 which shows the aural annunciation of the RAs (FAA, 2011). Moreover, all the decisions are displayed on the display unit for the visual alerts and the magnitude of the decisions according to the above-mentioned symbols. (Figure 43) is an example of a TCAS display unit (EUROCONTROL, 2016).

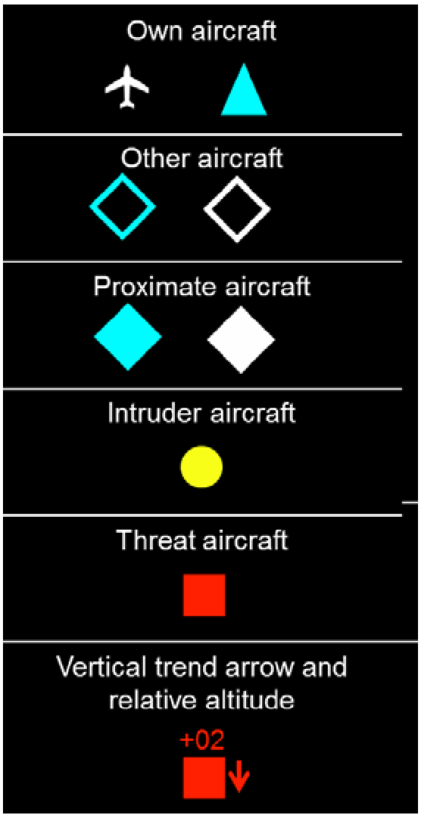


Figure 42 Traffic Display Symbol (EUROCONTROL, 2016)

Figure 43 TCAS display Unit (EUROCONTROL, 2016)

Table 9: RA Aural Announcements (EUROCONTROL, 2016)

Upward sense			**Downward sense**		
RA	**Required vertical rate (ft. /min.)**	**Aural**	**RA**	**Required vertical rate (ft. /min.)**	**Aural**
Climb	1500	Climb, climb	Descend	–1500	Descend, descend
Crossing Climb	1500	Climb, crossing climb; climb, crossing climb	Crossing Descent	–1500	Descend, crossing descend; descend, crossing descend
Maintain Climb	1500 to 4400	Maintain vertical speed, maintain	Maintain Descent	–1500 to –4400	Maintain vertical speed, maintain
Maintain Crossing Climb	1500 to 4400	Maintain vertical speed, crossing maintain	Maintain Crossing Descent	–1500 to –4400	Maintain vertical speed, crossing maintain
Level Off	0	Level off, level off	Level Off	0	Level off, level off
Reversal Climb	1500	Climb, climb NOW; climb, climb NOW	Reversal Descent	–1500	Descend, descend NOW; descend, descend NOW
Increase Climb	2500	Increase climb, increase climb	Increase Descent	–2500	Increase descent, increase descent
Preventive RA	No change	Monitor vertical speed	Preventive RA	No change	Monitor vertical speed
RA Removed	n/a	Clear of conflict	RA Removed	n/a	Clear of conflict

5.4.6 The TCAS System Components

The TCAS system is an avionics system that consists of many units and antennas, which collect data, then analyses to find the optimum manoeuvre to avoid a collision. (Figure 44) is an illustration of TCAS units in an aeroplane's cockpit (EUROCONTROL, 2016). Following are the system's units and antennas:

- Air Data Computer: this is the heart of the system, where all the processes perform; surveillance, intruder-tracking, threat-detection, avoidance-manoeuvre determination and advisories generation (FAA, 2011).

- TCAS and Mode S Transponder Control Panel: this is where the pilot can control the system and select the desired mode and sensitivity level. (EUROCONTROL, 2016, CÎRCIU and Luchian, 2014).

- Antennas: there are two TCAS antennas, located on top and bottom of the aeroplane, which is for transmitting interrogations (1030 MHz) and receiving the transponder replay. (1090 MHz) (Williamson and Spencer, 1989). The other two antennas are also located on top and bottom of the aeroplane and are the Mode S transponder antennas, which receive interrogations (1030 MHz) from other the TCAS system and replays to them. (1090 MHz) (EUROCONTROL, 2016).

- The connection between the TCAS and Mode S transponder: to coordinate the RA with other TCAS II equipped intruders. (EUROCONTROL, 2016).

- Connection with altitude altimeter and radar (radio) altimeter: to determine the aeroplane's altitude, and when the aeroplane is in close proximity to, or on, the ground it stops issuing RA. (EUROCONTROL, 2016).

- Speakers: for aural annunciation of TA and RA (FAA, 2011).

- Cockpit display: there are many kinds of display units for the TCAS system in aeroplanes. However, they all display the same information (Williams, 2004).

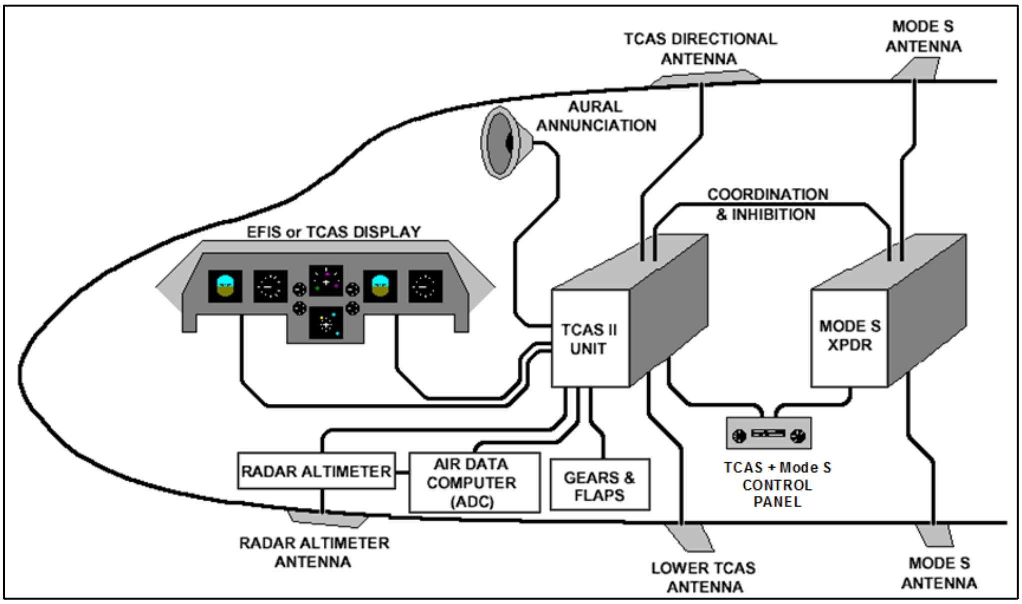


Figure 44 TCAS system's Components (EUROCONTROL, 2016)

5.4.7 Coordination, Complementary Decisions and Performance Monitoring in TCAS System

One of the most substantial advantages of the TCAS system is the automatic coordination between aeroplanes before issuing the avoidance manoeuvres (FAA, 2011, Munoz et al., 2013, Kuchar and Drumm, 2007). This function allows the system to provide complementary decisions, which is acknowledged by both aeroplanes. In order to have this Resolution Advisory Complement (RAC), both aeroplanes must be equipped with TCAS system (EUROCONTROL, 2016). The coordination establishes after the detection of the intruder, by the first surveillance interrogation, via the mode S transponder (FAA, 2011). Once the TCAS declares the intruder as a threat, it starts the connection via the Mode S data link (Murugan and Oblah, 2010). The first aeroplane which detects the other as a threat calculates the avoidance manoeuvre and send its selection to the threatening aeroplane to restrict its selection of the avoidance manoeuvre (EUROCONTROL, 2016). For example, if the first aeroplane decided to descend, it will inform the other about its decision to restrict it from descending, so the threatening aeroplane will avoid the collision by climbing up. The coordinated decisions (RAC) function is introduced to prohibit the TCAS system from providing the same avoidance decision to the aeroplanes, which leads to mid-air collisions.

After the Resolution Advisory (RA) is issued, the TCAS system monitors the performance of the aeroplanes and the vertical separation at the CPA every one second (FAA, 2011). However, sometimes the issued RA does not provide enough separation between aeroplanes, because even one of the pilots are not manoeuvring the RA properly, or the issued RA is not sufficient enough for a safe passing distance (Figure 45). As a result, the magnitude of the issued RA will be increased, or it will be reversed to prevent the collision (Figure 46) (Kuchar and Drumm, 2007). Avoidance decision without crossing in front of the intruder is more favourable, but if it is not possible then a crossing decision will be provided (Figure 47). The scenarios where the RA is reversed can be; firstly, the intruder is not equipped with a TCAS system, and it follows the ATC instruction for collision avoidance (FAA, 2011). Secondly, in case of automatically coordinated avoidance decision has been made in the same direction by both aeroplanes (EUROCONTROL, 2016). In this case, the aeroplane with the higher mode S 24-bit address will reverse its RA and coordinated with the lower mode S 24-bit address one (the lower one is not allowed to reveres its RA) (Kuchar and Drumm, 2007). Thirdly, in case one of the pilots is not following the RA, which is issued by the TCAS system. However, the monitoring and reversing techniques are of great importance to reduce human errors and enhance the flight's safety be preventing the mid-air collision.

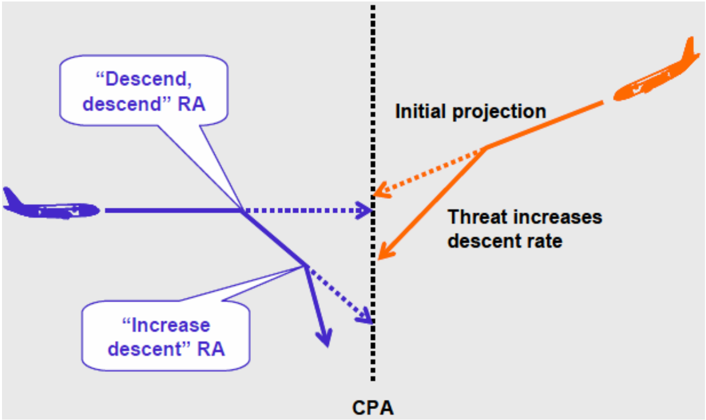


Figure 45 Increase descending, as a result of performance monitoring (EUROCONTROL, 2016)

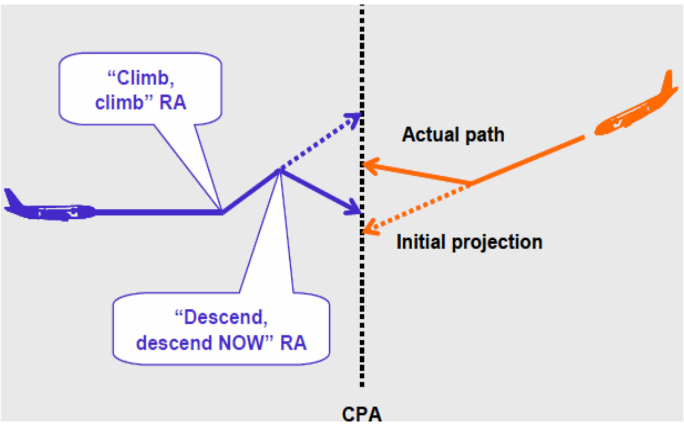


Figure 46 RA reversal (EUROCONTROL, 2016)

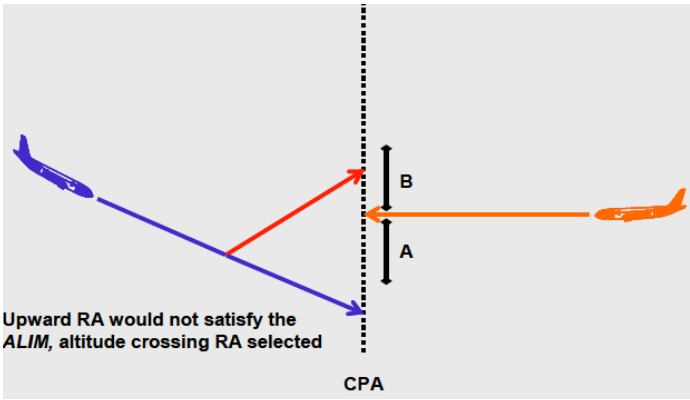


Figure 47 No decent separation, crossing path selection (EUROCONTROL, 2016)

5.4.8 Pilot responses to TCAS alerts

The TA alert is only to inform the pilot about intruders, and he/she should not manoeuvre the aeroplane as a response to it (ICAO, 2006). However, once the TA is received, the pilot should be ready for any potential RA with all available means of the best action. Moreover, the TA is also to help the pilot in the visual acquisition of intruders, but pilots should be careful when visually acquire intruders as they may not be the same which issues the TA (ICAO, 2006). Once the RA is issued, the pilot must follow its decision within five seconds (FAA, 2011). For the importance of following the RA to meet the ultimate objective of the TCAS system, which is eliminating the mid-air collision, the flying regulation has been amended as following;

"In the event of an RA, pilots <u>shall</u> *respond immediately by following the RA as indicated unless doing so would jeopardise the safety of the aircraft. The pilot must not manoeuvre contrary to the RA" (EUROCONTROL, 2016).*

Additionally, pilots must follow the RA even if it does not comply with the Air Traffic Control ATC instructions, as the ATC does not recognise the RA (ICAO, 2006). Also, the RA must be reported to the ATC with its direction and deviation from the original path, once the situation allows this (ICAO, 2006). In case of any modification or reversal in the RA, the pilot shall comply with it. Once the conflict is clear, the pilot should return to the ATC instructions and inform them when he is back on the original path unless otherwise has been instructed by the ATC (ICAO, 2006).

5.4.9 TCAS Limitation

In order to obtain the maximum benefits of the TCAS system, the pilots must respond to the TCAS indications correctly and within the time frame of the alerts. Hence this needs effective and recurrent training in all scenarios and procedures of the TCAS system, to gain an adequate level of experience to respond to the TCAS indications correctly (ICAO, 2006).

As the TCAS system is relying on the interrogation and transponder technique; however, the system cannot detect any non-transponder intruder (FAA, 2011). In addition to this, the TCAS needs to receive the intruder's altitude, when it replies to the interrogation, to be able to issue the RA (Honeywell, 2004). Accordingly, if the altitude information is not available, the TCAS cannot calculate the avoidance manoeuvre and cannot issue the RA. In the case of no altitude information, the system will issue the TA only without the relative altitude (FAA, 2011).

The TCAS system does not display or issues the TAs/RAs for intruders that have a vertical speed of more than 10,000 feet/minute (EUROCONTROL, 2016).

The TCAS system works independently from any other navigational system or connection with ground stations. Thus, the ATC will be unaware of the TCAS indications, which can cause confusion or conflicting orders to the TCAS decisions (Honeywell, 2004). Moreover, the pilot shall inform the ATC about the RA and its direction once the workload on the cockpit allows doing so, which can be a source of human error of extra workload (ICAO, 2006).

5.5 Chapter summary

In this chapter, the technical details and specifications of the navigational equipment have been discussed for the maritime and the aviation industries. These technical details and specifications have provided a complete understanding of the available systems and technologies on ships and aeroplanes. Moreover, this chapter has provided a valuable source of comparison between the two industries and give beneficial information that will help to improve the navigational duty on-board ships. More specifically, this helped to understand the utilised automatic collision avoidance system in the aviation industry, the TCAS system, which provided useful techniques to be developed to enhance the maritime safety and the development of an automatic collision avoidance system for ships.

6 The framework of the proposed collision avoidance model

6.1 Introduction

In this research, an extensive study has been carried out about the ship navigational bridge in the context of navigational aids, equipment and the information presentation to the OOW. More attention is given to the availability and efficiency of collision avoidance systems and the risk of collision assessment methods. This research reveals the need for an automatic decision support system for collision avoidance to improve the OOWs' situational awareness and to allow more time for data analysis and decision making by OOWs. In addition, it appears that all navigational aids and equipment are information systems only, which leave all the analysis and decisions to the OOW. However, this leads to subjective decisions based on the understanding and interpretation of the situation.

Although other scholars addressed the needs for automatic collision avoidance system and suggested framework and models for the systems, none of these studies has considered the data link and decision sharing techniques with other ships. However, this study proposed a new approach for collision avoidance process by introducing the principle of data link channel between ships and decisions sharing technique in the system's framework. The suggested procedure and technique will enhance situational awareness by providing real-time and broadcasted information about all target's parameters, plus explicit knowledge about other ships navigational information and decisions. These procedures and techniques will remove the uncertainty of the collision situations and the ambiguity of COLREG regulation by knowing other ships' actions and their efficiency to avoid conflict situations. In addition, this will reduce the cognitive load on the OOW, by reducing targets monitoring time for such detection of action and the efficiency of actions.

This framework is inspired by the Traffic Alert and Collision Avoidance System (TCAS), which is used in the aviation industry to prevent mid-air collisions. The TCAS system has proven its reliability as a collision-avoidance system; however, this system became mandatory for all aeroplanes. Moreover, pilots are required to respond immediately to the TCAS system's decisions as it has been mentioned in the International Civil Aviation Organisation document ICAO (Procedures for Air Navigation Services).

The suggested data link and decision sharing techniques utilise electromagnetic waves to overcome the radar deficiencies in target detections, and for real-time broadcasted information or parameters of other ships. However, every ship will be continuously transmitting the interrogation message, when the interrogation message is received by ships in the detection range, they send back a reply messages, where these interrogations and reply messages have the ships positions and basic information (speed and course). This technique will be more accurate than the current process of calculating target's information in ARPA system, and it will overcome the weaknesses of the AIS system, as discussed earlier in chapter five.

Additionally, information flow control and management for better data processing and display are developed. This will allocate all the essential navigational information in one display unit in a logical presentation to improve the OOW's cognitive ability. Moreover, this will enhance the overall situational awareness by collecting and displaying all relevant information in one place to avoid missing valuable information by collecting them from different equipment and locations. Furthermore, the system can alert the OOW about dangerous targets and the best action to avoid a collision, based on COLREG regulation.

6.2 The main aim of the Automatic Collision Avoidance System

The main aim of the Automatic Collision Avoidance System is to enhance navigational safety. This aim will be achieved by improving the information flow and control in the navigational bridge in addition to the information exchange between ships in the vicinity. However, implementing these techniques will improve situational awareness with better understanding and interpretation of surrounding situations. Moreover, sharing the information with ships in vicinity lead to better situational awareness for all ships involved in an encounter situation. This will ensure the availability of all essential navigational information which is required by all ships in the vicinity. Accordingly, with the information flow and control technique, the information will be sorted by its importance to navigational decisions within one display unit, which will process all the information. This will solve the problem of poor ergonomics and design of the traditional navigational bridge, which needs data collection from different systems and locations.

The availability of accurate navigational information is crucial to enhance navigational safety generally, and especially for collision avoidance decisions. Consequently, sharing this information helps in sharing the same mental model among all ships in the vicinity, which ensure correct understanding and interpretation of the real situations by all ships. Real-time information about other targets gives the OOW more time for decisions making that also supported by the required and well-presented information to evaluate the best actions to avoid conflict situations. Indeed, this enhancement in information flow and sharing encourage the OOW to achieve more reliable and objective decisions based on the actual situations. Additionally, it cuts the likelihood of making subjective decisions that built on wrong understanding and interpretation of the surrounding situations.

Moreover, where every ship is forecasting its parameters, this makes it possible to detect targets' initial movements (action) and act accordingly to avoid collisions. Finally, the new system can suggest the best actions to avoid collision situations. These actions are categorised as; COLREG compliance, COLREG non-compliance, Best action and the last-minute action to avoid collisions. However, the OOW will be self-assured about the navigational decisions and its efficiency to prevent conflict situations.

6.3 Collision Avoidance System for Critical Situations Only

The proposed models for collision avoidance focus on critical collision situation. This is to prevent the immense danger of ship collision from happening, which will protect life, properties and the environment. With these considerations having the highest priority, the system design has not taken into account some route optimisation aspect. Consequently, the shortest route is not always selected by the system to avoid collisions.

Furthermore, not the fastest route should be selected for all avoidance actions. Economically efficient routes are not feasible at all times for collision avoidance. Also, non-environmentally friendly behaviours are essential in some critical situations. Finally, the smallest course alteration is not necessarily possible to avoid dangerous situations. All these factors are not of the utmost importance when it comes to collision avoidance due to the fact that other more essential restrictions need to be addressed first. Thus, COLREG instruction in avoidance manoeuvres should be followed at all times. Then, actions result in further navigational complexes are prohibited. Additionally, the under-keel clearance and water depth could limit the availability of sea room for manoeuvrability. The most crucial factor that should be considered when actions to avoid a collision or critical situation are about to be taken is the safety of the ship and navigation. Therefore, the developed collision avoidance system provides the optimum action to ensure the safety of the ship at all times. The next section discusses the developed models for collision avoidance.

6.3.1 The system architecture for the developed collision-avoidance models

In general, the traditional collision avoidance procedures are characterised by only providing the required information to the OOW, without decision support. However, this information needs to be processed and analysed to gain valuable meanings that will help decision making for collision avoidance. Additionally, technological advancement in the shipping industry and the enhancement inclination of marine navigation are increasing. This transformation is following the path of automated calculations and processes. Moreover, it takes long time to develop and approve a new navigational system, which leads to poor planning and improperly designing a bridge that has inadequate layout systems and lack of ergonomically integrated navigational equipment. Especially for old ships where they need to fulfil the requirement of new regulations by retrieving the new equipment in any empty space on the bridge. As a result of all these factors, the current navigational systems only provide information to the OOW; then additional processes, by the OOW, are required to gain full understanding and interpretation of the situation.

Unfortunately, these information systems are not sufficient for conducting safe navigational watches these days, where high traffic density and increased sizes and fast ships are cruising around the oceans and especially coastal waters. Consequently, the OOW has less time to detect targets, collect their information, analyse it and take the most appropriate actions to avoid critical situations. Moreover, there is a higher chance of missing information and human error occurrences with the high number of navigational aids equipment and information analysis. Any wrong or missing information affect the OOW’s situational awareness and deteriorate the interpretation of the situation, which causes a wrong decision making by the OOW.

In order to improve the collision avoidance procedures, it is vital to develop a decision support system that helps the OOW in decision making. In this case, the system will be able to do all the analysis and provide processed information to the OOW, who will then consider the best-avoiding action. Furthermore, the system can calculate and provide the best actions to avoid critical situations. It is appropriate for the case where a reliable system is critical, it is essential to feed the system with full and accurate information about all targets in the vicinity. In order to do this, it is essential to develop new techniques for data link and sharing to ensure the availability and accuracy of information.

The beneficial side of these techniques is to enhance situational awareness by better information availability and sharing between ships. Hence the system is meant to process the data; this will give the OOW more time for decision making, as well as correct understanding and interpretation of the situation. Also, sharing the same mental model of the situation among all ships in the vicinity will enhance the overall situational awareness.

This section will discuss two models, which have been developed to operate as automatic collision avoidance systems. The first model is a modification to the traditional collision avoidance procedures that aim to enhance navigational safety by improving data exchange and availability. The second model is the proposed new automatic collision avoidance system. This proposed system has new procedures and techniques that are developed to automate the whole collision avoidance procedures in the navigational bridge.

6.3.2 Model 1, The traditional collision avoidance procedures with new techniques

In model one; there are no proposed changes in the current collision avoidance practices. However, new techniques are introduced to enhance the OOW's situational awareness and actual interpretation of situations, especially in critical situations. The proposed system architecture is explained in (Figure 48). As it has been mentioned in this model, the current navigational practices have not changed, where it starts with the standard navigational equipment monitoring plus the visual lookout. This is to help in conducting a safe and successful voyage, which needs to fulfil the four stages of passage planning; appraisal, planning, execution and monitoring. Thus, the first stages are included in the initial step, which needs to be completed before leaving the berth. In the navigational watch, the OOW monitor the performance of the ship and ensure the best execution of the passage plan is retained.

Additionally, the OOW must detect any critical situation at an early stage and take the required actions to ensure the safety of the ship. One of the most dangerous situations at sea, yet frequently happening, is a collision with other ship. Despite, all the efforts are being carried, by stakeholder, to stop maritime collisions; still contacts and collisions are entailing of 34% of the maritime accidents (EMSA, 2017). This has motivated the researcher to utilise new technology to find solutions for such an issue. Accordingly, four new techniques have been proposed in which they can improve the availability of information and remove the ambiguity of critical navigational situations;

- Data-link, sharing and exchange.
- Decisions sharing and acknowledgement.

- Target's information availability.
- Target's information and decisions validation.

In general, the execution and monitoring duties are the same as the classical navigational duties. Monitoring the navigational equipment, in case of collision situation development, then the OOW collect the required information to analyse the case. If it is a collision situation, then according to COLREG, the best action to avoid collision must be taken by the give-way vessel. Using the proposed model, a data link connection needs to be established for data sharing and exchange. A data exchange channel between own ship and the target vessel will establish a connection channel for data exchange. This channel transfers all the required information between both ships. First, the essential information about ships movement will be available, including positions and direction, for accurate interpretation of the situation and decision making. Second, when the give-way vessel decides to take an avoidance action, the stand-on vessel will be informed about the action. Also, the stand-on vessel should acknowledge the awareness about the avoidance manoeuvre and actions. This technique will remove the ambiguity of the collision situation by ensuring both vessels involved in the situation are fully aware. Also, this confirms that the required action is taken by the responsible ship.

Additionally, if the give-way vessel is not taking the required avoidance action, or if its action alone is insufficient to avoid the collision, the stand-on the vessel will be aware of this through the decision sharing and acknowledgement technique. Where in the current collision avoidance practises, there is no technique that immediately informs the OOW if the give-way vessel is taking action or not, it is only by monitoring the target and detect its movement and the ARPA system, which takes up to three minutes to give accurate data. The required avoidance action should be taken as early as possible, by the stand-on vessel, according to COLREG. Likewise, if the own ship is the stand-on vessel, she will be attentive about the target ship's (give-way) consciousness about the situation. This will allow the stand-on the vessel to evaluate and validate the give-way vessel's action to avoid the collision, and if necessary, she can take the required action.

The implementation of such techniques will allow a closed-loop decision-making process for collision avoidance. This will confirm that all parties involved in a critical situation are alerted, informed of actions were taken by any vessel and can validate the actions and act accordingly. Furthermore, this will improve the situational awareness level for the OOW, for the safer maritime environment. It is essential to mention that all these data-link connection, sharing and exchange happen automatically without human intervention. The only required action by the OOW is to acknowledge the alertness about the other ship’s decisions and actions and validate them to ensure the safety of the ship. The new proposed technique is illustrated in (Figure 48), which are the data link and manoeuvring acknowledgement features between own ship and the target ship. In (Figure 48), the automated processes are labelled by the green colour and the manual processes, which need the involvement of the OOW are labelled by the orange colour.

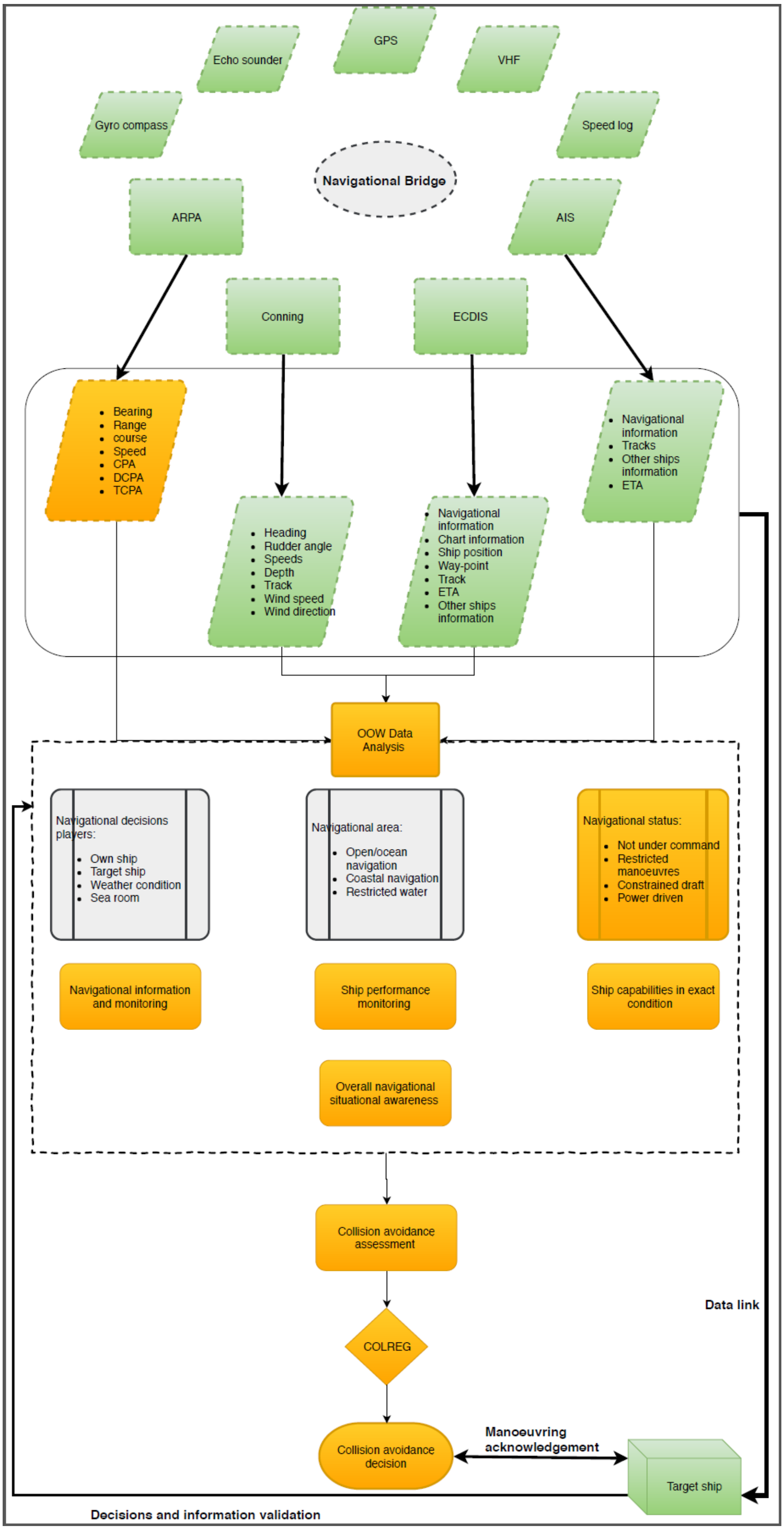


Figure 48 Traditional procedures with new technique

6.3.3 Model 2, The proposed New Automatic Collision Avoidance System

The new suggested collision avoidance procedures are based on full automation for the collision detection and avoidance processes as given in (Figure 49). This automation will only leave the execution to the OOW, with suggestions from the system about the best action to avoid the collision and further conflicts. Basically, the new system exchanges data with other ships, then processes it with own ship's data, to provide the OOW with comprehensive collision avoidance suggestion. However, the availability and accuracy of the data to be utilised by the system is vital to have reliable results. In (Figure 49), the green colour indicates the automatic processes that done by the system, the orange colour shows the manual input of the required parameters and the grey colour are the information available to the OOW for monitoring.

The basic principle of the new proposed model is the automation of the navigational processes, also by sharing data and decisions between ships. The main aim is to promote a robust situational awareness, based on correct and accurate information to structure a right level of understanding and interpretation of surrounding situations. As it has been mentioned before, all navigational aids and equipment on traditional bridges are information systems only. However, the OOW is required to collect the data, analyse it and decide the best actions. The new procedures propose a fully automated collision avoidance process. This will be achieved by;

- First, an automatic collection of all required data from the navigational equipment and sensors.
- Second, processing the own ship's information, then consider the user's parameters' values. This includes consideration to the COLREG regulation, to satisfy own ship conditions and capabilities.
- Third, retrieve target ships' information from the data link channel, and process it to resolve other targets situation and influence own ship's progressing decision. By this stage, the system will calculate and process all necessary data and information to conclude the navigational and collision situation (Head-on, Crossing Give-way, Crossing Stand-on and Overtaking) and decide the collision avoidance responsibilities (stand-on or give-way) in relation to COLREG, if the risk of collision exists.

- Fourth, the information display and availability stage, where it is categorised in four groups; Collision Avoidance, Tracking and Passage Progress monitoring, Navigational Information and Ship Performance and Capabilities.

In Collision avoidance stage, the system recognises suspected targets, threating targets and targets in a collision course, together with targets' information display in an automatic manner. After this, it provides the OOW with the best action to avoid the collision and the last-minute action. After collision avoidance calculation and decision, the system implements the technique of Decision Sharing and Acknowledgment with the target ship to make her aware of the collision situation and the avoidance action. Likewise, the Data Link, Sharing and Exchange are implemented between both, own and target ships, for closed-loop manoeuvring decision and better situational awareness. Accordingly, the other three groups of information displays are for monitoring and general awareness purposes. However, this information is displayed in one place to make it convenient for the OOW to retrieve the required information promptly. Additionally, with the new automatic collision avoidance technique, the OOW will focus on the decisions rather than the analysis and detection processes. Moreover, the decisions support technique, which advice the OOW about the best action and last minute to avoid collisions.

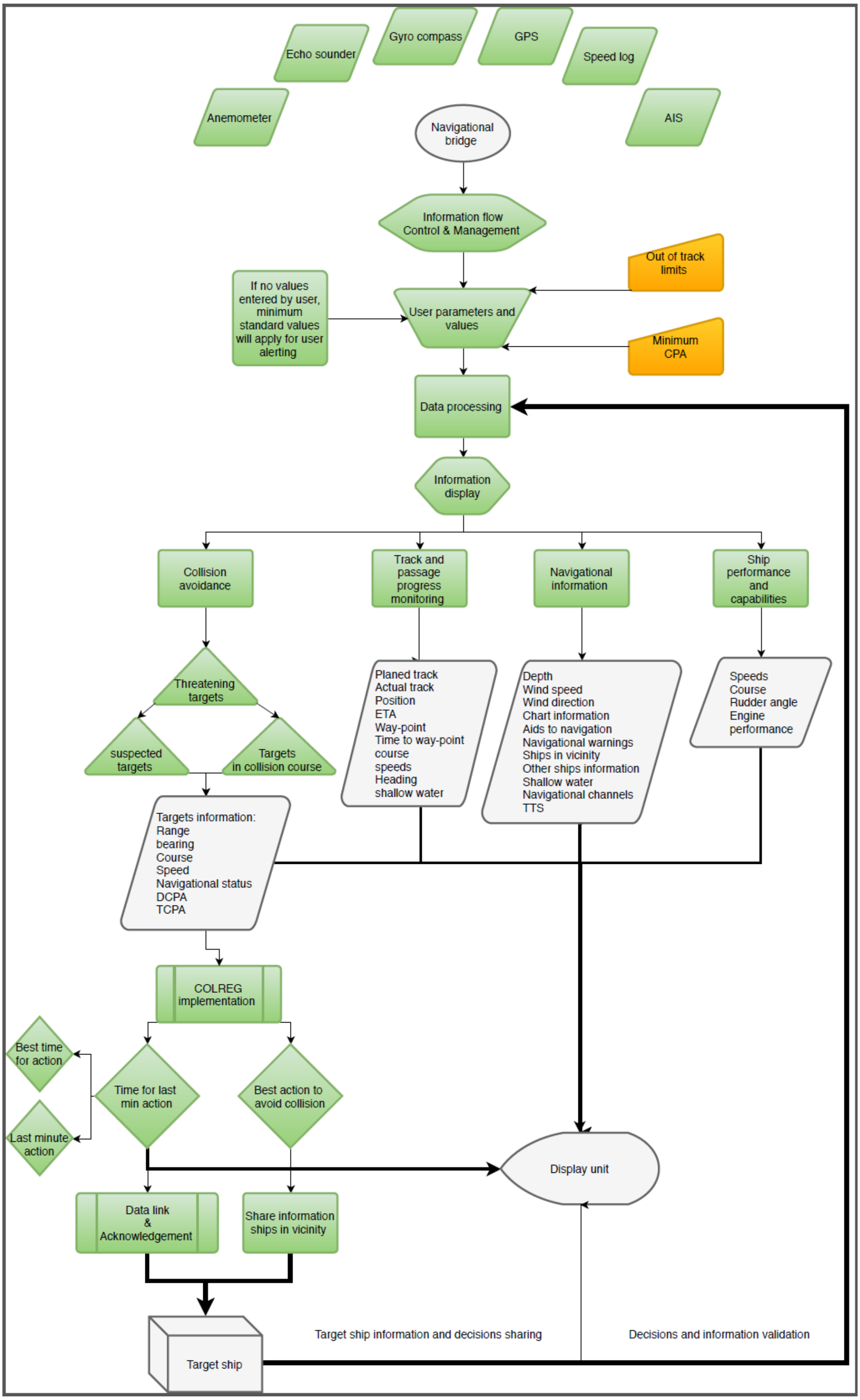


Figure 49 The proposed new procedures

6.4 Definitions of terms and techniques used in the system

This section will explain the terms that are used in the new collision avoidance system to enhance usability and to develop a better understanding of the system utilisation. Then, to improve the standardised phrases and terminologies used from the system's operation.

Data-Link: is an automatic communication channel between ships and shore station in the navigation area. This channel allows the ship to send and receive digital data automatically for all other ships, within the detection range, to be used for collision avoidance calculations.

Last-Minute Action: the last minute for a ship to take action to avoid a collision. After this time the collision is unavoidable by any action (no return moment).

Sharing Information: to exchange navigational data between ships in the vicinity to allow the automatic collision avoidance system to perform the required calculations. Also, to enhance the OOW's overall situational awareness.

Decisions Sharing: Automatic sharing of avoidance decisions with the target ship (in real-time), to make them attentive of the avoidance actions. To share the same mental model of the situation.

Decision acknowledgement: after performing the decisions sharing technique, it should be accepted by the target ship, to ensure the target ship's awareness about the collision situation and the avoidance manoeuvre.

Information flow and control: the management of navigational information based on its importance and relation to the navigational situation. The availability of the required information at all times in a user-friendly display.

Mental model: share the same understanding and interpretation of the actual navigational situation by all ships and people engaged in the navigational duties.

Suspected targets: targets are not on a collision course, but still needs to be aware of them to avoid future confliction.

Threatening targets: targets on a collision course, but no action is required to avoid the collision, careful monitoring is required. This can include the following scenarios; Stand-on situations, Traffic Separation Scheme (TTS), near way-point, course alteration, Ships responsibilities, etc.).

Targets in collision course: collision situation exists, and an avoidance manoeuvre is required.

Alerts: warnings about critical situations.

Advice: the required action to be taken to avoid critical or collision situation.

Best time to take action: the best time to perform the optimum avoidance manoeuvre.

6.5 The Data Link and Exchange Channel method

For the data link and exchange channel technique, the new under-development system, the VHF Data Exchange System (VDES), is proposed to be utilised. This system has been developed by The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) to enhance the digital data exchange for the maritime VHF radio band. The VDES system has already been developed, and the International Telecommunication Union (ITU) has approved the operational standard (Recommendation ITU-RM.2092-0) for the utilisation of the system in the World Radiocommunication Conference (WRC-15) (IALA, 2017). The only issue that needs to be approved is the satellite arrangement for the VHF data exchange (VDE) channel, which is expected to be completed in the (WRC-19), (IALA, 2017). The primary consideration has been taken when developing the VDES system to the e-navigation concept and its requirement of data link and exchange. Thus, the IMO's definition of the e-navigation concept is, *"the harmonized collection, integration, exchange, presentation and analysis of marine information on board and ashore by electronic means to enhance berth to berth navigation and related services for safety and security at sea and protection of the marine environment"*. Indeed, the e-navigation concept was the core inspirational aspect that has been considered in developing the maritime collision avoidance system.

Additionally, the Traffic Alert and Collision Avoidance System (TCAS), the aviation collision avoidance system is the other influencing system that has been studied to develop a similar collision avoidance system for ships. The main feature that attributed to the successful development of the TCAS system is the ability to exchange and coordinate the avoidance manoeuvres between aeroplanes. Therefore, developing such a data link and exchange channel techniques for ships, to be utilised for collision avoidance, will assist the OOW to make the right decision and reduce ships collision at sea (Figure 50). Further details about the VDES system are available in the chapter (5).

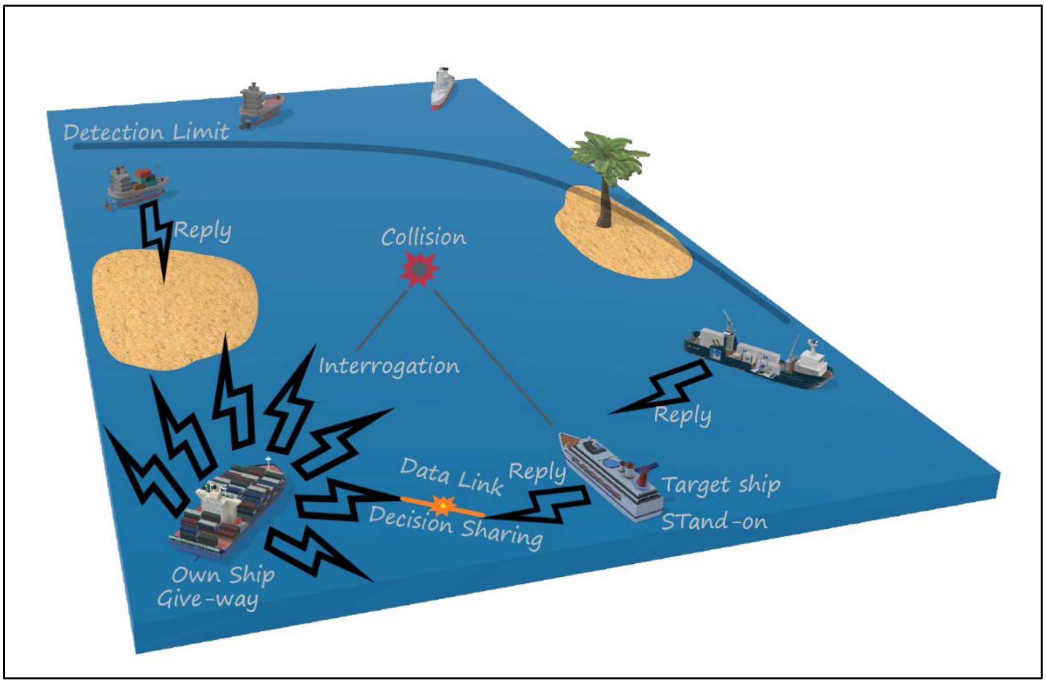


Figure 50 Data link and decision sharing

6.6 Threat Detection technique

For threatening target detection, the proposed model will utilise two techniques for the detection of the ultimate target.

First Technique is the VDES-to-VDES system as an ‘interrogation and respond’ technique for both ships equipped with the VDES system. In this case, own ship will send an interrogate signal to other ships in the vicinity (Figure 51). When a target receives the interrogation signal, it responds by sending a reply message that contains the required information for collision detection (position, course, speed, bearing and range, the AIS information) (Figure 52). This information will be used in the mathematical calculation model to find out if a collision situation exists. Then, if the collision situation exists, the model calculates the best avoidance action and provides it to the OOW.

The second technique is the VDES-to-none VDES ships using the current radar system (ARPA) on-board ships. For the none-VDES equipped targets and threats (including fixed objects, buoys, lighthouses, lands, etc.). This will be less accurate than the VDES detection method, depending on the quality of the radar echoes. However, it is vital to detect targets that are not equipped with the VDES system. Although, in this case, the automatic collision avoidance system (on own ship) can collect the required data, from the ARPA system, and calculate the collision avoidance manoeuvre. Nevertheless, in none-VDES equipped targets the function of decision sharing and acknowledgement will not be available.

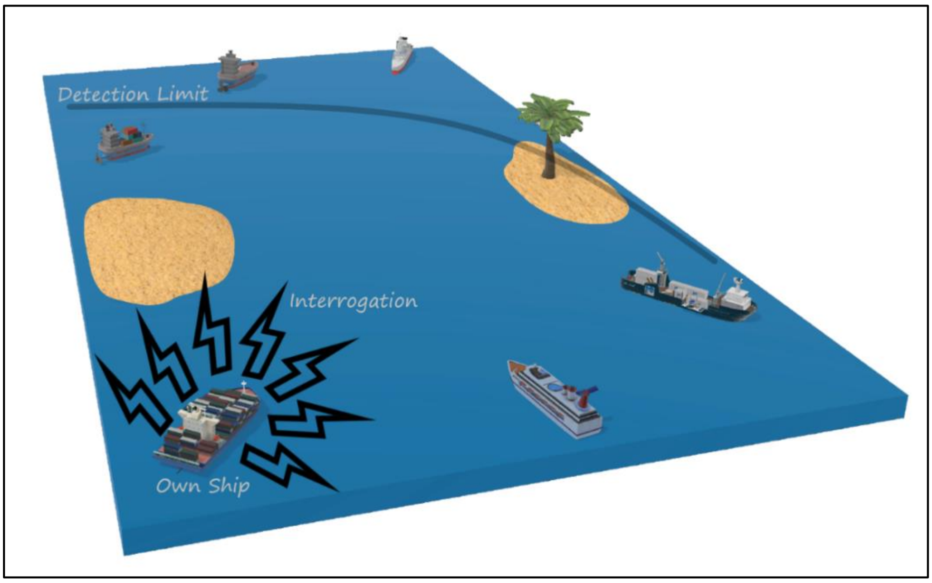


Figure 51 Interrogation technique

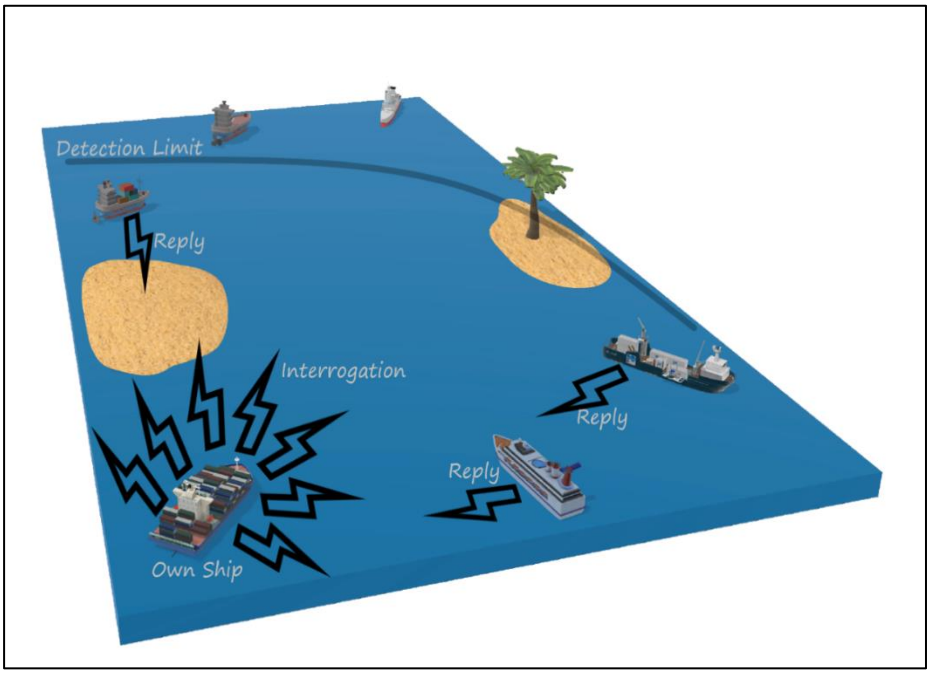


Figure 52 Reply to an interrogation

6.7 Automatic coordination and connection for decision sharing and acknowledgement

The main feature of the proposed collision avoidance procedures is the coordination of the avoidance decision between ships in a collision situation. This is an automatic process that allows the system to share the decided manoeuvre by the give-way vessel with the stand-on vessel. Additionally, the stand-on vessel is required to acknowledge its alertness about the collision situation and the decision being taken by the give-way vessel to avoid the collision (Figure 53).

The main advantage of such a technique is to enhance the overall situational awareness in all ships that are involved in a conflict situation. Furthermore, this will remove the ambiguity of COLREG regulation, especially rule 17 (stand-on vessel). As a stand-on vessel, she should maintain her course and speed, and keep monitoring if the give-way vessel is taking avoidance action and if this action is enough to avoid the collision. If the give-way action is not enough, or no action is taken, then the stand-on vessel must avoid the collision by her own manoeuvre. Accordingly, sharing the decisions and acknowledge them will remove all these ambiguities of the situation.

Moreover, it will allow the stand-on vessel to know, early enough, if the give-way vessel is not taking any avoidance action or her actions alone is not adequate to avoid the collision, and she can act accordingly. Such a technique will allow the involving parties to share the same mental model, which will enhance human performance and decision making. Likewise, this will improve the human response to emergency situations and have a real understanding and interpretation of the surrounding situation.

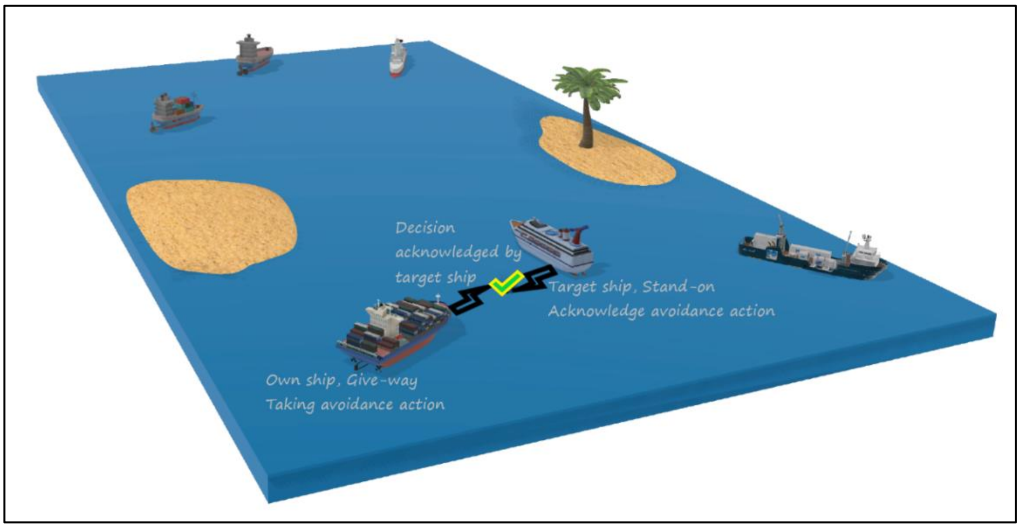


Figure 53 Avoidance action and decision acknowledgement

6.8 Sensitivity level for targets detection

The sensitivity level determines the range of interrogation on which the system runs the calculations and provides an avoidance manoeuvre in case of collision situation. This is to be selected by the OOW to decide how far the system reacts for targets that might threaten the own ship (Figure 54). Thus, the system will ignore targets that out of the selected sensitivity level to prioritise ships within the detection range. Therefore, upon the selection of the sensitivity level, several navigational factors need to be well studied to avoid any close quarter passing or collision situation from developing. First is the area where the ship is sailing in, such as; open water (ocean), restricted areas, narrow channels, TTS, restricted depth, etc. Accordingly, the sensitivity level will stop unnecessary alerts communicated to uncritical targets, and allow the OOW to focus on the dangerous situation, which needs immediate action. This can be the case in crowded areas, where the priority should be given to the surrounded targets rather than further away targets. Also, this function is useful in TTS, to reduce the number of unthreatening targets that navigating out of the TTS. In nutshell, this will reduce the nuisance of unnecessary alerts, which could lead to ignorance of critical alarms. This is due to the fact that the OOW losses the trust in the alarms if they do not provide real support when they are required the most, and keeps raising alarms unnecessarily and frequently.

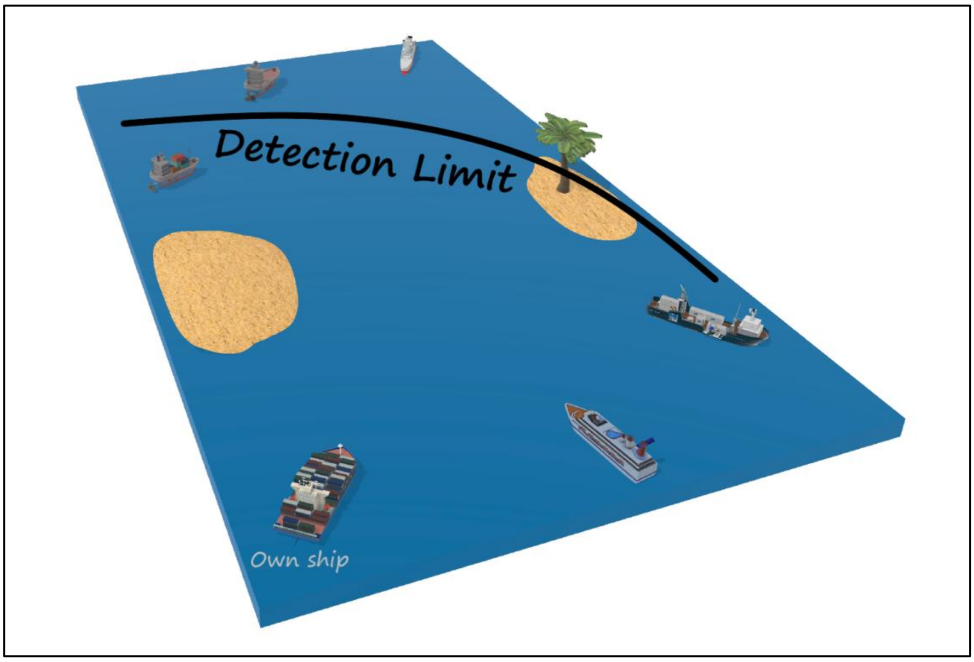


Figure 54 Sensitivity level and target detection

6.9 OOW execution of the avoidance manoeuvre

After the running of the collision avoidance calculation in the mathematical model, the system will provide the avoidance decision to the OOW. Hence, the OOW is responsible for the execution of the avoidance manoeuvre, which is provided by the system. Once the OOW starts executing the avoidance manoeuvre, the system automatically shares the actions with the target ship. This is to confirm the awareness of the OOW on the target ship about the situation and the action. Indeed, the OOW is required to execute the avoidance actions due to the lack of international regulation of the use of automation in maritime navigation. Thus, it will be confusing to assign the responsibilities, among the involved ships in the collision, whether to blame the autonomous system, the manufacturer of the system or the OOW.

Moreover, this will result in an increase in the insurance prices so the insurance companies can cover the damages and costs. Therefore, the automatic collision avoidance system is a decision support tool to help the OOW to take the best action to avoid a collision at sea. Moreover, this will give longer time for analysing the situation and the decision where all the required data and actions are available in advance. This left the responsibility to the OOW to ensure the safety of the navigation.

6.10 Alerts status; Green, Amber and Red

The collision avoidance system is capable of providing three status of navigational interaction with other targets in the vicinity. This is to alert the OOW about the navigational situation, with regards to targets in the surveillance limits. Thus, this will clearly inform the OOW if it is safe to navigate with no actions need to be taken, whether caution needs to be given to any of the targets in the surveillance limit, alternatively, if action needs to be taken to avoid a collision situation. The status of these alerts is clearly illuminated and audibly announced to ensure the alertness of the OOW about the situation. Therefore, these alerts are to be coded as; green, amber and red. The explanation of each of these as follows.

- Green: no action, no threatening targets: where it is safe to navigate, and no threat is detected, no action needs to be taken.

- Amber: no action required, suspicious targets, close passing, stand-by vessel: where it is safe to navigate with caution needs to be given to a target/targets that are passing in a close distance. In this case, the situation can easily and rapidly develop into a collision situation, where action needs to be taken. Also, this can be the case of being a stand-on vessel in a crossing situation. However, the OOW needs to ensure that action is being taken by the give-way vessel. If the give-way vessel is not taking an avoidance action, or its action is insufficient to avoid the collision, then the OOW needs to take action to prevent the collision from happening. If the situation has changed to a collision, the alert will change to “Red”.

- Red: action required, collision situation: where a collision situation exists, and the OOW needs to take action to avoid the collision, in this case, the system will audibly announce the alert as “collision, collision, collision”. Also, the collision avoidance model will provide the best action to avoid the collision.

6.11 Alarms and decision acceptance by other targets

The system provides an alarm when a target ship is in a collision course with own ship, and she is the give-way vessel. This is to alert the OOW, on own vessel, about the situation. Furthermore, this is to share the target ship's decision about her action to avoid the collision through the decision-sharing technique. In such a case, the OOW on own ship must acknowledge the awareness about targets ship's actions to broadcast his awareness about the situation.

On the other hand, if own ship is the give-way vessel and she shared an avoidance decision with the target ship, but target ship does not respond, an alarm will be set off. This is to alert the OOW that the target ship is uninformed of the collision situation and unaware about own ship's decisions to avoid the collision. In this case, the OOW will have to be extra cautious about the situation and does not assume that the target ship is aware of the actions being taken.

6.12 System override to stop unavoidable collisions

As the last barrier for collision avoidance, an additional feature is introduced to mitigate the consequences of a collision, or perhaps stop it from happening. A system override technique is intended to take control of the ship's manoeuvring decisions. By doing this, it will respond to a collision situation without the intention or intervention of the OOW. This can only happen when the collision situation becomes critically dangerous, and if no action is taken immediately, the collision becomes unavoidable. As an overriding technique, this can be done in two methods. First, is to stop the propulsion system completely (or perform a crash stopping) to reduce the speed of the ship. This will result in a reduction of the impact and consequences of the collision, without any interference to regulations and rules, as well as no further complication can develop out of this action. Second, the system can perform the avoidance manoeuvre, which is calculated by the collision avoidance model. The system will alert the OOW in advance and before start overriding on the ship's control. Technically these two options are applicable and can be performed by the automatic collision avoidance system. The only obstacle that could disrupt these functions is the legalisation issue, where the IMO must approve such techniques for automatically controlling the ship's movement, which in this case will be considered as autonomous ships and they are not regulated by the IMO yet.

6.13 Real-time calculation

The collision avoidance model is capable of providing real-time decisions for the avoidance manoeuvre. This requires the availability of the data so the model can run the calculations. However, the availability of the data depends on other systems and sensors on-board own ship and target ships. As it was mentioned before, the VDES system is the best-suggested method for data collection and sharing between ships. Thus, the VDES can be used as a database for all the required information. Then, the collision avoidance system gets a feed from the VDES with the required information to perform the collision detection and avoidance calculation.

6.14 Chapter summary

A thorough discussion has been completed in this chapter to explain the architecture of the developed collision avoidance system. This includes the operational principle and techniques that are followed to develop the system. This technical chapter has given details about the new system’s functions and its relativity to the real navigational processes. Accordingly, this ensures a comprehensive automatic collision avoidance system. This system is capable of providing the best decision that guarantees the safety of the ship.

7 The collision avoidance model, mathematical calculation and formulas

7.1 Introduction

The closest point of approach (CPA) is the most used method to evaluate the risk of collision at sea to date. The CPA used to be calculated manually on a radar plotting sheet, where the OOW plots three (minimum) consecutive plots from the radar screen and calculate the target ship’s information based on these plots. However, manual plotting requires a long time to assess the situation and begin the calculation for each target in the vicinity. In modern ships, the ARPA system (integrated with AIS) provides all the required information for acquired targets, then the OOW does the analysis and performs the best decision to conduct a safe navigational watch. Due to the increased number of ships and the traffic density, this has restrained the OOW’s capability to monitor all targets around his ship. Also, it paves the way for potential human errors which contribute to an accident at sea. Accordingly, the main aim of this model is to fully automate the collision avoidance process and provide the OOW with the best action to avoid the collision. First, the model starts with the automatic acquisition of suspected targets, which have smaller CPA than the pre-required minimum CPA selected by the OOW. Then it provides the best actions to avoid the collision, either by reducing the speed, changing course or speed and course to pass the target ship safely and according to the pre-required CPA. The availability of such a decision support system on-board ships will reduce the probabilities of human errors. In addition, this will give the OOW longer time to evaluate the situation and the avoidance decision, rather than spending time analysing ARPA’s information.

7.2 Assumption

In the modelling stage, a number of assumptions have been taken into consideration to simplify the process. Also, to avoid over-complicated calculations. However, some of these assumptions will be addressed in a later stage of modelling, for development and overall results of collision avoidance.

- Own and target ships are considered as particles. This means the dimensions (length, breadth, draft and weight) of the ships are not accountable in the calculations, and they are treated as a point moving on its path (Meriam and Kraige, 2012).

- Live data streaming is provided to the model to perform the calculation in real-time. Target ship's information is streamed from the AIS system and own ships information streams from the ship's sensors and systems.

- The mathematical calculation solves the collision situation for fixed parameters (course and speed). Yet, live streaming overcomes this issue be recalculating the collision situation with every change in parameters.

- No drift angle is considered in the calculation (external factors affecting ship's movement, like; wind and current). This will be discussed further in section 7.5 Weather condition (wind and current).

7.3 Models inputs, outputs, parameters and results

7.3.1 Inputs

The collision avoidance model requires some input data that needs to be available all the time to calculate the collision situation and solve the problem. This data is related to ships parameters that involved in the collision avoidance manoeuvre for both own and target ship. The following table presents the required data (Table 10);

Table 10 Inputs to the collision avoidance model

Own ship	**Target ship**	**Pre-required parameters**
Speed over ground	Speed over ground	Minimum CPA
Course over ground	Course over ground	Time of minimum CPA
True bearing to the target ship		
Range to the target ship		

To ensure accurate calculations, the following conditions must be fulfilled in the inputs data;

- Courses and speeds over the ground for target and own ships should be taken to make the calculation based on the true movement of the ships on the ground.

- Target bearing must be true and taken from own ship, the angle measures from the true north to the target ship.

- The range is the distance from own ship to target ship.

7.3.2 Outputs

After entering the inputs, the model performs the calculation and provides the best actions to avoid the collision if a critical situation develops. Thus, the calculation is based on the OOW's pre-required CPA and Time to CPA (TCPA). The outputs of the calculation are in Nautical Mile for distances, Knots for speeds and minutes for time. The outputs of the calculations are presented in the following table (Table 11);

Table 11 The model's outputs

Collision evaluation		**Speed change**		**Course change**		**Speed and Course Changes**	
CPA	TCPA	Pass ahead	Pass astern	Pass port	Pass astern	Course	Course
				Pass starboard	Pass ahead	Speed	Speed

7.3.3 Explanation of the Outputs

In order to understand the outputs of the model, it is worthy of splitting the results and explaining each part in more details. The results are separated into four parts, as follows;

- Collision evaluation; this is the first part of the model calculations. In this part, the criticality of the situation can be evaluated depending on how close the target ship is going to pass own ship. Also, at what time this event is going to happen. This can be evaluated by the CPA and TCPA, the smallest they are, the more critical the situation is.

- Speed change; this is the decision part to avoid collision by speed change. The model provides two results, either to pass target ship ahead or astern. However, in most of the case, it is unfeasible to pass target ships ahead as this needs a significant increase in ship's speed, where the ship cannot reach. Moreover, passing ahead in a critical situation is not advised by COLREG. Furthermore, speed change for collision avoidance is not recommended by COLREG, especially in the close-quarter situation

(Cockcroft and Lameijer, 2012d). Although course change is more effective for collision avoidance and recommended, the speed change is used in restricted water if no room for manoeuvre is available (Pietrzykowski et al., 2016).

- Course change manoeuvre; This is the most common practice to avoid a collision at sea. The developed model can provide up to four-course changes to pass the target ship within the pre-required CPA. Depending on the collision situation, it provides courses to pass ahead, astern, port and starboard sides of the target ship. In most of the cases, only one of these courses is the best course to avoid collision due to COLREG restriction or the unfeasibility of massive course change.

- Speed and course change manoeuvre; This is the best avoidance manoeuvre in restricted waters. It is useful when the ship does not have enough room to avoid collision by course change only, where this will provide an optimised manoeuvre with a minimum course and speed change. For better results, the Speed Over Ground (SOG) and Course Over Ground (COG) are used in the model's calculation to include all factors that affect the ship's movement. For more details see section 7.5 Weather condition (wind and current).

7.4 Mathematical Model

Mathematical algebra, geometry and trigonometric calculations have been utilised to develop the collision avoidance model (Croft and Davison, 2003). Vector addition and substitution is plotted on a Cartesian Coordinate system (x,y axis) to find the position and speed of the target ship (Meriam and Kraige, 2007, Meriam and Kraige, 2012). Moreover, the trigonometrical functions implemented to find the course and bearing of the target ship. The following figure explains the formulas used to detect and calculate the collision situation (Figure 55).

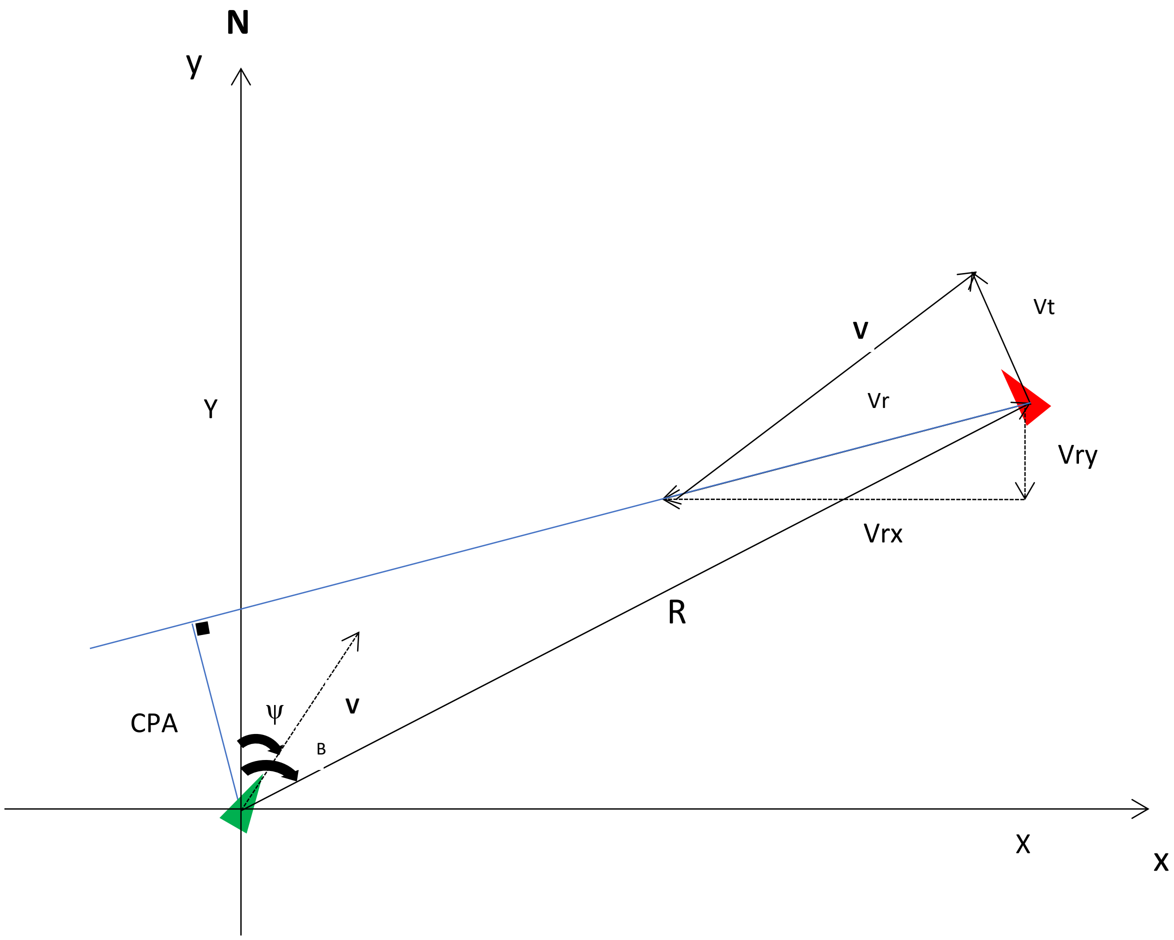


Figure 55 Collision avoidance explanation

- N: True north
- R: Range to target
- Ψ: Own course, (COG)
- CPA: Closest Point of Approach
- V: Own speed, (SOG)
- Vt: Target Speed
- Vr: Relative speed
- Red: Target ship
- Green: Own ship
- B: Bearing to target
- Vrx/Vry: Relative speed component

The following equations have been obtained and driven from Lenart paper, which has been utilised with the geometric and trigonometric calculation, to find the solutions in this model (Lenart, 1999, Croft and Davison, 2003, Stewart, 2011).

Equations (1) and (2) calculate the position of the target on the coordinate system in a given time. Where equations (3) and (4) calculate the target's position as a function of time.

$$X = R \sin B \text{(Eq. 1)}$$

$$Y = R \cos B \text{(Eq. 2)}$$

$$X(t) = X + Vrxt \text{(Eq. 3)}$$

$$Y(t) = Y + Vryt \text{(Eq. 4)}$$

Equations (5) and (6) calculate the own ship speed's component.

$$Vx = V \sin \Psi \text{(Eq. 5)}$$

$$Vy = V \cos \Psi \text{(Eq. 6)}$$

Equations (7) and (8) calculate the target speed's component (tco it the target's true course).

$$Vtx = Vt \sin\,(tco) \text{(Eq. 7)}$$

$$Vty = Vt \cos(tco) \text{(Eq. 8)}$$

Equations (9) and (10) calculate the relative speed component.

$$Vrx = Vtx - Vx \text{(Eq. 9)}$$

$$Vry = Vty - Vy \text{(Eq. 10)}$$

Equation (11) calculates the relative speed to the target ship.

$$r \; = \; \sqrt{Vrx^2 + Vry^2} \text{(Eq. 11)}$$

Equations (15) and (16) calculate the TCPA and DCPA, which are used to evaluate the criticality of the situation and if a collision avoidance manoeuvre is required. The following mathematical method has been used to calculate it. By substituting equations (3) and (4) in equation (12) and then simplify it, equation (13) will be given. Then to find the DCPA, the minimum D (t) must be found by taking the derivative with respect to time as in equation (14). After that, by setting the equation (14) to equal zero, the TCPA will be found from equation (15). Finally, by substituting the TCPA in equation (13) then simplifying it, equation (16) is derived to calculate the DCPA.

$$D(t) = \sqrt{X(t)^2 + Y(t)^2}\text{(Eq. 12)}$$

$$D(t) = \sqrt{R^2 + Vr^2 t + 2t(XVrx + YVry)}\ \text{(Eq. 13)}$$

$$\frac{dD(t)}{dt} = \frac{Vr^2 t + XVrx + YVry}{\sqrt{R^2 + Vr^2 t^2 + 2t(XVrx + YVry)}}\text{(Eq. 14)}$$

$$TCPA = \frac{-(XVrx + YVry)}{Vr^2}\text{(Eq. 15)}$$

$$DCPA = \left|\frac{XVry - YVrx}{Vr}\right|\text{(Eq. 16)}$$

By squaring equation (15) and (16) and reorganising them, the quadratic equation of Vry will be developed in equation (17). After that, solving equation (17) by the quadratic formula the equation (18) will be obtained. From equation (18), equation (19) will be found. By utilising Equations 19 and 20, equation (21) calculates the speed that is required to pass the target ship in the required CPA. This equation provides two speeds to pass in the required CPA (ahead and astern). The two speeds are the result of equation (19), which has two values (+ and -). In order to calculate equation (21), (19) and (20) must be found first.

$$(X^2 - DCPA^2)Vry^2 - 2XYVrxVry + (Y^2 - DCPA^2)Vry^2 = 0\text{(Eq. 17)}$$

$$Vry = AVry\text{(Eq. 18)}$$

$$A = \frac{XY \pm DCPA\sqrt{R^2 - DCPA^2}}{X^2 - DCPA^2}\text{(Eq. 19)}$$

$$B = AVtx - Vty\ \ \text{(Eq. 20)}$$

$$V = \frac{B}{Asin\Psi - \cos\Psi}\text{(Eq. 21)}$$

Equation (22) calculates the course change to pass a target ship in the required CPA. This equation provides up to four courses as a result of the two values of equation (19) and the (+ and -) of the equation itself.

$$\Psi = 2tan^{-1}\left[\frac{-A\,V \pm \sqrt{(A^2+1)V^2 - B^2}}{B - V}\right]\ \text{(Eq. 22)}$$

Equation (25) and (26) calculate the speed and course change to pass the target ship in the required CPA and TCPA. These equations provide two speeds and two courses as a result of the values of equation (19). Equations (23) and (24) must be executed to find (25) and (26).

$$Vx = Vtx + \frac{X + A\,Y}{(A^2+1)TCPA}\text{(Eq. 23)}$$

$$Vy = Vty + \frac{A(X+AY)}{(A^2+1)TCPA} \text{(Eq. 24)}$$

$$V = \sqrt{Vx^2 + Vy^2} \text{(Eq. 25)}$$

$$\Psi = tan^{-1}\frac{Vx}{Vy} \text{(Eq. 26)}$$

7.5 Weather conditions (wind, current)

The wind and current have a significant effect on ships in marine navigation. The wind has a direct effect on the ship's structure above the water line, air draught. Where the current has a direct effect on the underwater part of the ship, ship's draught. According to the significant influence of wind and current on the speed and course of the ship, thus, it is vital to consider these factors in the calculation of collision avoidance. Indeed, adding such factors to the mathematical calculations would add a considerable number of challenges to the model. Also, adding the magnitudes of current and wind to the mathematical calculation will reduce the accuracy of the result, especially if the data itself is not accurate. However, an alternative method has been used to get the better of the situation. The Course Over Ground and Speed Over Ground (COG and SOG) has been used in the calculation rather than the engine speed and the compass course. Where the SOG is a vector quantity (its unit is knots per hour), this considers the direction of movement, which is the COG and the direction is the angle that is measures from the north, refer to Figure 55. Moreover, the COG and SOG are used in the automatic collision avoidance model, this will include the wind and current (drift) effect on the ship's movement. Therefore, it provides the ship's movement with regard to the ground, which includes wind and current effects (the set and drift) that has an impact on the ship sailing path and speed. Additionally, this will improve the accuracy of the collision avoidance results and the reliability of the system (Bowditch, 1995).

7.6 Calculating Delay of Action

Early detection of the threatening target poses a potential danger to the safety of navigation. This is due to the fact that human in general, OOWs in this case, tend to forget or involve in another task, which prevents the OOWs from performing the avoidance action at the best time (Paas et al., 2003a, Sweller, 2016). In addition, early action will divert the ship far from its original track, and it could lead to a conflict situation with another target. Accordingly, an action delay feature has a significant benefit in such a situation (Figure 56). This will inform the OOW about the required action that needs to be taken based on the time limits entered by the user. For example, if the system detects a target in a collision situation after an hour and the OOW sets the actions to be not more than 30 minutes before the collision. In this case, the system will provide the best action to be taken 30 minutes before the collision. Also, it will alert the OOW at the time when this action needs to be taken. This will give the OOW time to evaluate the situation and the action, as well as a reminder at the time of action.

Moreover, this will provide the minimum deviation from the original track, where minimum deviation distance from the original track will maintain a precise Estimated Time of Arrival (ETA). Furthermore, a less travel distance and less fuel consumption will be achieved for less CO2 emission and cleaner ships.

Mathematically, this will be calculated by finding the relative positions of own and target ships and then recalculate the collision avoidance manoeuvre from the new positions. For this critical collision situation, in these calculations, it is assumed that course and speed of both ships are fixed. In case of any change with course and/or speed the model will re-evaluate the situation and provide any required manoeuvre accordingly.

The decision tree for time delay;

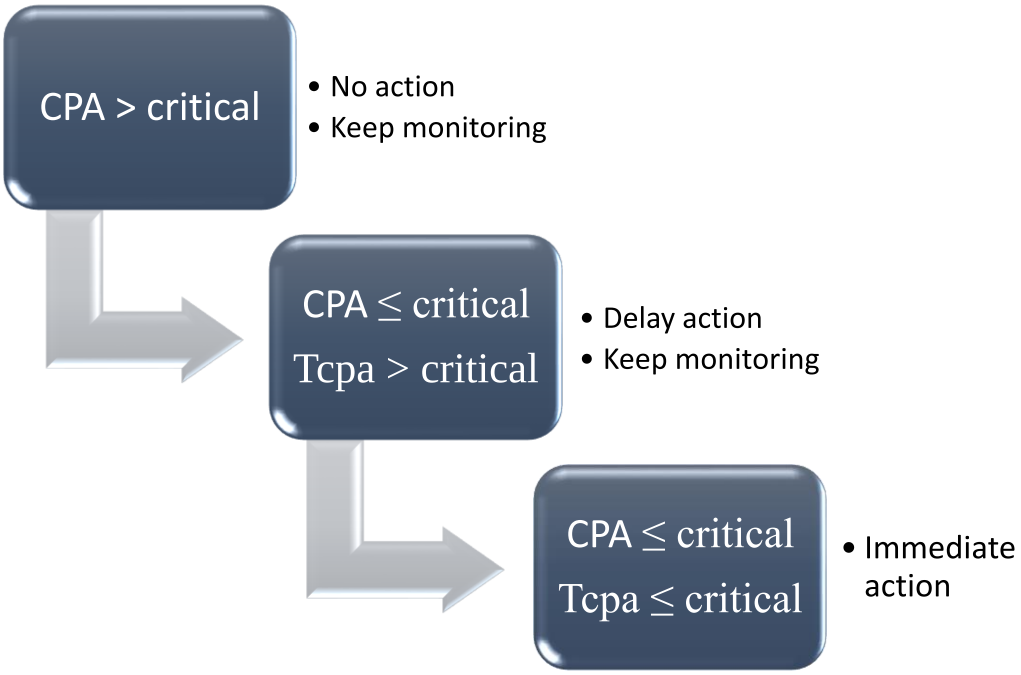


Figure 56 Time delay decision tree

7.7 Avoidance of two targets

Two targets avoidance model has been developed to make sure a comprehensive and reliable decision support system is developed (Figure 57). In a real navigational environment, the number of encountered targets is unpredictable. However, a capable decision support system is required to be able to deal with all targets in the vicinity. In this section, the criteria for the avoidance of two targets are discussed as given in the following section. Figure 58 presents the collision avoidance flow chart, which shows how the system is operating to avoid two targets.

For two targets-avoidance manoeuvres, the same mathematical calculations are used. Additionally, the model calculates the avoidance manoeuvre for the first detected target (T1) and then checks if avoiding (T1) will lead to a conflict situation with the other target (T2). If it is safe and no conflict with (T2) is detected, the system accepts this decision and alert the OOW about it. On the other hand, if avoiding (T1) will cause a dangerous situation with (T2), the system recalculates the avoidance manoeuvre to provide avoidance manoeuvre for (T1 & T2) together. In other words, the system keeps checking all the suggested avoidance manoeuvres to ensure avoiding one target will not lead to a conflict situation with the other one. If the first decision causes a conflict with the other, then the system provides an avoidance manoeuvre for both ships at once.

Two targets encounter scenarios:

- No collision. No action.
- Collision with target one (T1). Manoeuvre to avoid (T1), and not to collide with (T2).
- Collision with target two (T2). Manoeuvre to avoid (T2), and not to collide with (T1).
- Collision with (T1 & T2). Manoeuvre to avoid (T1 & T2).

The decision tree for two targets is given in Figure 57 and Figure 58.

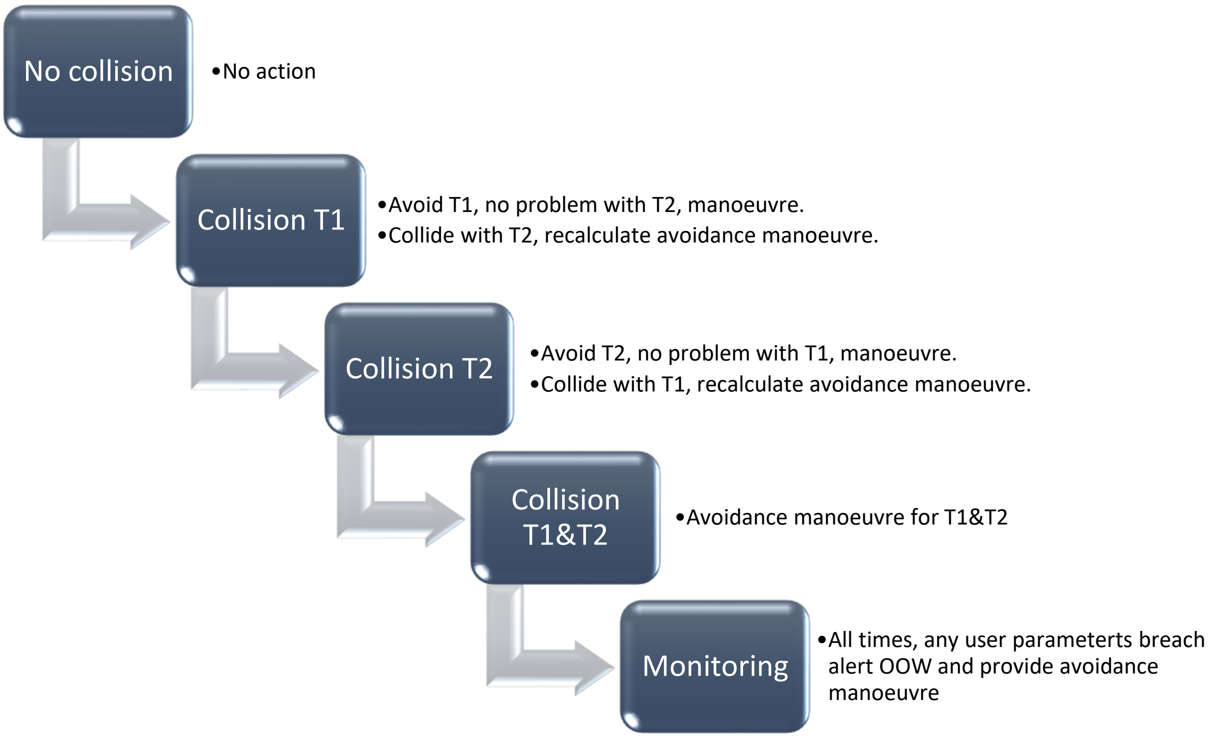


Figure 57 Two targets decision tree

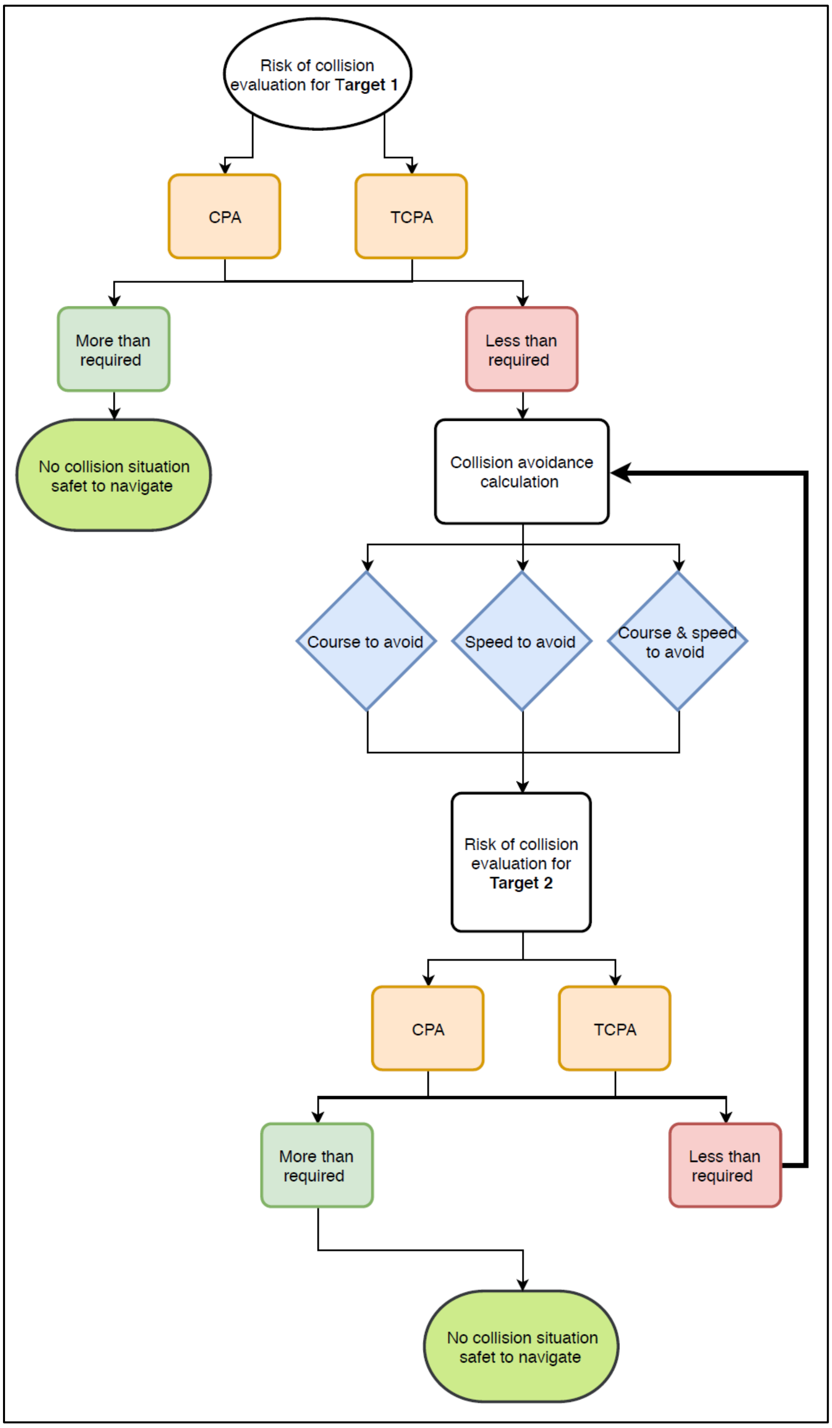


Figure 58 Collision avoidance process for two targets

7.8 Multi-targets

In multi-targets avoidance, the mathematical approach is similar to one target avoidance method. However, in case of a multi-targets encounter, the system must provide an avoidance manoeuvre that is capable of avoiding all targets. Thus, in multi-targets process the system calculates the avoidance manoeuvre to the first detected target. After that, the decision needs to be checked through all other targets in the vicinity to ensure it does not create a conflict situation with any other targets. (Figure 58) shows two target avoidance process, then for multiple targets, the same concept will be used to check all decisions to ensure no collision with any other targets. In order to do this, a script should be written on one of the simulation software, such as Matlab, which has the capability to run a While Loop, which is a command that allows the statement to be repeated until it satisfies all the conditions stated in that situation. This will allow the system to calculate and provides the best avoidance manoeuvre for all targets. However, these While Loop and the calculations of multiple targets collision avoidance have not been implemented in this thesis and it will be considered as a future work of the research. For the feasibility of the results and the calculation, the distance of the search by the system, where collision evaluation and avoidance manoeuvres are considered must be controlled. This will be determined in the sensitivity level sets by the user. The sensitivity level is explained in more detail in Chapter 8.

7.9 COLREG consideration

In international waters, every vessel must comply with international regulations. Likewise, in marine navigation, ships must follow the Collision Regulation (COLREG) all the time. The main aim of COLREG is to regulate ships movement and to prevent collisions from happening. Furthermore, implementing this Rules of the Road (ROR) is beneficial to remove the burden of uncertainty about the actions of other vessels, especially in a collision situation.

According to the above mentioned, the importance of the automatic collision avoidance system to be compliant with the COLREG. From here, a thorough study and analysis of the COLREG regulation have been done to find the best methods that enable the system to provide COLREG's compliance decisions. Following is a discussion about every rule that influences the decision to avoid collision will be mentioned. The rules will be discussed first, and then the implementation of the COLREG regulation in the automatic collision avoidance system will be explained.

Rule 8: Actions to avoid collision (Cockcroft and Lameijer, 2012d)

B) Any action to avoid collision must be large enough to be seen visually or by the radar by other observing vessels. A series of multi small changes are not recommended.

C) Course alteration is the most recommended action to avoid a collision at sea if there is enough sea room to avoid other ships.

Rule 13: Overtaking (Cockcroft and Lameijer, 2012d)

A) The overtaking vessel (coming from the stern) should keep away of the vessel being overtaken (ahead of the approaching vessel).

Rule: 14: Head-on situation (Cockcroft and Lameijer, 2012d)

A) For vessels in a head-on situation (in front of each other), both of them must alter course to the starboard side to allow a port to the port passing situation.

Rule 15: Crossing situation (Cockcroft and Lameijer, 2012d)

In a crossing situation, the vessel sees the other on her starboard side (is the give-way vessel) must tack action to avoid the collision; the vessel sees the other on the port side (is the stand-on vessel) should maintain her course and speed. Crossing ahead of the stand-on vessel must be avoided if it is possible.

Rule 16: Action by give-way vessel (Cockcroft and Lameijer, 2012d)

Take early and sufficient action to avoid collision with the stand-on vessel.

Rule 17: Action by stand-on vessel (Cockcroft and Lameijer, 2012d)

A) i) should keep her course and speed

ii) If the give-way vessel is not taking action or her action alone is not enough to avoid the collision, then the stand-on vessel must avoid the collision by her own actions.

C) When the stand-on vessel is taking action to avoid collision with the give-way vessel, she should avoid altering course to port side, if it is possible.

Rule 19: Conduct of vessels in restricted visibility (Cockcroft and Lameijer, 2012d)

D) i) Avoid course alteration to port side, if possible.

After mentioning the related rules that control the collision avoidance actions in COLREG regulation, the following arrangement has been applied in the automatic collision avoidance system. Such an arrangement allows the automatic collision avoidance system to provide

COLREG complied decisions for collision avoidance manoeuvres. First, the course alteration, which is the favourable action to avoid a collision, if there is enough sea room to manoeuvre, is provided to avoid the collision. Such course alteration will allow the OOW to change to the required course to avoid the collision from the first change, no need for multiple changes. Second, to satisfy rules 14, 15, 16, 17, and 19, the collision avoidance system will always provide the smallest course alteration to the starboard side. This will ensure that the manoeuvres provided are compliance with these rules. Finally, in the overtaking situation, where the port or starboard alterations are acceptable to be clear of the vessel being overtaken, the system provides the smallest course change to avoid the collision. Furthermore, where the speed change is the most favourable action in narrow channels or restricted waters, the automatic collision avoidance system provides a speed change or a combination of speed and small course change to satisfy this condition. By satisfying all these rules and conditions, the developed automatic collision avoidance system has proven its capability to work as an automatic decision support system, which is capable of providing COLREG compliance manoeuvres.

7.10 Ship’s manoeuvring capability

For the feasibility of the system’s results, the ship’s manoeuvring capability need to be considered. This is to confirm that the decisions provided by the system can be executed by the own ship. Additionally, it needs to be checked that the ships do not collide during the turn until it reaches the required course, especially in a critical situation, when the ships are already very close to each other. For the ship’s capability purpose, the manoeuvring data diagrams, which are based on every ship’s sea trials, are used. (Figure 59) shows the turning circle test from a sea trial.

In order to add the ship’s manoeuvring data in the collision avoidance system, the new position of the ship after the turn needs to be calculated; also, the target ship’s new position needs to be calculated. For own ship’s new position, the advance, transfer and time of execution are used from the manoeuvring data.

Advance: is the forward distance from the point of full rudder turn (ABS, 2017).

Transfer: is the side distance from the point of full rudder turn (ABS, 2017).

For target ship’s new position, the speed and time are used to find the new position, with the assumption of no change in the speed and course. After calculating own and target ships’ new position, the range between the own ship and the target ship is used to evaluate the capability of own ship to execute the avoidance manoeuvre and not to collide during the turn.

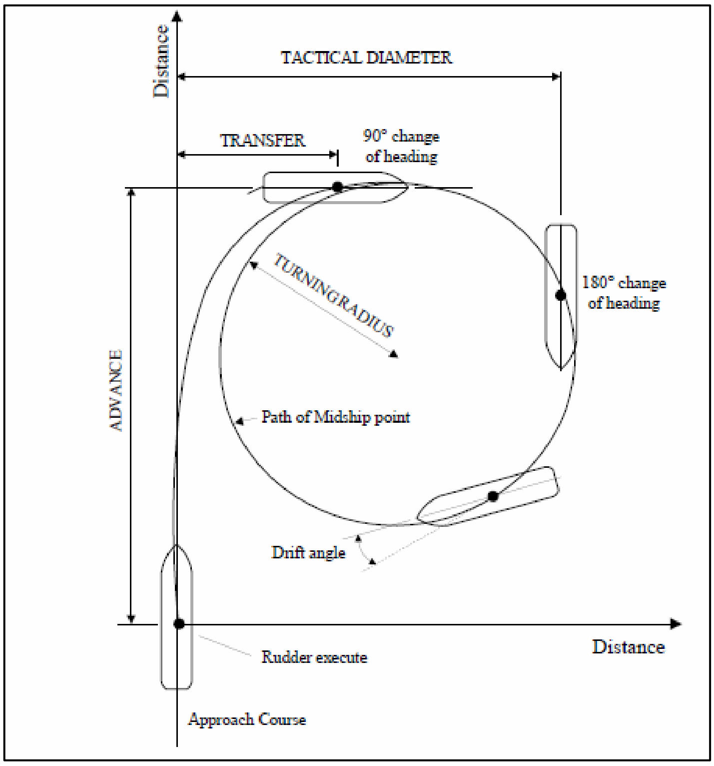


Figure 59 Turning circle sea trial (ABS, 2017)

7.11 Numerical validation of the Model (Desk Validation)

After developing the model, an essential validation process is necessary to ensure a satisfactory level of operation is achieved. The main aim of this validation tests is to prove the correctness of the calculations, which are made by automatic collision avoidance model. Thus, the following validation tests will examine the model's calculations of the course changes and its effect on the CPA, the accuracy of calculating the CPA's distance and the reliability of the provided avoidance actions. The results of the model calculation have to be validated in many ways and scenarios to confirm acceptable and reasonable decisions can be reached by utilising the model. For the validation techniques, four methods have been used in this model to confirm the satisfaction of the calculations and results. Three cases have been tested using the model, which covers the entire collision situation at sea, Crossing, Head-on and over-taking situations. The validation techniques are:

- Manual radar plotting.
- Trend capturing by fixed course changes (10° course changes).
- Real case scenarios from the Marine Traffic AIS web page.
- Real collision scenario from MAIB, with real scales.

7.11.1 Manual radar plotting

First, the traditional technique of manual radar plotting has been used to calculate the CPA and TCPA. After that, the comparison of the results that have been obtained from both the model and the manual plotting results is made and it confirms the same outcome. This finding confirms the correctness of the formulas used to develop the model and ensures that the calculations provide correct solutions to collision avoidance problems at sea.

7.11.2 Trend capture

Second, the trend of the model's results captured by applying a number of course changes in the same direction and magnitude to record the results' trend. Due to the requirement of the COLREG in the course and speed changes, course change must be significant and easily recognised for visual and radar observers (Cockcroft and Lameijer, 2012d). To satisfy this condition, a change of 10° has been frequently applied to the initial ship's course. Usually, a course change of 30° to 60° degrees is enough to avoid a collision. Overall, 12-course changes are applied to the initial ship's course to ensure that the model will always increase the CPA distance when a course change is applied. Also, the suggested course change by the model, to pass within the required CPA, has been applied in the curve to compare it with the model trend.

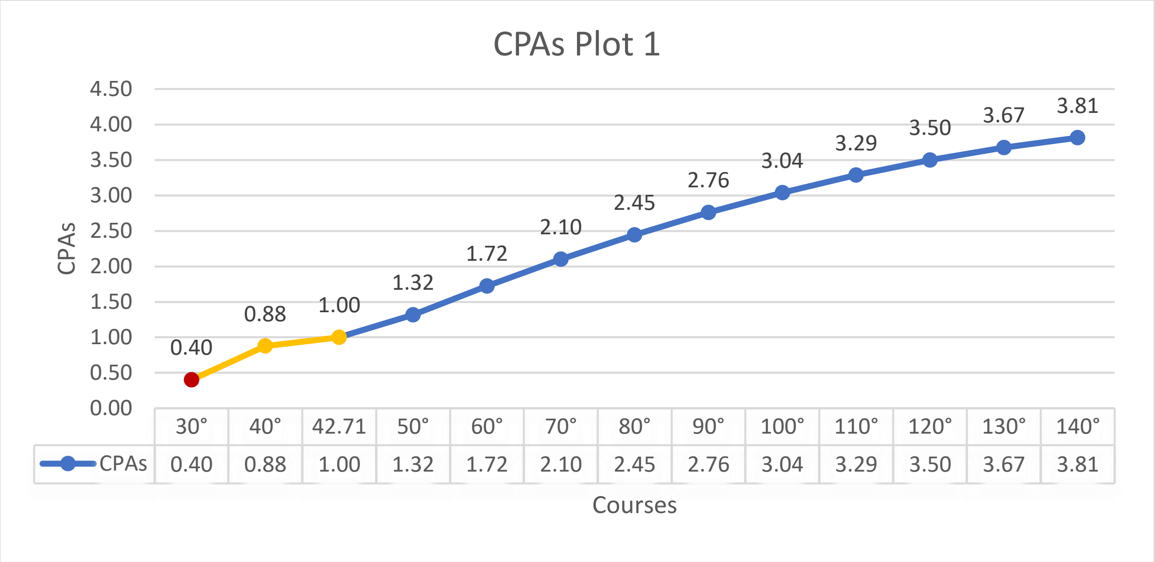
In this validation method, three scenarios have been tested to obtain the results. In these three cases, the automatic collision avoidance model was capable of providing a reliable result, which indicates a promising operation of the model. The basic concept of this test is to prove that with the increase of the ship's course magnitude, in the opposite direction of the target ship, the CPA will increase continuously. In other words, these tests show a positive correlation between the changes of course and the CPA, which indicate that with the increase of course change the ship will pass in more distance from the target ship. Accordingly, the three scenarios that have been tested in this validation method have shown a linear increase in the CPA with the increase in course change. Next is a brief explanation of each curve for the three cases of collision avoidance.

Case one: Crossing situation

Table 12 Table of parameters for case one

Own ship parameters	**Target ship parameters**	**Relative parameters observed from own ship**
Speed 20 Knots	Speed 15 Knots	Bearing to target 068°
Course 030°	Course 321°	Range to target 4 NM

In case one, the collision situation is crossing, where the own ship is the give-way vessel, and it is required to take the avoidance action. The target is the stand-on the vessel and should maintain her course and speed. The initial course of the own ship is 030°, the model's decision to pass target ship within 1 NM is to change course to 043°, which is a starboard turn, and this satisfies COLREG regulation in this situation. Moreover, by changing the course 10° to starboard side up to 140°, the CPA has continuously increased. (Figure 60) shows the linear increase in the CPA with every 10° change in course and a positive correlation between the variables. The yellow part in the curve denotes the model's decision to pass 1 NM from the target ship.



	30°	40°	42.71	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°
CPAs	0.40	0.88	1.00	1.32	1.72	2.10	2.45	2.76	3.04	3.29	3.50	3.67	3.81

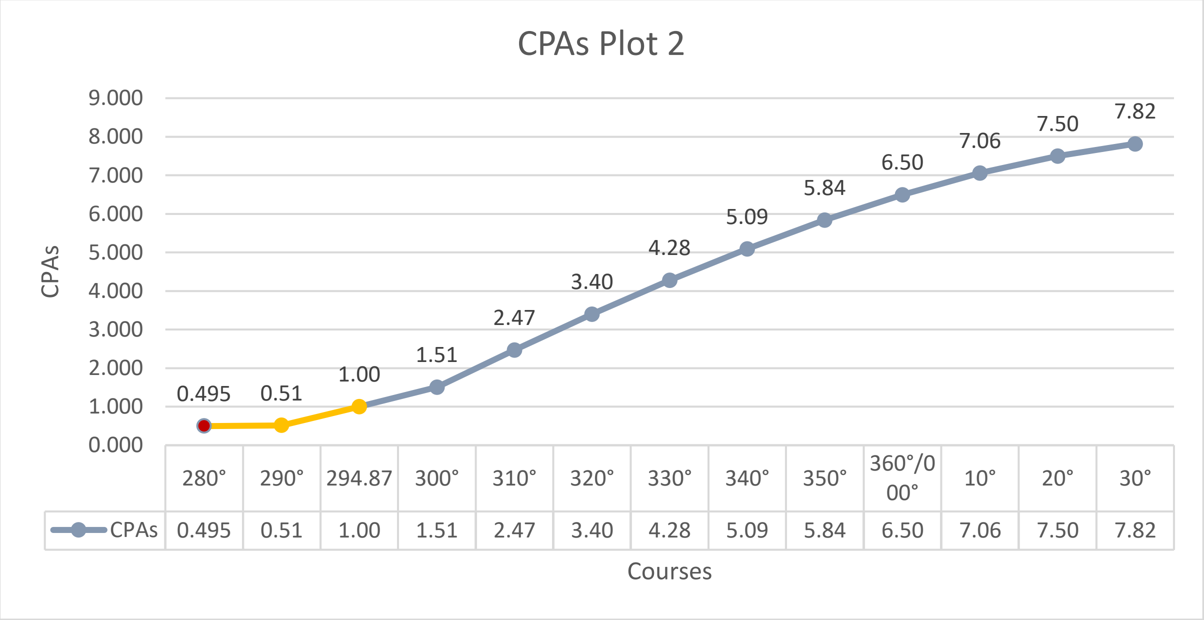
Figure 60 CPA plot case 1

Case two: Head-on situation

Table 13 Table of parameters for case two

Own ship parameters	**Target ship parameters**	**Relative parameters observed from own ship**
Speed 15 Knots	Speed 6 Knots	Bearing to target 292°
Course 280°	Course 130°	Range to target 8 NM

In case two, a head-on situation, where both ships must alter course to the starboard side. The model's decision to pass the target 1 NM is to alter course to 295°, which is the COLREG compliant avoidance manoeuvre by altering to the starboard side. This is denoted by the yellow part in the curve. In this case, the own ship was on the starboard side of the target. Thus, this explains the reason why the CPA in the first 10° course change to starboard has not increased; then once the own ship crossed the bow of the target, the CPA started to increase steadily. Figure 61 shows the positive correlation and linear increase in CPA with course changes.



	280°	290°	294.87	300°	310°	320°	330°	340°	350°	360°/000°	10°	20°	30°
CPAs	0.495	0.51	1.00	1.51	2.47	3.40	4.28	5.09	5.84	6.50	7.06	7.50	7.82

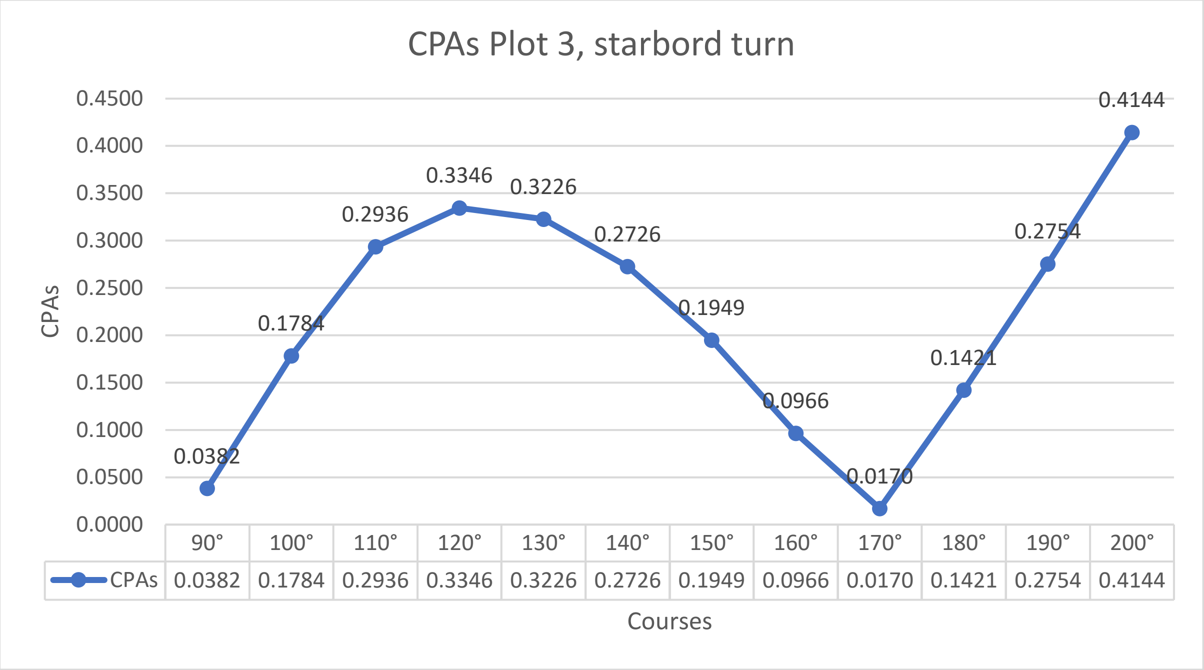
Figure 61 CPA plot case 2

Case Three: Over-taking situation

Table 14 Table of parameters for case three

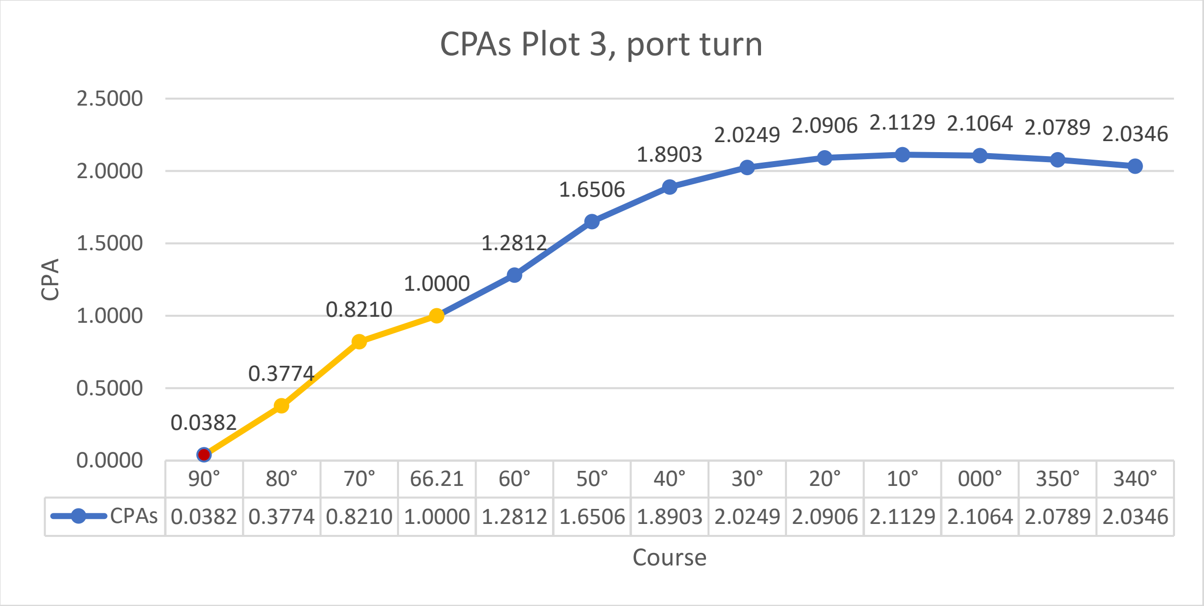
Own ship parameters	**Target ship parameters**	**Relative parameters observed from own ship**
Speed 12 Knots	Speed 22.2 Knots	Bearing to target 220°
Course 090°	Course 065°	Range to target 2.5 NM

In case three, an over-taking situation, where the ship being over-taken (in front) should not impede the over-taking ship (coming from back). The over-taking vessel should keep clear of the overtaken vessel (in front). In this case own ship should not change her course and speed, and the target ship is the give-way vessel. The model has been tested in this scenario to examine its ability to provide avoidance manoeuvre in all situations. Furthermore, if the give-way ship is not taking action, then the stand-on vessel must take the best action to avoid the collision, as per COLREG regulation. In this scenario, with the starboard turn the CPA has increased up to a small distance, then it started to become closer with each starboard course change. The first increase happened as the ship is moving away from the target ship to the starboard side until it reaches the maximum CPA. Then the collision situation changes from over-taking to the head-on situation, and the CPA stares to decrease again to a collision situation on course 170°. After passing course 170° the CPA increases in a constant trend, (Figure 62) shows the curve of the manoeuvre. However, this is unacceptable behaviour to avoid a collision at sea, especially when the avoidance manoeuvre leads to a change in the collision situation. On the other hand, port course alteration would lead to safe avoidance manoeuvre if the stand-on vessels had to escape a dangerous situation. (Figure 63) shows the curve of port side manoeuvre with a constant linear increase in the CPA and the suggested course to pass in 1 NM from the target ship and the positive correlation between the course change and CPA distance.



	90°	100°	110°	120°	130°	140°	150°	160°	170°	180°	190°	200°
CPAs	0.0382	0.1784	0.2936	0.3346	0.3226	0.2726	0.1949	0.0966	0.0170	0.1421	0.2754	0.4144

Figure 62 CPA plot case 3, turn to starboard



	90°	80°	70°	66.21	60°	50°	40°	30°	20°	10°	000°	350°	340°
CPAs	0.0382	0.3774	0.8210	1.0000	1.2812	1.6506	1.8903	2.0249	2.0906	2.1129	2.1064	2.0789	2.0346

Figure 63 CPA plot case 3, turn to port

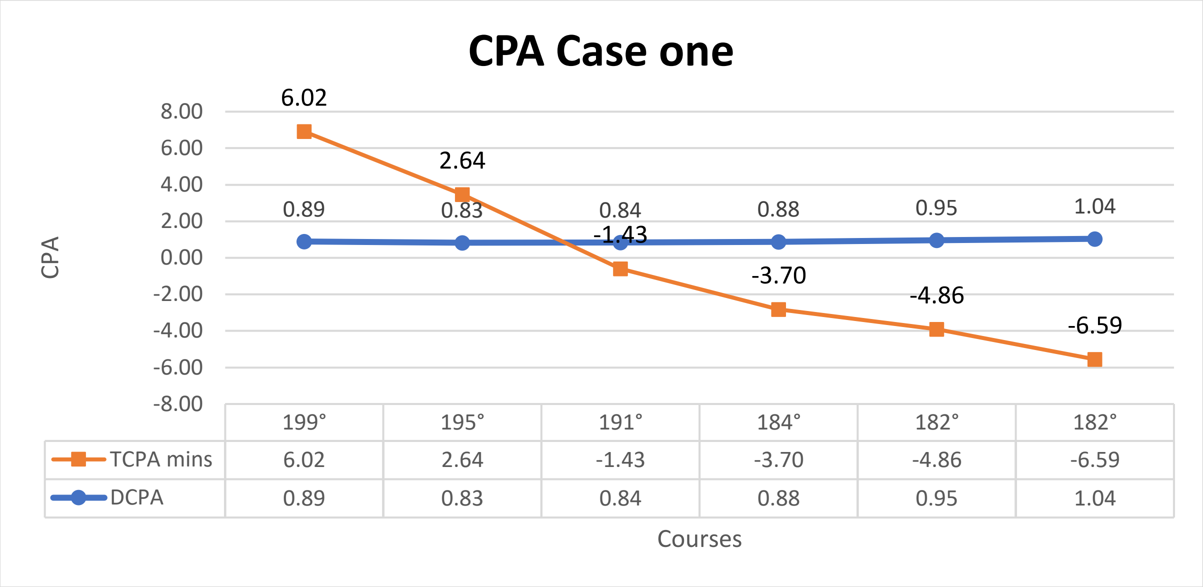
7.11.3 Real case scenarios

Collecting real-life data and implementing it on the model shows the capabilities and feasibility of the model to be utilised in real collision situations. For this validation technique, live monitoring had to be performed to collect a real data of ships which are passing in near-collision situations; data had been collected from the Marine Traffic AIS website (MarineTraffic, 2019). Three cases had been successively monitored, and the data had been collected. First, depending on the case, the own and target ships had been chosen from the Marine Traffic AIS website, and then their parameters were plotted for a period of time (depending on the updating time on the website). The data was collected from the website are the speed and course for own and target ships, and the bearing and range from the own ship to the target ship. After plotting the parameters, it has been applied in the model to see the changes in CPAs and TCPAs.

The aim of this validation method is to test the accuracy of the model's calculation for the CPA and TCPA. This will be achieved by the calculation of the CPA and TCPA for a period of time and analyse the results to capture their changes with the progress of the ships. However, in these scenarios, there was no collision between the ships, but they were sailing close to each other and this has been reflected on the result, which has not shown a significant change in the CPA's distance until the ships started to move away from each other. Knowing that the negative results for the TCPA mean the ships have passed each other and this is the moment where the CPA distance starts to increase. Thus, this behaviour of the results was the trend for the three scenarios and follows the discussion of the scenarios and their results in more details.

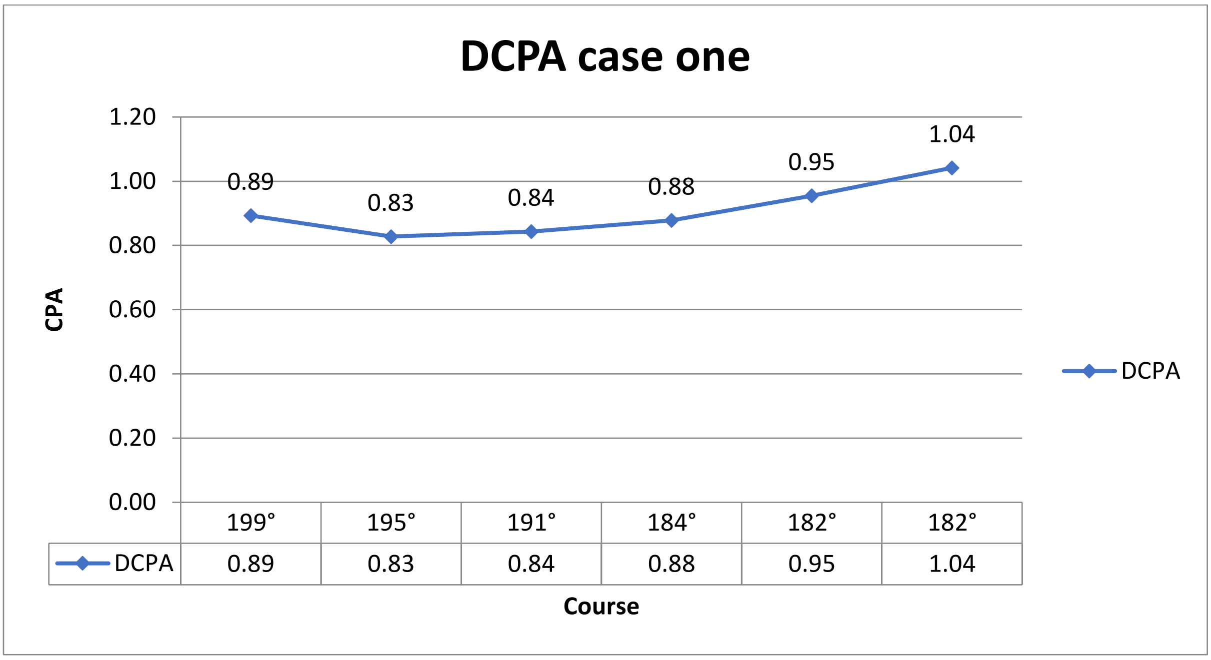
Case one: Crossing situation

This is a crossing situation between a container ship MSC Luciana and RO-RO ship Suecia Seaways. (Figures 64 and 65) show the changes in CPAs and TCPAs from the plotted data. In (Figure 64), the CPA and TCPA are plotted, the blue line shows small changes in the CPA as no avoidance manoeuvre had been taken. The orange line shows the changes in the TCPA; the negative values mean the ships have passed the CPA.



	199°	195°	191°	184°	182°	182°
TCPA mins	6.02	2.64	-1.43	-3.70	-4.86	-6.59
DCPA	0.89	0.83	0.84	0.88	0.95	1.04

Figure 64 CPA and TCPA changes case one



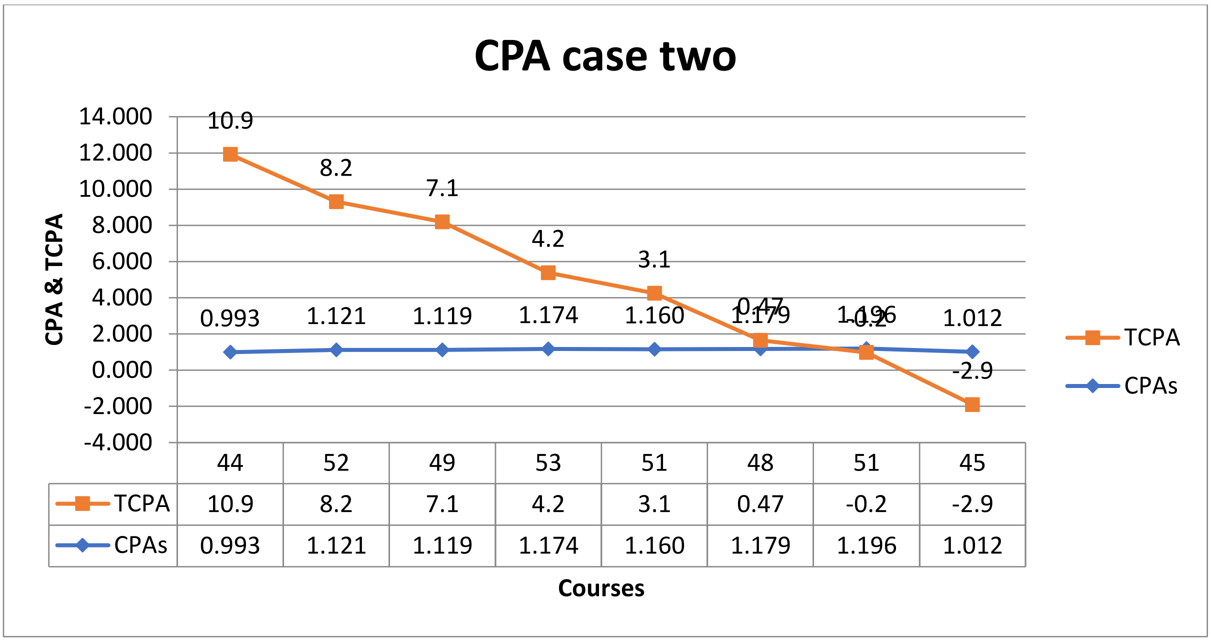
	199°	195°	191°	184°	182°	182°
DCPA	0.89	0.83	0.84	0.88	0.95	1.04

Figure 65 CPAs case one

Case two: Crossing Situation

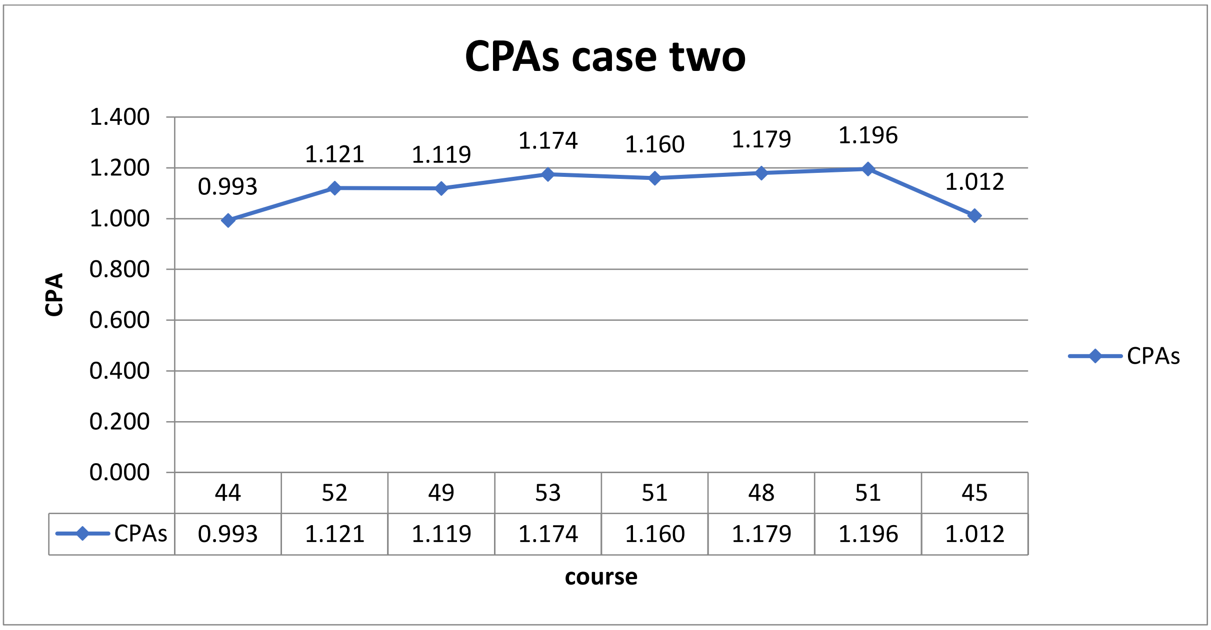
This is a crossing situation between the LPG tanker Alphagas and the RO-RO ship Spirit of Britain. After plotting their data on the model, curves of the change in the CPAs and TCPAs were created (Figures 66 and 67). These results show that the CPA distance was not changing significantly until the ships passed each other, where the CPA distance started to increase.

Also, the results depict the intention of the ships to maintain the CPA at 1 NM and not to come closer from each other.



	44	52	49	53	51	48	51	45
TCPA	10.9	8.2	7.1	4.2	3.1	0.47	-0.2	-2.9
CPAs	0.993	1.121	1.119	1.174	1.160	1.179	1.196	1.012

Figure 66 CPA and TCPA case two

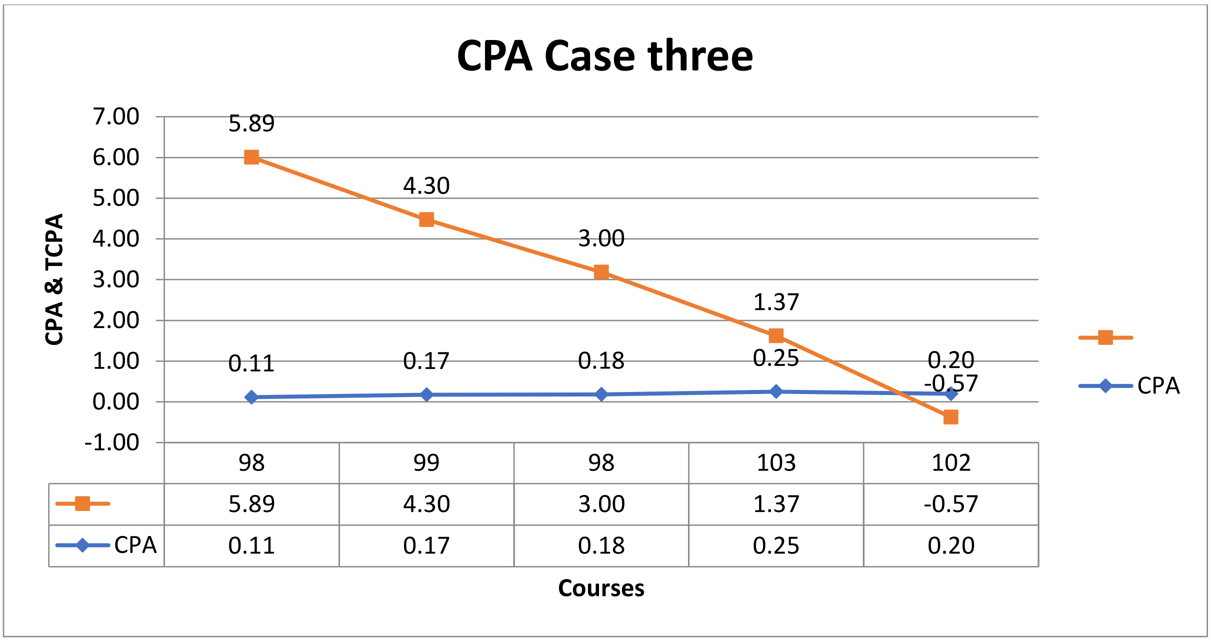


	44	52	49	53	51	48	51	45
CPAs	0.993	1.121	1.119	1.174	1.160	1.179	1.196	1.012

Figure 67 CPA case two

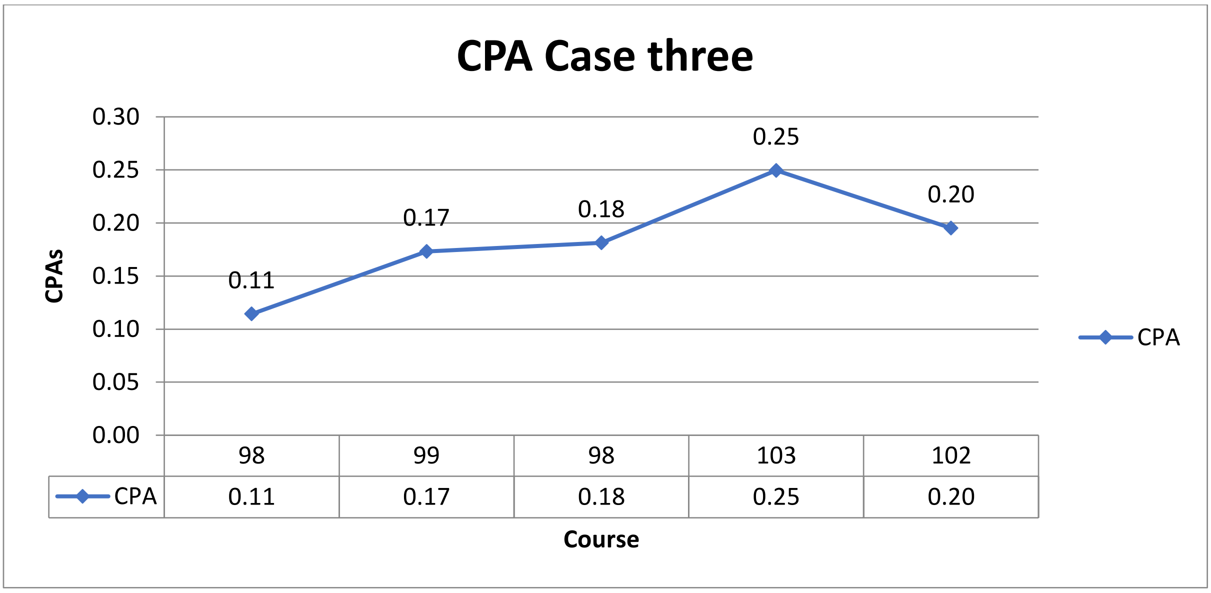
Case three: Head-on situation

This is a case of head-on situation between the tanker ships Hafnia Green and the bulk carrier Genco Warrior in a narrow channel. (Figures 68 and 69) show the changes in CPAs and TCPAs, which have been plotted from the Marine Traffic AIS website.



Courses	98	99	98	103	102
🟧	5.89	4.30	3.00	1.37	-0.57
CPA	0.11	0.17	0.18	0.25	0.20

Figure 68 CPA AND TCPA CASE THREE



Course	98	99	98	103	102
CPA	0.11	0.17	0.18	0.25	0.20

Figure 69 CPA three

The previous cases and their curves have shown reliable data regarding the changes in the CPA and TCPA for the cases that have been monitored in the Marine Traffic AIS. This shows good validation results that prove the credibility of the model in solving real collision situation. This has been observed by monitoring the results of the CPAs’ distances and how it shows a steady result, which depicts the normal behaviour of ships in such close-passing situations. Moreover, the fluctuation in the curves in the previous live data plots is due to the inaccuracy of data collected from the Marine Traffic AIS and the delay in the updating time for ships parameters. However, these curves still show credible and trustworthy results and trends for the changes in the CPAs and TCPAs of live navigating ships.

7.11.4 Real collision scenario from MAIB, with real scales

This validation tests a real collision scenario that has been adopted from the Marine Accident Investigation Report (MAIB) (MAIB, 2013). This scenario tests the usability and reliability of the model to observe its performance in a real collision situation. The navigational details of this collision situation have been taken from the investigation report and it was plotted on the radar manual plotting sheet in real distances scale Figure 70. After plotting the collision situation, the information has been used in the developed collision avoidance model to validate and examine its performance in a real collision situation. Then, the avoidance manoeuvres and decisions that have been provided by the model has been plotted on the manual plotting sheet. This shows the decisions of the collision avoidance model and how it reacts to the changes in the navigational situation. In (Figure 70) the own ship (Hyundai Discovery) is located in the centre of the plotting sheet and its movement is indicated by the blue arrows. The green arrow indicates the best action to avoid the collision, which has been provided by the collision avoidance model. The red arrows indicate the target ship (ACX Hibiscus). After the course change of own vessel, the collision avoidance model recalculated the avoidance manoeuvre and provided the best action to avoid the collision in this situation. The orange arrow is the new avoidance decision. With the change in ships’ courses, the model keeps calculating the avoidance manoeuvres which are required to avoid the collision. In this scenario, the collision avoidance model has provided an avoidance manoeuvre two minutes before the collision. At this time, the range to target ship was 1.6 NM, and the CPA was 0.19 NM, but the model was capable of providing an action to avoid the collision. This scenario proves the reliability and capability of the collision avoidance model to provide an avoidance decision for the real case, as well as providing decisions as the situation progresses. Indeed, the collision situation should not have developed to this very critical stage, if the collision avoidance model has been utilised on this ship. The model is capable of detecting collisions and providing avoidance decisions in early-stage and before it is too critical. However, if the situation has deteriorated, the model is still able to avoid imminent collisions. All the navigational information related to this scenario and the model decisions are provided in (Table 15).

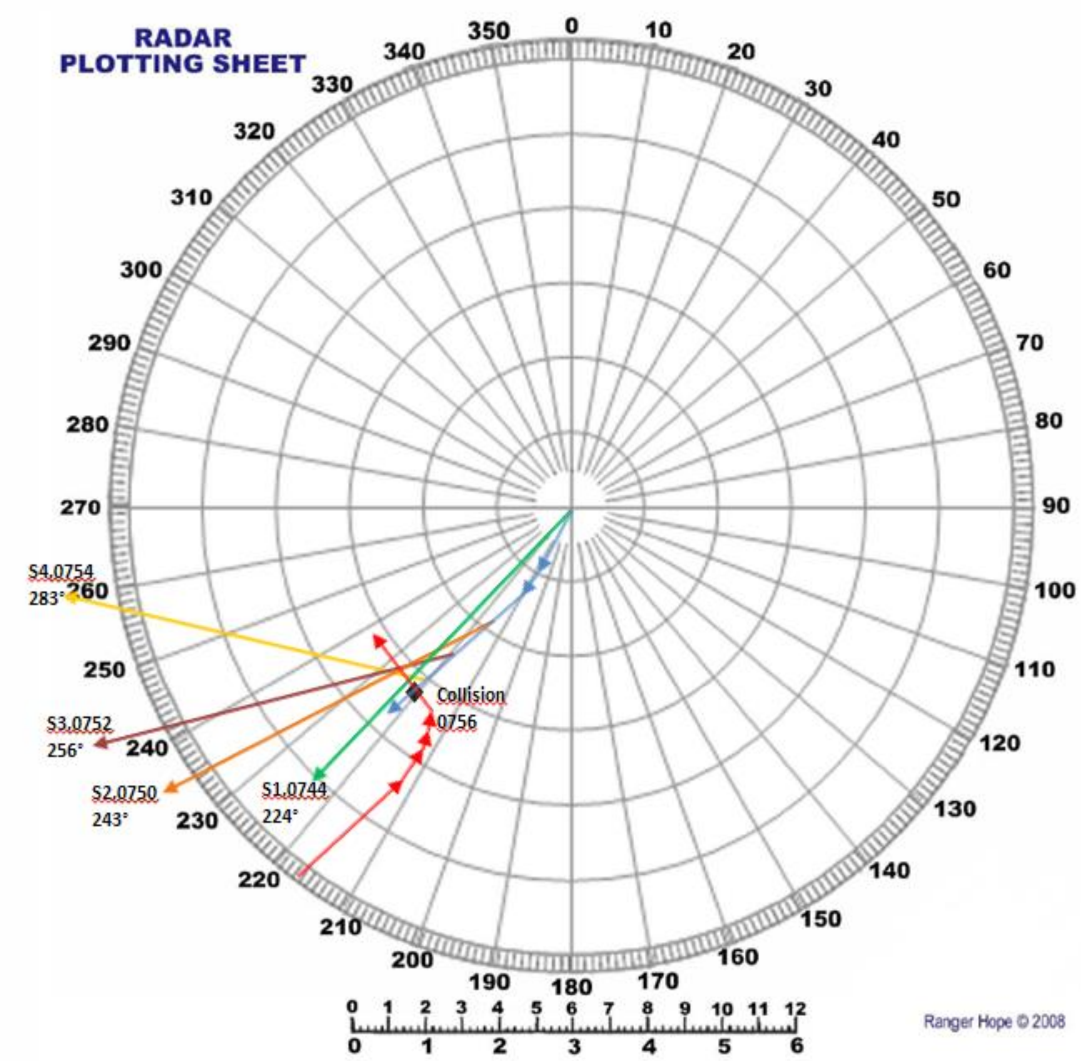


Figure 70 Collision scenario between own ship (Hyundai Discovery) and target ship (ACX Hibiscus).

Table 15 Table of parameters for the collision situation between Hyundai Discovery and ACX Hibiscus

	own ship - Hyundai Discovery				**Target ship - ACX Hibiscus**				**Avoidance decisions**							
time	**Speed in knots**	**course**	**bearing**	**range**	**Speed in knots**	**course**	**CPA**	**TCPA in minutes**	**SP 1 in knots**	**SP2 in knots**	**Co1**	**Co2**	**Co3**	**Co4**	**SP2 in knots**	**Co2 in knots**
744	18	209 °	217°	6.1 NM	14.5	49°	0.09 NM	11.4	211	2	190°	45°	224°	48°	2.5	61
747	18	216°	225°	5.5 NM	14.5	49°	0.3 NM	10	-140	-5	203°	46°	241°	50°	3.9	31
748	18	229°	225°	4.9 NM	14.5	49°	0.3 NM	9	-14.5	-14.5	201°	46°	243°	51°	5	34
750	18	229°	219°	3.5 NM	14.1	49°	0.6 NM	6	-14.1	-14.1	182°	43°	241°	50°	7.4	43
752	18	229°	216°	2.7 NM	14.1	34°	0.3 NM	5	-8	-37	179°	30°	256°	39°	9.7	22
754	18	229°	208°	1.6 NM	14.1	17°	0.19 NM	3	-7.5	-35	11°	148°	283°	30°	12.6	8
755	18	229°	198°	0.2 NM	14.1	10°	0.04 NM	0.3								
756	18	229°	198°	0 NM	14.1	321°	0 NM	0								

7.12 Chapter summary

In this chapter, the mathematical model and calculations methods have been explained together with formulas and their utilisations in the collision avoidance model to solve ship collision situation problems. Furthermore, it indicates the required information that is needed to do the calculations with its description. Besides this, an explanation of the model results has been done to facilitate its interpretation. After this, validation tests have been performed on the model to ensure that correct and feasible results are being provided. The validation tests have been completed in three approaches;

- First, with constant changes in own ship's course to capture the behaviour of the model in such changes. Obviously, this should provide a liner change in the CPA, and that was the case, which proved the integrity of the model.

- Second, it is the validation using real ships date in real-time; this was done through the Marine Traffic website. This test shows a very promising implementation of the model as a decision support system for ships.

- Third, it is the reliability of detecting the risk of collision and the calculated avoidance actions, which was elaborated in the manual radar plotting sheet.

The successful completion of these Desk Validation has proven the accuracy and reliability of the model's calculations, which has been discussed earlier. These validation results have provided an optimistic overview of the developed automatic collision avoidance system, which was tested in various approaches to make sure that the system is trustworthy in a critical situation. The model was accurate for calculating the CPA with the changes in the ship course, which was captured in course changing test and provided linear results with a positive correlation between the course change and CPA. Moreover, the accuracy of the CPA and TCPA calculation were tested by the real case scenarios from the MarineTraffic website and this shows the integrity of the results, which provided consistent results between the CPA and TCPA changes, as well as a corresponded with what is expected at real navigational situations. The response of the system for the collision situation was tested using the MAIB collision report. In this test, the system was capable of providing collision avoidance action at several times, even with the changes in own and target ships courses. With these efficient results, the developed automatic collision avoidance system has a great potential to play a significant role to enhance maritime safety by supporting the OOW in the navigational duties and the collision avoidance procedures.

The ship’s manoeuvring capability have been included in the model to ensure feasible manoeuvres are given by the automatic system. Likewise, feasible decisions are required. Also, COLREG compliance decisions are crucial. Thus, the model’s decisions have shown consistent outcomes that satisfy all the regulations.

8 Validation experiment for the developed Automatic Collision Avoidance Model in full-mission ship's navigational bridge simulator

8.1 Introduction

In this chapter, the developed Collision Avoidance Model will be tested in full-mission ship navigational bridge simulator. For testing procedures, real collision scenarios will be utilised in the simulator environment. These scenarios are obtained from the Maritime Accidents Investigation Branch (MAIB), the United Kingdom governmental organisation, which is authorised to investigate maritime accidents.

In this experiment, full consideration has been taken to scrutinise and harmonise the concept of the developed Automatic Collision Avoidance System and the collision avoidance procedures within the navigational duties. This includes the feasibility of implementing such a system on-board ship. Moreover, it is to confirm the efficiency and usability of the system within the navigational duties and bridge's procedures to test that the system works correctly and accurately in an emergency collision situation. This will be concluded by the enhancement in the navigational safety that would have been achieved if this system is installed on-board ships.

The outcome of the experiment will be analysed qualitatively by explaining the effect of implementing the Automatic Collision Avoidance system in each scenario in comparison to the *classical approach* of navigational duties in the same scenario. Furthermore, a quantitative analysis will be done to measure the navigational performance of participants (Seafarers) against the Key Performance Indicators (KPIs) for the classical collision avoidance approach and the automatic collision avoidance approach.

The discussion and recommendation will take place at the end of this chapter to provide a sort of a guideline that clearly explains the best practices of implementing the developed Automatic Collision Avoidance system.

8.2 The validation experiments procedures

The validation experiments have been performed to justify and ensure the best operational level of the developed Automatic Collision Avoidance system in real ships. These validation processes have been executed in the full-mission ship navigational bridge simulator. The PhD candidate has got the approval to visit the King Abdulaziz University, to perform the experiment in the maritime simulator centre.

The experiment's protocol has been approved by the Architecture Department Ethics Committee and obtained the approval number: (DE19/05) and titled as: "Experiments in Full Mission Ship Bridge Simulator to measure the navigational performance of Deck officers".

8.2.1 The full-mission ship navigational bridge simulator at the Faculty of Maritime Studies FMS

At King Abdulaziz University, the Faculty of Maritime Studies (FMS), in Jeddah, Saudi Arabia, they have maritime commercial training solutions for the advanced level of maritime training. With the Full-Mission Ship Bridge Simulator 270 HFOV facilities (TRANSAS Navi-Trainer 5000), the faculty is capable of running an advanced level of ship bridge simulator training, as well as standard training requirements. The advanced level of simulator capabilities includes specific training scenarios with real imitation of the vessels, layouts and equipment. Whereas in standard training, a generic model of vessels and maritime equipment are utilised for better familiarisation to the new seafarer trainees about the navigational bridge. The available simulator facilities meet the bridgemanship and navigation training requirements and objectives. These simulator facilities comply with the IMO standards, and it has the Det Norske Veritas (DNV) statement of compliance certificate. Figure 71 shows the navigational bridge simulator at the simulator centre in FMS.

To control the simulator scenario, the instructor control station for the simulator training, where exercises are developed, arranged and modified with full control over the training scenario. This allows full monitoring over own ship, target vessels and its information and parameters, either, in the graphical or tabular presentation of the data. Furthermore, the instructor has full control over the own and target ships, such as; changing courses, speed and positions of any ship. Also, the playback function is available to assess the instructor in the debriefing sessions and for performance monitoring and enhancement. Thus, all the information and parameters of the exercise are recorded and saved. This exercise's recorded data can be presented as a graphical or tabular report.

Additionally, it can be transferred to MS Excel sheet for further analysis and examination. The exercise data recorded reports includes the following areas of ships' information;

- Ship's motion parameters.
- The dynamic movement of the ship.
- Ship's manoeuvrability; speed, course, and rudder angle.
- Target ships' parameters.
- Target ships' manoeuvrability.

Figure 71 The Navigational bridge simulator at FMS

8.2.2 Experiment procedures

For the purposes of this research, the navigational simulator has great benefits for the validation of the Automatic Collision Avoidance model and to build up the collision scenarios and case studies. In general, the fundamental concept of the experiment is to run a collision scenario twice in the simulator.

- In the first exercise, the OOW performs normal navigational duties and collision avoidance procedures (*Classical Approach*).
- In the second exercise, the OOW is trained to utilise the developed Automatic Collision Avoidance model, in case of collision situation (*Automatic Approach*).

The performance of the OOWs and the navigational parameters are measured in both exercises to quantify the differences between the *classical approach* and the *automatic approach*. In this experiment, four phases process were performed to execute the scenarios to validating the developed Automatic Collision Avoidance system, as follows;

- Phase one: General familiarisation about the ship bridge simulator.
- Phase two: the experiments and scenarios.
- Phase three: Data collection.
- Phase four: Data analysis.

8.2.2.1 Phase one: General familiarisation about the ship bridge simulator

Simulator familiarisation

In the beginning, it was a general familiarisation about the simulator centre and the operational procedures of the simulator. This step includes a brief introduction, by staff members of the simulator centre, about the simulator's functions and utilisation. After this, full access to the simulator has been granted. This allowed the author to intensively practise the operation of the simulator, and scenarios creation techniques. Moreover, a review of the validation experiments plan was done in this stage, to ensure the suitability and feasibility of the proposed plan to be performed. Fortunately, the proposed plan for the experiments was matching with the capabilities of the simulator, with some changes that will be mentioned later in the limitation section.

Creation of the Scenarios

For these experiments, eight collision scenarios were developed and performed; these scenarios are adopted from the Marine Accident Investigation Branch (MAIB) reports. These collision scenarios have been utilised to develop the automatic collision avoidance system, in the earlier stage of the research, and they are the most suitable scenarios to test the developed system. Also, they cover all the collision situations at sea, head-on, crossing and overtaking situations. These exercises were constructed, based on the information and details from the accident reports, and saved on the simulator's database. This step is to ensure the smooth running of the experiment on the day of the exercise. For the limitation of available areas and locations on the simulator database, alternative locations were used for the construction of the scenarios, mainly open sea. Generally, the main features and impacting factors were carefully considered to match with the real scenarios from MAIB, such as TTS, limited sea room, shallow waters, navigational instruction, weather condition, etc. these scenarios will be mentioned in the results section with a full description of each scenario.

Data records and reports

A familiarisation about the data records and exercise reports have taken place in this phase. The importance of this step lies in the highlights of the required data and information that need to be collected from scenarios. This step will guarantee the availability of all required data and reports for every exercise, which allows further analysis to be carried out afterwards. For this purpose, the most useful and valuable source of information and parameters are the report generation and the diagrams related to the ship motion parameters. The report generation feature allows the instructor to create a various number of reports about the performance of the exercise. The required reports, which have been collected and all the needed data for this experiment are;

- The ship dynamics report, this has the motion parameters of the ship.
- The log report, this has the extended list of motion and external parameters, such as wind speed and the side movement of the ship.
- The traffic reports, this has the target ship motions and parameters.

Additionally, the diagrams of the ship motion parameters will be utilised, to help the instructor, who can monitor the selected parameters and see how it changes during the course of the exercise. In the window, which shows the diagram, the instructor can choose any parameters that he/she would like to monitor in a graphical or tabular mode. For these simulator tests, the following data are selected;

- The Closest Point of Approach (CPA).
- The Time to Closest Point of Approach (TCPA).

Exercises briefing documents

Three briefing documents were developed and distributed to all the participants about the simulator experiments.

- General briefing about the experiment.
- Briefing paper for the group about the classical collision avoidance approach.
- Briefing paper for the group about the automatic collision avoidance approach.

The briefing papers are available in the appendix section.

8.2.2.2 Phase two: the participants, experiments and scenarios

Two experimental methods were performed in the simulator with different scenarios. The participants in these experiments were all from the Faculty of Maritime Studies FMS students and recently graduated seafarers.

The participants and scenarios

For the successful conduction of the navigational simulator experiment, the participants should be selected carefully to ensure their adequate background and knowledge of the maritime navigational procedures. To identify the participants in these experiments a selection criterion has been created. Every participant should fulfill these criteria to participate in this experiment.

The required criteria for identifying and selecting the participants in the experiment:

- All the participants should have a nautical background and navigational experience, OOW qualification.

- All the participants should be in their final year of study in the nautical science department.
- All the participants should have done a minimum of six months sea training.
- All the participants should have been trained in the maritime simulator for the navigational procedures.

The participants were either freshly graduated or in the final year, who finished their studies and were waiting for the Certificates of Competency (COC) exams to graduate. They all have a sea training experience for one year, except one of them who just finished six months' sea time. Thus, the participants were familiar with the *classical approach* for collision avoidance procedures, which is the standard procedures at sea. The main aim of the experiments is to measure the Key Performance Indicators (KPIs) for the classical collision avoidance approach and the automatic collision avoidance approach and then, to perform the required analyses and quantify the enhancement in the safety of navigation when utilising the developed automatic collision avoidance system. The figures below are the pictures taken from the scenarios in the navigation bridge simulator (Figures 72, 73, 74 and 75).

Figure 72 the scenario of Hyundai Dominion

Figure 73 The scenario of CMA CGM Florida

Figure 74 the scenario of ACX Hibiscus

Figure 75 The scenarios of CMA CGM Florida

The first experiment group:

In this experiment, the participants were asked to perform a *classical approach* in case of a collision situation and the participant is not trained for the *automatic approach*, yet. When the exercise is completed, the participant has attended a training session for the utilisation of the developed automatic collision avoidance system. Then the same participant (who performed the *Classical approach*) performed the same exercise again. And this time, the Automatic Collision Avoidance system was utilised in the *Automatic approach* for collision situation. Four OOWs were participating in this approach, and they performed four different scenarios, each scenario is tested with the classical and automatic approach.

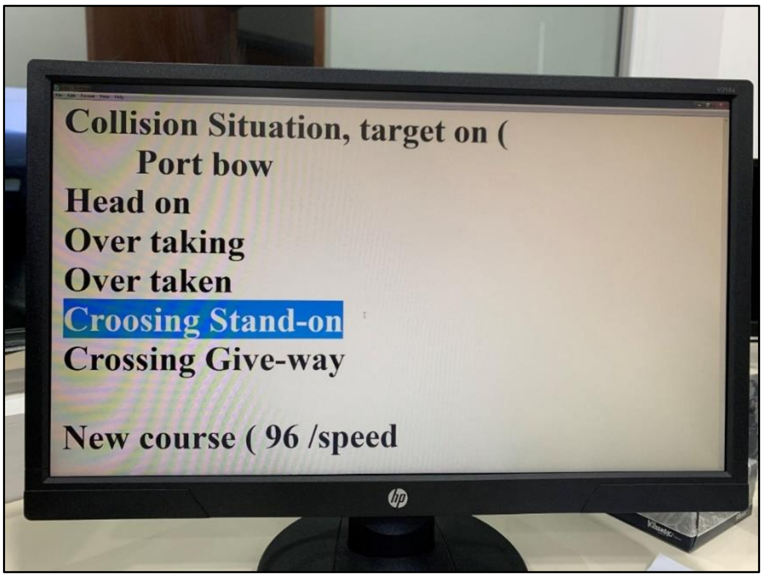
The second experiment group:

The participants in this group of experiments are different than the ones participated in the first group of experiments. In this experiment, 8 participants were divided into two groups. The first group (four OOWs) performed the *Classical approach* for collision situation. Whereas, the second group (four OOWs) attended the training session for the utilisation of the Automatic Collision Avoidance System and performed the *Automatic approach*. In other words, each scenario has been performed by two OOWs, the first OOW in the *Classical Approach* and the second OOW in the *Automatic approach*.

The automatic collision avoidance system utilisation in the ship bridge simulator

Due to the difficulties of integrating the developed Automatic Collision Avoidance System within the ship bridge simulator software, the developed system was utilised manually by the author. Accordingly, the author was running the exercise from the control station, where all the required data is available. Then, he was utilising the Automatic Collision Avoidance System to calculate the avoidance action, then acts as the system to alert the OOW about the collision situation. When a collision situation exists, the author advises the OOW about the avoidance action as well. The author was acting as the system, which means no human conversation was taking place. The automatic avoidance instructions were provided to the OOW by mirroring the instructor’s computer in a screen in the bridge simulator. The Note software was used to write the instructions (Figure 76 and 77). After that, the VHF was used to orally (phonetically) alert the OOW about the existence of the collision situation. The fact that it was impossible to integrate the developed Automatic Collision Avoidance System in the simulator platform has introduced a limitation in the performance of the system. This limitation has been overcome by the intervention of the author, which has a little delay in delivering the required information to the OOW in the bridge. This delay of the avoidance decision to the OOW is approximately one minute. The OOW needs to look at the screen, after he hears the oral alert, to see the collision situation and instruction. Alerting and decision example, such as;

- Collision situation detected on the starboard side.
- Collision situation is (Over-taking, Head-on, Crossing Give-way or Crossing Stand-on)
- Alter course to *** ° to avoid a collision.
- Change speed to *** knots



Collision Situation, target on (
Port bow
Head on
Over taking
Over taken
Croosing Stand-on
Crossing Give-way

New course (96 /speed

Figure 76 The Automatic Collision Avoidance instruction screen on the control station

Figure 77 The Automatic Collision Avoidance instruction screen on the bridge simulator

8.2.2.3 Phase three: data collection

Where the ship bridge simulator records all the exercises' data and parameters, consequently, this data was collected for the records and further analysis. Moreover, the simulator provides detailed reports about the exercise, which include the ship's dynamics, data log and the traffic; all these reports were collected. These records and reports were collected from the simulator system itself, as well as exporting it to MS Excel sheet in table forms. Additionally, the parameters' comparative assessment in the simulator has been performed, by providing a graphical comparative representation of the exercise's parameters. For the non-numerical data and parameters, the author has taken note about the OOW's performance and actions while observed the video recordings of the OOW during the exercise. This helped with the qualitative analysis to understand the reasons behind the OOW actions. The data, which was collected from the simulator exercise in real-time, are;

- Time of target appearance in the bridge, visually or by radar.
- Time of target detection by the OOW.
- Time of risk recognition by the OOW.
- Actual avoidance action time by the OOW.
- Monitoring the OOW's behaviour for risk recognition.

- OOW's performance and behaviour for any abnormality.

8.2.2.4 Phase four: data analysis

In this phase, all the collected data and parameters were grouped and sorted based on its relevant source and impact on the collision avoidance process. This step is performed to measure the participants' performance in collision avoidance procedures, in both the *Classical and Automatic approaches*. This will be discussed in more detail in the following section.

8.3 Key Performance Indicators (KPIs) for the OOWs performance measurement

In this section, the Key Performance Indicators (KPIs), which have been used to measure the performance of the OOWs (participants), will be explained. The Key Performance Indicators (KPIs) are the parameters that are utilised to quantify and observe the performance of a process, in order to capture the trend that the process is following (Klipfolio, 2019). This will help to accurately forecast the future trend based on the changeable parameters. Based on Oxford's dictionary, the KPI has been defined as *"A quantifiable measure used to evaluate the success of an organization, employee, etc. in meeting objectives for performance" (Oxford, 2019).* Therefore, after a brief introduction about the meaning of KPI, the utilisation of this technique to measure the performance of the OOWs (participants) in this experiment will be detailed below. In this experiment, the KPI Karta approach has been selected to identify the most valuable data and information needed to develop and measure the KPIs.

8.3.1 KPI Karta

KPI Karta is a structured approach to develop the required KPIs, which easily identify trends of the performance. The KPI Karta technique has been adopted from (Enhorning, 2013) and modified to be utilised for the purpose of this experiment. This approach is intended to facilitate the integration between the main goals and objectives of the experiment, and the calculated parameters (measures) that have been collected from the experiments (Enhorning, 2013). After defining layer one (goals and objectives) and collecting the measures, the whole process will be centralised moving downward and upward in the direction to layer two. The final stage will be the core of the technique, the KPIs in layer three. The KPI Karta approach is illustrated in Figure 78 (Enhorning, 2013) and has been modified by the author. For better understanding, and before explaining the KPI Karta method, it is worth explaining the parameters, which were used in the experiment as presented in Table 16. The parameters in the table are categorised based on the KPI Karta development steps, which indicate the step where these parameters are involved within the KPI Karta framework. Figure 79 illustrates the parameters and definitions on the navigational chart.

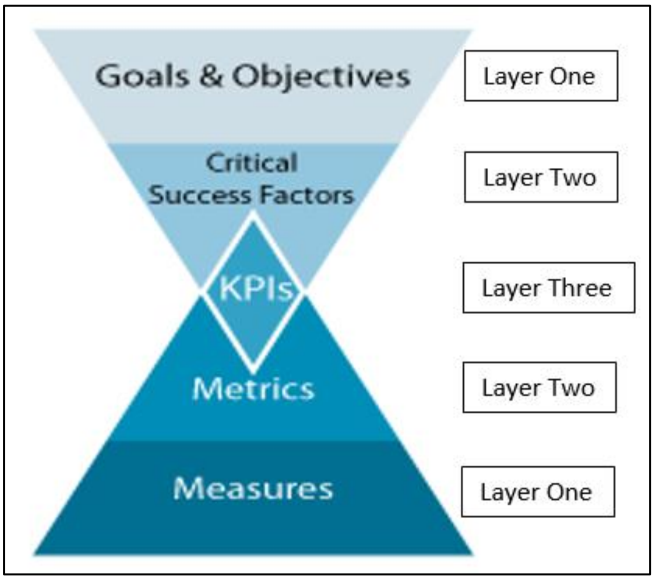


Figure 78 KPI Karta framework (Enhorning, 2013)

Table 16 The parameters, units and definitions used in the experiment

KPI Karta Framework	**Parameter**	**Unit**	**Definition**
Critical Success Factor (CSF)	CPA	Nautical Mile (NM)	The Closest Point of Approach, the closest distance where the ships are going to pass each other if no actions are taken.
	TCPA	Minutes to collision	The time to the closest point of approach, the time when the ships are going to pass in the closest distance from each other.
	Range	Nautical Mile (NM)	The distance between the own ship and target ship in any given time.
	Track Deviation	Nautical Mile (NM)	The distance that ship is moved away from the original planned track.
Key Performance	Target Detection	Time difference in minutes	When the target is detected by the OOW on the bridge by the radar or visually. This is calculated by the time difference between the time of target

Indicators (KPIs)			appearance and the time when the OOW has detected the target. The time is measured from the beginning of the scenario.
	Risk Recognition	Time difference in minutes	When the risk of collision with the associated target ship is recognised by the OOW. This is measured by the time difference between the actual time of risk and the time of recognition by the OOW. The time is measured from the beginning of the scenario.
	Action Time (Response)	Time difference in minutes	When the action should be taken by, then OOW to avoid the collision. This is measured by the time difference between the required action time and the actual action time by the OOW. The time is measured from the beginning of the scenario.
	Accuracy of Action	Ratio	The accuracy of the avoidance action that has been taken by the OOW to pass the target ship within the required distance of CPA. This is to measure the efficiency of the action to prevent large (unnecessary) moving distance by own ship. This is measured by finding the ratio between the required CPA and the actual Range at the time when the ships are passing each other.
	Track Deviation	Ratio	This is the distance that own ship has moved from the original planned track to avoid the collision. This is to measure the efficiency of the OOW avoidance action to avoid the collision in the smallest possible distance. This is measured by finding the ratio between the actual deviation distance from the original planned track and the tolerance deviation distance.
Collected Measures	Time of Appearance	Time from starting the scenario. hours, in 24 hours unit	The time when the target is appearing (possible to detect) in the simulator bridge, either visually or on the radar.
	Time of Detection	Time from starting the scenario.	The time when the OOW detected the target in the simulator bridge, visually or by radar.

		hours, in 24 hours unit	
	Actual Time of Risk	Time from starting the scenario. hours, in 24 hours unit	The time when the risk of collision has to be recognised by the OOW. In this experiment, 10 minutes before collision has been selected to be the latest time to recognise the risk of collision.
	Time of Recognition	Time from starting the scenario. hours, in 24 hours unit	The time when the OOW recognise the risk of collision with the target ship.
	Required Action Time	Time from starting the scenario. hours, in 24 hours unit	The time when the avoidance action needs to be taken by the OOW. In this experiment, this time is when the distance between the two ships is 1 NM.
	Actual Action Time	Time from starting the scenario. hours, in 24 hours unit	The time when the OOW starts to take the avoidance action.
	Required CPA	Nautical Mile (NM)	The minimum allowed passing distance from any target ship.
	Range	Nautical Mile (NM)	The distance from the target ship at the time of passing.
	Cross Track Error (XTE)	Nautical Mile (NM)	The tolerance distance to deviate for the original planned track, where no course correction needs to be taken.
	Actual Deviation	Nautical Mile (NM)	The distance that own ship has moved from the original planned track to avoid the collision.

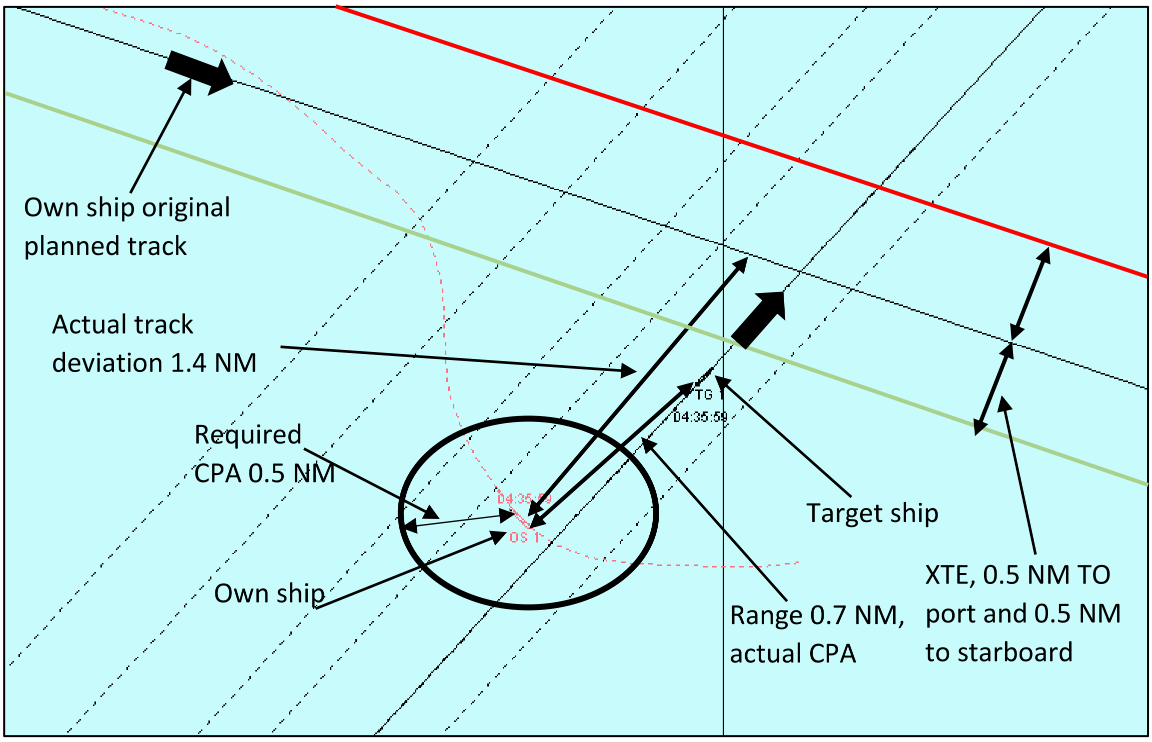


Figure 79 Parameters and definitions

8.3.2 5 steps of developing the required KPIs

Step 1: Goals and Objectives

The primary goal of the experiment is to prove the safety benefits of utilising the newly developed Automatic Collision Avoidance System. This will be achieved by examining the operational concept of the system when it is installed on-board ships and how it will be utilised in the navigational watch for collision avoidance situations. Moreover, it is to validate the operational performance of the developed system as a method for automatic collision avoidance and the efficiency of its collision avoidance decisions. Table 17 defines KPIs and its benchmarks.

Step 2: Critical Success Factors (SCF)

The Critical Success Factors (SCF) are indicators about the successfulness level of operation. These CSFs are gauges to facilitate the immediate acknowledgement of the performance of a task or operation, whether a success or not. In this experiment, if the situation has been dealt with safely or not. These SCFs are not KPIs. Thus, they are essential factors to prove that a successful approach has been taken to perform a task or duty.

The Critical Success Factors (SCF) in this experiment are;

- The Closest Point of Approach (CPA); this is the least distance that own ship will pass away from the target ship if no action has been taken. This is the most important factor to measure the safety performance of the navigational duty, which indicate the distance between ships when they are going to pass each other if no action is taken. If the result of this factor is zero, it means the ships are going to collide with each other.

- The Time of Closest Point of Approach (TCPA); this is the time it required to reach to the CPA, if no action has been taken. This factor is important to assess the level of risk involved in any navigational conflict (collision situation), which indicate the time that is remaining before the point of closest approach (collision). The result of this factor changes with any action that is taken by either own or target ship.

- The Range; is the actual distance that own ship has passed the target ship, after performing the avoidance action. The importance of this factor is to measure the efficiency of the action that was taken to avoid a conflict situation (collision), which measures the actual distance between the ships at the passing moment to assess the result of the taken action. When this distance is compared with the required CPA, it will provide a clear image of the successfulness of the taken action. If this distance is smaller than the required CPA it means it was not enough to avoid the conflict situation (collision), bigger than the required CPA, the action was enough to avoid the collision. Also, if the distance is much more than the required CPA, it means the action was excessively cautious to avoid the collision situation (inefficient).

- The Track deviation distance; this is the distance that own ship has moved from its original planned track. This factor is essential to measure the efficiency of the avoidance action by measuring the total travelled distance from the original planned track to avoid the collision. This distance has no restrictions, the OOW can deviate from the planned track to avoid any dangerous situation by any distance, but this distance provides a clear image of the efficiency of the taken action. The smallest the distance from the original planned track, the more efficient the action, where it needs to satisfy the requirement of the CPA distance, without breaching the minimum required CPA.

Step 3: Identification of Key Performance Indicators (KPIs)

This step is about the identification of each measurable KPI with its importance as a safety or efficiency factor. As a final result in Step 5, these KPIs will be quantified as a performance measurement. Accordingly, in this experiment, the KPIs will be calculated for the *Classical Approach* and the *Automatic Approach*, then they will be compared against each other. This will provide a measurable analysis of the performance of the OOW in each collision avoidance approach. The procedure for identifying the required KPIs is adopted from the logical navigational and collision avoidance processes on board ships. In more details, to avoid any collision at sea there are number of processes must be followed to ensure the right collision avoidance decision is taken. Thus, these processes have been adopted in this experiment to capture the performance of the OOWs in every scenario, which have been identified below as the KIPs for performance measurement. Each KPI will be explained to emphasise its importance within the collision avoidance procedures and its contribution to make the best decision for collision avoidance. Five KPIs have been selected for this experiment, and they are identified as follows;

- Target Detection Time (KPI 1): the time that the target has been detected by the OOW or the lookout on the navigational bridge. This KPI indicates the awareness about the target being in the vicinity. The importance of this KPI is to identify the efficiency of detecting the targets around the ship. In many MAIB accident reports, it was the case that both ships did not see each other until they collided. In this experiment, out of the eight MAIB accident reports three of them were the cases that no target detection took place by both vessels until the collision moment in the real accident event. One of the scenarios, the give-way vessel did not detect the target ship, and the stand-on vessel took a very late action that they could not avoid the collision. This shows the significant impact of the fundamental concept of navigation, proper lookout.

- Risk Recognition Time (KPI 2): The moment that the target has been recognised by the OOW as a risk for the navigation. This indicates the awareness about risky situations. This KPI is essential to measure the efficiency of the OOW in identifying the risks associated with targets in the vicinity. The time of risk recognition is recorded from the moment that the OOW acquires the target on the radar. As in the classical process of collision avoidance, the radar is the only available method to find accurate information and parameters about the target ship. And to get this information the target ship should be acquired first. Thus, the time of target acquisition is the time when the OOW starts to realise the risk associated with the target, which is the Risk recognition time.

- Action Time (Response) (KPI 3): the time that an action has been taken by the OOW to avoid the risk of collision. This indicates a response time to measure the efficiency of the OOW in the decision-making process.

- Accuracy of Action (KPI 4): the result of the action taken by the OOW to avoid the collision situation. This is measured by the distance between the ships when they pass each other, as it provides an indicator for the efficiency of the action, too big or too small action. This KIP is essential to judge the safety level of the action taken to avoid the collision.

- Track Deviation (KPI 5): the distance that own ship has sailed away from the original planned track to avoid the collision. This indicates the efficiency of the action taken to avoid the collision. This distance does not affect the safety of the navigation, but it informs about the accuracy of the action taken by the OOW to avoid target ships that leads to short deviation distance.

Step 4: Data Collection from the simulator experiments

In this step, the raw data are collected directly for the performed task (the experiment in this case). The data are collected from the simulator in the playback mode at the data analysis stage. The playback mode provides full information about the performed scenario, which has all the required data for this process. Although this raw data on its own has a limited meaning and indications, after the calculation and analysis, this data will be a very valuable and meaningful indication about the performance of OOW. These collected measurements are used in step 5, in the KPIs formulas to calculate the performance metrics. The following parameters were collected from the experiments, in the playback mode;

- Time of Appearance
- Time of Detection
- Actual Time of Risk
- Time of Recognition
- Required Action Time
- Actual Action Time
- Required CPA
- Range
- Cross Track Error XTE
- Actual Deviation

Step 5: KPIs' formulas and Performance Calculation to get Metrics and the interpretation of each KPI

In this step, the design of the required formulas is completed to calculate the performance metrics, which will be used later to compare the *Classical and Automatic approaches*. The data for individual parameters from Step 4 has been used in these formulas to perform the calculation and to obtain the results of the KPIs. Therefore, each KPI has its own formula and benchmark as follows. The interpretation of each KPI is discussed below to explain its importance and identifying the benchmarks. This will justify the need of the KPIs with the justification of the benchmarks and the valuable meaning of the results. By explaining the benchmarks and the results, it will identify the performance of the OOW and how to capture the deterioration in the OOW capability for decision making.

- KPI 1: Target detection, this KPI indicates the response time of the OOW with regards to target detection, when it appears in the vicinity, either by radar or visually. The detection distance usually depends on two factors: the condition of environmental visibility for the visual detection and the selection of operational range in the radar (ARPA) by the OOW. This KPI is measured by the time difference (in minutes) between the appearance of the target (when it can be detected) and the actual detection time by the OOW, in the navigational bridge. Accordingly, if the OOW detects the target immediately (when it appears in radar or visually), the time difference will be zero (zero is the benchmark for this KPI), and this is the ideal result/ the perfect performance. When the OOW is late in detecting the target, the time difference between the time of appearance and the time of detection will be given a negative (-) sign; this means a late detection. The assumption of target detection in the *Automatic Approach* is to detect the targets when they enter the detection zone, which is set to be within 10 NM range. This assumption has been made based on the principle operation of the developed Automatic Collision Avoidance System for target detection by the interrogation and reply technique. Thus, when targets are in 10 NM distance from own ship, the system immediately detects them. This KPI is calculated by using the Formula (27), and the result is the time difference in minutes. This KPI is a safety factor in the navigational performance.

$$\Delta t = Time\ of\ Appearance\ (hours) - Time\ of\ Detection(hours) * 60$$
$$= Time\ difference\ (minuts)$$

(Eq. 27)

- KPI 2: Risk recognition, this KPI indicates the awareness of the OOW about the target that is being a threat to his/her ship when risk of collision exists. Risk of collision can be evaluated either by; monitoring the CPA from the radar (if the target is acquired), or the changes of that target's bearing over time. For risk recognition, the TCPA is the most appropriate parameter to monitor, which is also used in the aviation TCAS system to evaluate the risk of collision. The TCPA indicates the time that is remaining before the collision happens. However, there are no rules or regulation that provide any advice about the best time when risk should be recognised, and it is all left to the good seamanship practices to decide in such situations. In this experiment, 10 minutes before collision has been set as the latest moment when risk should be recognised. 10 min is considered a short time before the collision, as some ships need a long time to respond. Yet, it has been decided to be 10 minutes to test the capabilities of the developed system to provide efficient collision avoidance decision in a short time. Less than 10 minutes could be too dangerous, where additional time is still required to provide the avoidance decision to the OOW and then to be performed. Also, the slow response ships (such as VLCC tankers) will not be able to perform the provided avoidance action, as they take a long time to respond. To calculate this KPI, the time difference between the actual time of risk (10 minutes before the collision) and the time where the OOW recognises the risk is calculated by using the Formula (28). Zero is the benchmark for the risk recognition if the OOW recognises the risk earlier, the time difference will be in positive (+) sign. If the OOW recognises the risk when it is less than 10 minutes to the collision, this will be a late recognition and the time difference will be negative (-) sign. The result is the time difference in minutes. This KPI is a safety factor in the navigational performance.

$$\Delta t = Actual\ Time\ of\ Risk\ (hours) - Time\ of\ Recognition(hours) * 60$$
$$= Time\ difference\ (minuts)$$

(Eq. 28)

- KPI 3: Action time (response), this KPI indicates the point that the avoidance action should be taken to avoid the collision. However, the maritime rules and regulations never advice about the best distance to start taking actions, and it is all up to the good seamanship practices by the OOW to decide when. These decisions depend on the size of the ship, speed, under keel clearance, weather condition and ship's manoeuvrability. In this experiment, the point of action performing is set to be when the distance to the target ship is 1 NM. This is a very small distance before any action is taken. However, it has been selected to prove the capability of the developed Collision Avoidance system to provide a last-minute avoidance action to prevent a collision from happening at the last moment. To calculate this KPI, the time difference between the required action time (when it is 1 NM from the target) and the actual time when the action is taken. Zero is the ideal result, the benchmark, and if the action is taken earlier, the time difference will be positive (+). If the action is taken late, the time difference will have a negative (-) sign. Formula (29) calculates this KPI, and the result is the time difference in minutes. This KPI is a safety factor in the navigational performance.

$$\Delta t = Required\ Action\ Time\ (hours) - Actual\ Action\ Time (hours) * 60 = Time\ difference\ (minuts)$$

(Eq. 29)

- KPI 4: Accuracy of action, this KPI indicates the efficiency of the action that is taken by the OOW to avoid the collision. This is measured by the possibility to avoid the collision situation without breaching the minimum allowed CPA. The minimum CPA is set to be 0.5 or 1 NM, depending on the navigational area (in every scenario and navigational situation). Formula (30) calculates this KPI by dividing the range by the required minimum CPA. The benchmark for this KPI is 1 (the range is equal to the minimum required CPA), if the result is bigger than 1, this means the range is larger than the minimum CPA (safer situation). If the result is smaller than 1, this means the range is smaller than the required minimum CPA (dangerous situation). The result is the ratio of the distance over the required CPA. This KPI is safety and efficiency factor in the navigational performance.

$$Accuracy\ of\ Action = \frac{Range\ (NM)}{Required\ CPA\ (NM)}$$

(Eq. 30)

- KPI 5: Track Deviation, this is the KPI showing the efficiency of the action taken. This indicates the distance that the ship has deviated from its original planned track to avoid the collision. The Cross-Track Error (XTE) is the tolerance distance around the planned track, to port or starboard side. This distance is between 0.5 to 1 NM (depending on the scenario and the navigational situation). Formula (31) calculates the Track deviation KPI by dividing the distance that the ship has travelled away from the original track by the XTE. If the result is 1, then the distance travelled is the maximum allowed, which is the benchmark for this KPI. If the result is smaller than 1 then the ship is in the allowed limit of deviation. Otherwise, larger than 1 means the ship is getting far away for the original track. The result is the ratio of the deviation distance over the XTE. This KPI is an efficiency factor in navigational performance.

$$Track\ Deviation = \frac{Deviation\ Distance\ (NM)}{XTE\ (NM)}$$

(Eq. 31)

Table 17 table of KPIs and benchmarks

KPI	**KPI's factor Safety/efficiency**	**Unit**	**Benchmark**
Target detection	Safety	Time difference in minutes	Zero is the ideal performance. A negative result is a delay in performance.
Risk recognition	Safety	Time difference in minutes	Zero is the ideal performance. (+) A positive result is an early performance. (-) A negative result is a delay in performance.
Action time (response)	Safety	Time difference in minutes	Zero is the ideal performance. (+) A positive result is an early performance. (-) A negative result is a delay in performance.
Accuracy of action	Safety and efficiency	Ratio	One is the ideal performance, the passing distance equal to the required CPA. Bigger than one, the passing distance is larger than the required CPA (safe). Less than one, the passing distance is smaller than the required CPA (dangerous).

Track Deviation	efficiency	Ratio	One is the maximum allowed travel distance from the planned track. Less than one, within the allowed deviation distance XTE. Bigger than one, out of the allowed deviation XTE.

After discussing the KPIs and its calculation method, it is important to clarify the interpretation of each KPI and its importance level.

- First, KPI 4, the accuracy of the action. This is the most important performance monitoring factor, which provides a measure about the safety level of the action taken. This is the KPI that indicates the safety of avoidance action, and if the ships are passing in safe distance or dangerously close.

- Then, KPIs 1, 2 and 3. They are the safety performance measures KPIs. These provide an indication about the OOW performance in the navigational procedures and decision making.

- Finally, KPI 5, the track deviation. This is an efficiency factor, it is essential to monitor the quality of the decision making and the performance of the OOW.

In this section, the analysis method has been explained with all the definitions and required information being mentioned. In the next section, the results of the experiments will be displayed and discussed thoroughly.

8.4 The validation experiment

In this experiment, eight scenarios were tested to validate the developed system. After the execution of the validation experiments in the full-mission bridge navigational simulator, the data which has been obtained from these experiments and the video recordings were utilised for direct analysis of the developed Automatic Collision Avoidance System to validate its functionality. Accordingly, the above-mentioned method of data analysis has been applied to carry on these validation tests. The results of these tests are going to be explained in this section. Additionally, the result of the performance observation from the videos will be discussed as well.

Two methods have been tested in this experiment. The first one is the same OOW performs both approaches. The second, two OOWs, each one performs one of the approaches. After this the detailed explanation, the analysis and results are presented. The scenarios of each group are as follows;

Group one, same OOW for both approaches (for each scenario different OOW performs the task, total of 4 OOWs took part in these exercises)

- Scenario 1: *ACX Hibiscus*
- Scenario 2: *CMA CGM Florida*
- Scenario 3: *Dutch Aquamarine*
- Scenario 4: *Ileksa*

Group two, different OOW for each approach (for each scenario each approach has different OOW takes part, in total 8 OOWs took part in these exercises)

- Scenario 5: *Hyundai Dominion*
- Scenario 6: *Ever Smart*
- Scenario 7: *Lykes Voyager*
- Scenario 8: *Scot Isles*

8.4.1 Scenario 1 (*ACX Hibiscus*)

Accident report (MAIB, 2013)

This is a collision event that happened between the container ships *ACX hibiscus* and *Hyundai Discovery*, in Singapore Strait eastern approach on the 11th of December 2011, at 0756. Neither human injuries were recorded, nor was environmental pollution reported in relation to this collision. Both ships were severely damaged. It was a Head-on situation where *ACX Hibiscus* was outbound from Singapore Strait, and *Hyundai Discovery* was inbounding to the strait. The weather condition was unstable with heavy showers and thunderstorms, which has reduced the visibility to 2 cables (0.2 NM), because of the heavy rain. The wind was scaled as 5 in Beaufort scale. Both vessels saw each other four minutes and ten seconds before the collision, the distance was 2.2 NM, this was too late to avoid the collision. From the accident report, it has been found that *ACX Hibiscus* has detected *Hyundai Discovery* on the radar but did not acquire her. However, due to the bad weather and heavy rain, the target has been lost from the radar, which was not acquired to obtain the required information. On the other hand, *Hyundai Discovery* had *ACX Hibiscus* acquired on her radar at 0740 (16 minutes before the collision), then at 0744, the target was lost due to the bad weather (12 minutes before the collision). After both ships have lost targets from the radar, and no one has reacquired the targets again, *ACX Hibiscus* started to alter her course to the new planned course, which was toward Hyundai Discovery. The moment they started to see each other visually, they were too close, and no immediate action has been taken to avoid the collision. Instead, they were trying to establish a VHF communication to agree on the avoidance manoeuvre. Yet, the use of VHF communication to agree on the collision avoidance manoeuvre is against the COLREG regulation. Thus, with the late detection of the threatening target and the delayed decision-making process, it was not possible to avoid the collision.

The event's scenario in the simulator, Classical and Automatic Approaches

For the construction of this experiment, the scenario was built based on the information available in the accident report from MAIB (MAIB, 2013). In the accident report, it has been mentioned that there was a number of vessels are sailing in the same route as *ACX Hibiscus*, but there was no information about these vessels to plot them in the exact positions and routes. However, these vessels have been located in random positions to build a similar scenario for this exercise. The illustration of the *Classical Approach* scenario is captured from the screen in the control station of the simulator Figure 80. The red dotted line denotes the track of the own vessel (*ACX Hibiscus*), she is the outbound vessel, and she is sailing to north. The black dotted line denotes the track of the target vessel (Hyundai Discovery), she is the inbound vessel, and she is sailing to the south-west. The black lines are the planned original track for both own and target vessels. The screen capture in Figure 81 illustrates the *Automatic Approach* scenario while Table 18 has detailed actions taken by the own and target ships from the real accident report, the best action should have been taken according to the point of view of the author and the Automatic Collision Avoidance system's decision for this accident event.

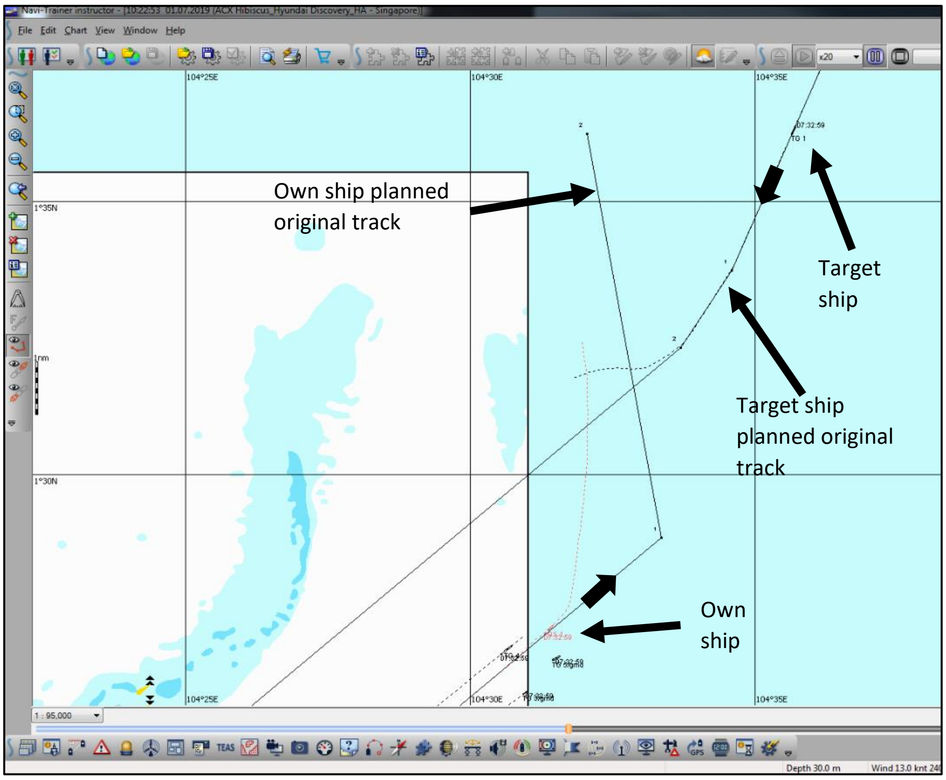


Figure 80 ACX Hibiscus Classical scenario

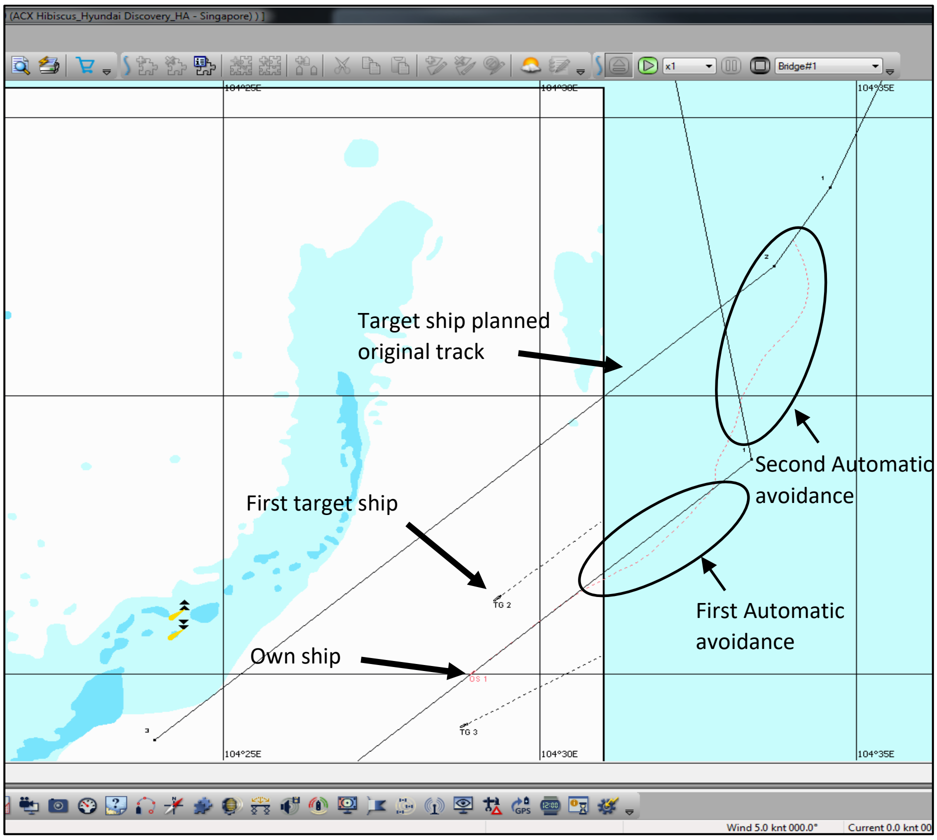


Figure 81 ACX Hibiscus Automatic scenario

The Classical Approach experiment

In this experiment, the same OOW has performed the *Classical Approach* and the *Automatic Approach*. The OOW has been trained to utilise the new Automatic Collision Avoidance system.

In the *Classical Approach*, the OOW was aware about the target ship from an early stage. Additionally, his ship was the give-way vessel, and he was required to take the avoidance action. Therefore, he decided to take an early course alteration, immediately after he passed the surrounded ships. His avoidance decision was correct. However, the instructor (the author) changed the course of the target ship, toward the own ship, to increase the risk of collision. Yet, the distance was large enough, and no accident happened. However, the range, the passing distance between the own and target ship was very small, 0.3 NM, which indicates a potential risk of collision. The below screen captures show the progress of the scenario until they passed clear of each other. Figure 82 shows the OOW decision to start the course alteration early to pass ahead of the target ship, where the planned track is on the starboard (right) side of the own ship. Figure 83 shows own ship just passing the target ship on her starboard quarter, which shows the small passing distance between the two ships. Figure 84 shows the target ship passing safely from the stern of the own ship.

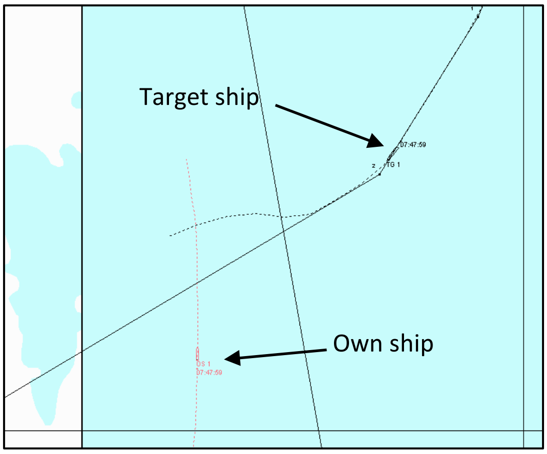


Figure 82 ACX Hibiscus Classical scenario

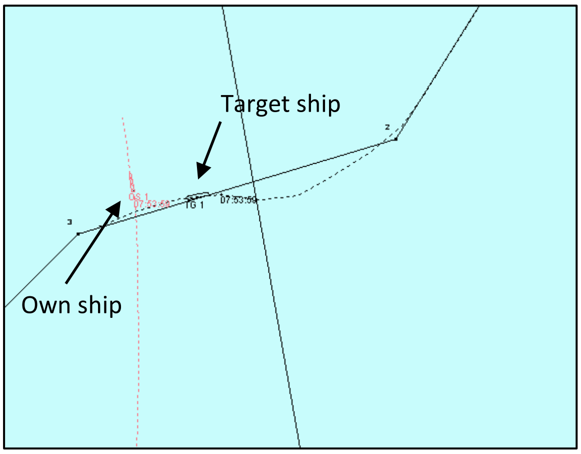


Figure 83 ACX Hibiscus Classical scenario

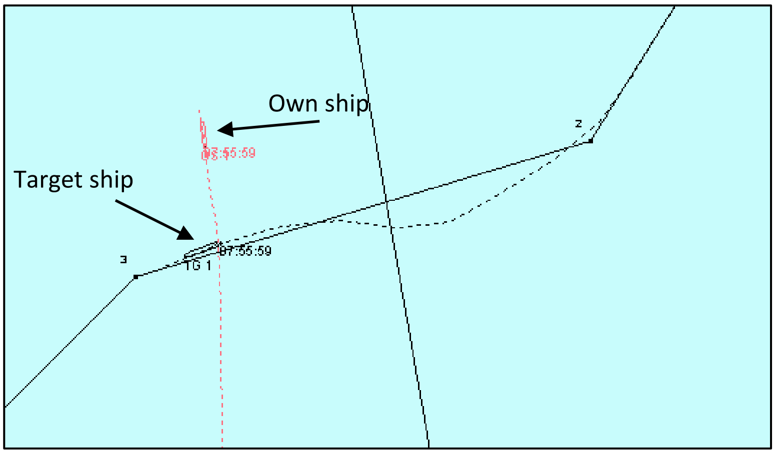


Figure 84 ACX Hibiscus Classical scenario

The Automatic Approach experiment

In the ***Automatic Approach***, there were two targets that needed to be avoided, the Automatic Collision Avoidance System has alerted the OOW about them and provided the avoidance manoeuvres separately as well (Figure 81). The OOW was trained about the utilisation of the new system, yet, it was a new experience for him. In the first avoidance manoeuvre to avoid the first target Figure 86, the OOW was not very confident and showed some hesitation about the system's capability to provide the avoidance decision. Still, he followed the system's instruction and performed the avoidance decision, which avoided the close passing situation safely and precisely within the required CPA. This has risen his confidence level and removed the hesitation of the OOW about the efficiency of the system to provide accurate avoidance manoeuvres. In the second collision situation with the second target ship, the OOW has been familiar and confident with the new system and he was waiting for the system decision, once the system has provided an avoidance manoeuvre, the OOW responded immediately Figure 85. The avoidance manoeuvre was safe and took the own ship clear from the target ship and within the required CPA. The Automatic System's decision was to pass astern of the target ship Figure 87, which resulted in safe and clear avoidance action within the required passing distance (CPA). During the experiment, it has been observed that the OOW has developed trust towards the developed system, after the first successful manoeuvre to avoid the first target. This has been obvious with his monitored behaviour, for the collision situation, where he was giving his full attention to the system and responded quickly in the second manoeuvre.

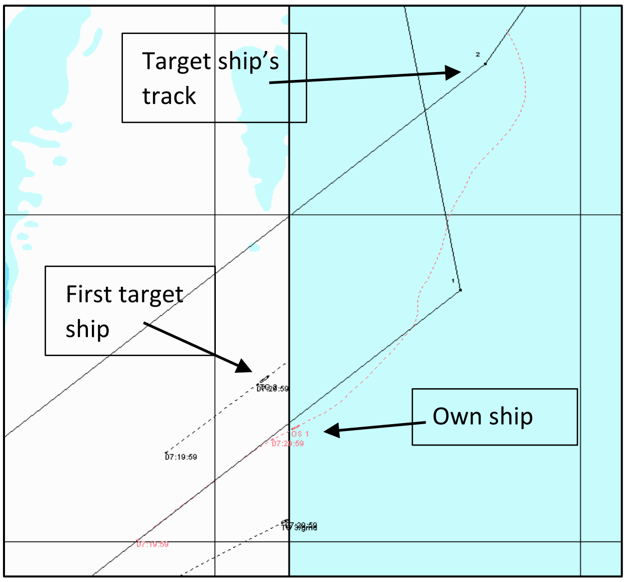


Figure 86 ACX Hibiscus Automatic scenario

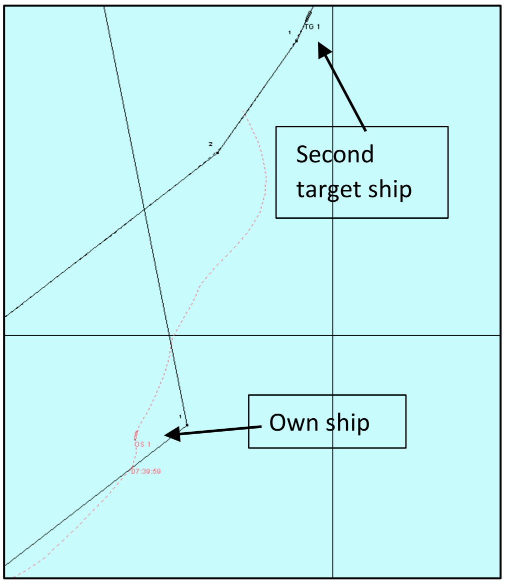


Figure 85 ACX Hibiscus Automatic scenario

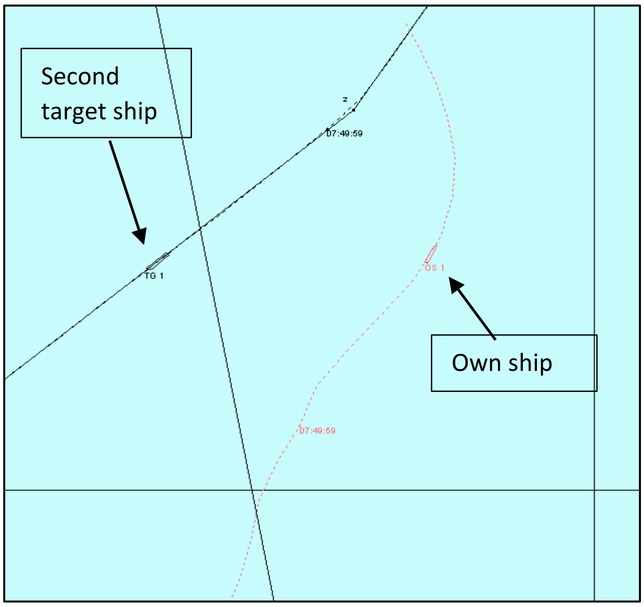


Figure 87 ACX Hibiscus Automatic scenario

Table 18 the ACX Hibiscus Actions table; real scenario action, best action and Automatic system action

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0700	Heading 049° Speed 14.5 knots	Heading 203° Speed 20 knots					
0720	Out of the Singapore Strait TSS						
0721		Speed reduced to 18 knots (To arrive on time). Entered rain, restricted visibility.					
0730	Entered rain, restricted visibility. Some targets were acquired but not Hyundai Discovery.		Human error, the target was not detected				The system could have detected *Hyundai Discovery* and alert the OOW on the *ACX Hibiscus*. sharing information
0733:40						Target (Hyundai Discovery) has been detected by the Auto	

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
						system on the detection zone (10 NM).	
0734:36						The Auto system has recognised the risk of collision with *Hyundai Discovery* (10 minutes before the collision).	
0740		*ACX Hibiscus* was acquired with other out-bound vessels					
0744		Course altered to a new heading of 209° by auto-pilot control. *ACX Hibiscus* was lost from radar sight.	Target lost because of heavy rain (clutter)				Data-link feature to ensure continues target detection and monitoring
0745	The rainfall led to the loss of targets because of clutter		High sea and heavy rain cause sea and rain clutter in Radar, this leads to unclear				Data-link feature to ensure continues target detection and monitoring

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
			picture and targets loss. When targets are lost, they need to be reacquired manually.				
0747		Rada showed *ACX Hibiscus* on 5 NM, clear but close pass port-to-port. Change heading to 216° for altering to the new course (229°) and to increase passing distance.	This is a head-on situation, both ships should alter course to starboard said to keep clear and pass port-to-port.			The Auto system has alerted the OOW about the risk of collision and provided the best avoidance decision. The decision was to change the course to 035°. The ships passed safely after taking this action by the OOW on *ACX Hibiscus* (own ship).	
0748:30		Turned to 229°. The new chart planned course.	Starboard alteration to the new course and to increase the separation.				Sharing information to enhance situational awareness

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0750	No sound signals for restricted visibility.	Steady at 229°, *ACX Hibiscus* 15° on port side and range of 3.5 nm. CPA 0.7 nm. No sound signals for restricted visibility.	Sound signals are required by COLREG in restricted visibility.				
0751:30	Started to alter course to the port side to the next planned course of 350°. Radar targets were not clear because of clutter.		*ACX Hibiscus* was not aware of *Hyundai Discovery* on her port quarter because of restricted visibility and targets loss in radar display	Should have checked the targets on the new route alteration. Should have waited to be clear of west bound vessels before started the alteration.			The system will alert the OOW about the Hyundai Discovery, which is in a collision course. Share information feature will inform *Hyundai Discovery* immediately about *ACX Hibiscus* alteration.
0752 (Collision situation detected,		2.2 nm distance between ships. *ACX Hibiscus* radar trail changed direction towards		This ship was not aware about Hyundai Discovery. This why it started	As *ACX Hibiscus* failed to keep clear, *Hyundai Discovery* should have taken		The system will alert *Hyundai Discovery* about the situation and advice the OOW

Time of Actions	*ACX Hibiscus* actions (East bound from Singapore)	*Hyundai Discovery* actions (West bound to Singapore)	Comments	Best actions by *ACX Hibiscus*	Best actions by Hyundai Discovery	The developed Auto system actions in the experiment	Collision avoidance system response
4:10 minutes before collision)		Hyundai Discovery, cross-checked with AIS and confirmed *ACX Hibiscus* course alteration to the port side.		to alter heading to the new planned course. This was a head-on situation and both ships should have altered courses to starboard to pass port-to-port.	the best action to avoid the collision.		with; Time remaining to collision, time of last-minute actions to avoid collision and the best action to avoid collision. Information sharing to enhance situational awareness.
0753:15		Called *ACX Hibiscus* on VHF channel 16. *ACX Hibiscus* did reply	*Hyundai Discovery* master's standing order, "The OOW should never rely on using VHF or AIS equipment as a method of avoiding a collision".		Start altering course to the starboard side. This is the best action to avoid this collision, as it takes the ship away from any conflict situations with other ships, does not interface with any actions by *ACX Hibiscus* and		Decisions sharing and acknowledgement to enhance situational awareness by alerting the other ship about the avoiding decision and to ensure other ship's acknowledgement about the situation.

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
					comply with COLREG.		
0753:30		Called *ACX Hibiscus* on VHF channel 16. Started communication and change channel to 06.					
0754 (2:10 minutes before collision) Last-minute to take effective avoiding action		VHF communication. Unclear conversation with no agreement on stopping port alteration of *ACX Hibiscus* to avoid bow crossing.	Unclear response from the *ACX Hibiscus* OOW, he just mentioned his ship is altering to the north (port side)		Should have used the time of communication to decide the best action to avoid the collision.		This is the last-Minute action, if no action is taken by the OOW, the system will automatically stop the engine or take the best action to avoid the collision.
0754:34	Still altering course to port passing heading of 017°		*ACX Hibiscus* still not aware of the collision situation, even after the VHF call.		If hard to starboard helm has been ordered 2:40 minutes before the		The system will alert the OOW about the collision situation and provides the best

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
			Also, no agreement reached by VHF calls yet.		collision it would give 0.4 nm bow crossing distance (BCR)		action to avoid it (Last Minute action). If the OOW did not take any action to prevent the collision, the system will override the OOW and automatically stop the engine or implement the action to avoid the collision.
0755	No reply for VHF calls and continues on course alteration to the port side.	Keep asking *ACX Hibiscus* to alter course to starboard to avoid the collision.					
0755:13 (One minute before the collision)		Change to manual steering and sounded one long blast on ship's whistle.			If hard to starboard helm has been ordered 2:10 minutes before the collision it would give 0.2 nm bow crossing distance (BCR)		

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0755:35		Master on the bridge and being reported about the situation					
0755:50	Change to manual steering and turn the wheel hard to port. Set engine telegraph to an emergency stop.	Estimated range of 0.2 nm and *ACX Hibiscus* became visible. Helm ordered hard to starboard.			20 seconds was not enough time to take any avoiding action		
0756:10 (Collision time)	Bow collided with Hyundai Discovery's port side. Heading 321° Speed 14.1 knots	Heading of 229° Speed 18 knots The rudder was turned hard to port to separate the sterns of both ships.					
0800		Reduced speed to 16 knots (manoeuvring speed) and continued on the passage to Singapore's outer anchorage.					

Time of Actions	***ACX Hibiscus* actions (East bound from Singapore)**	***Hyundai Discovery* actions (West bound to Singapore)**	**Comments**	**Best actions by *ACX Hibiscus***	**Best actions by Hyundai Discovery**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0830	Report the collision to Malaysian Coastguard. Started to turn heading west at slow speed.						
0920	Ensure stable condition and continued the passage to Singapore's outer anchorage at slow speed.						

General comments:

- The Chief Officer in ACX Hibiscus has altered course to the port side to follow the passage plan without proper lookout (visually or by radar) to ensure that there were no targets in his new course.
- The Chief Officer on ACX Hibiscus was fatigued and the master of the ship did not consider his ability to perform his duty.
- The lookout parson has warned the Chief Officer about a missing target in the radar due to the sea clutter, but the Chief Officer did not listen.
- The ships were sailing in restricted visibility without complying with the COLREG rule 19, restricted visibility, speed was not reduced by both vessels, no proper lookout for restricted visibility was conducted and no sound signal was used.
- The Chief Officer on Hyundai Discovery has realised the danger of a collision and he decided to conduct a VHF communication with ACX Hibiscus rather than take an immediate avoidance action, where he had a little time that was sufficient to avoid the collision if he responded immediately.

OOW's opinion about the developed Automatic Collision Avoidance System

After the experiment, the OOW was asked about his opinion about the system. He found it a very useful system, which provides accurate advisory instructions. Also, he commented on the time of instructions provided by the Automatic system to avoid targets in good time that makes it easy to avoid the collision and return to the planned track. This has given avoidance actions to fulfil the navigational requirements without the need for diverting for a long distance from the original track. Also, the system's decision support removes the uncertainty of the collision avoidance manoeuvre, wherein the classic collision avoidance procedure the OOW is always worried about his avoidance action whether it is enough to pass clear from the target ship or more actions are needed.

The ACX Hibiscus experiment KPIs

The tables below show the collected data from the simulator, which are used to calculate the KPIs for this scenario Tables 19 and 20. Additionally, the graph below, Figure 88, presents the KPI results of the *ACX Hibiscus* scenario for the *Classic and Automatic approaches*. For the *Classical Approach*, the results show that there is a slight delay in the time of target detection. On the other hand, risk recognition and action time were observed early. Yet, the avoidance action that has been taken resulted in a small passing distance (0.3 NM, due to the target's course change), which is far smaller than the required CPA of 1 NM. For the track deviation, the vessel has not passed the allowed deviation distance from the original track.

In the *Automatic approach*, the results represented in the chart show that the timing and the actions were in accordance with the ideal performance. This includes a just above the required passing range from the target ship, which is safe to proceed. Also, the deviation from the original track is still in the acceptable level.

Table 19 ACX Hibiscus Classical approach data

***Classical Approach* ACX Hibiscus**		
Measures	**Data**	**Unit**
Time of appearance	07:20:00	Time
Time of detection	07:21:20	Time
Actual time of risk	07:43:14	Time
time of recognition	07:38:00	Time
required action time	07:49:36	Time
actual action time	07:45:24	Time
required CPA	1	NM
Range	0.3	NM
XTE	1	NM
Actual Deviation	0.7	NM

Table 20 ACX Hibiscus Automatic approach data

***Automatic Approach* ACX Hibiscus**		
Measures	**Data**	**Unit**
Time of appearance	07:33:40	Time
Time of detection	07:33:40	Time
Actual time of risk	07:34:36	Time
time of recognition	07:34:36	Time
required action time	07:47:20	Time
actual action time	07:47:20	Time
required CPA	1	NM
Range	1.056	NM
XTE	1	NM
Actual Deviation	0.7	NM

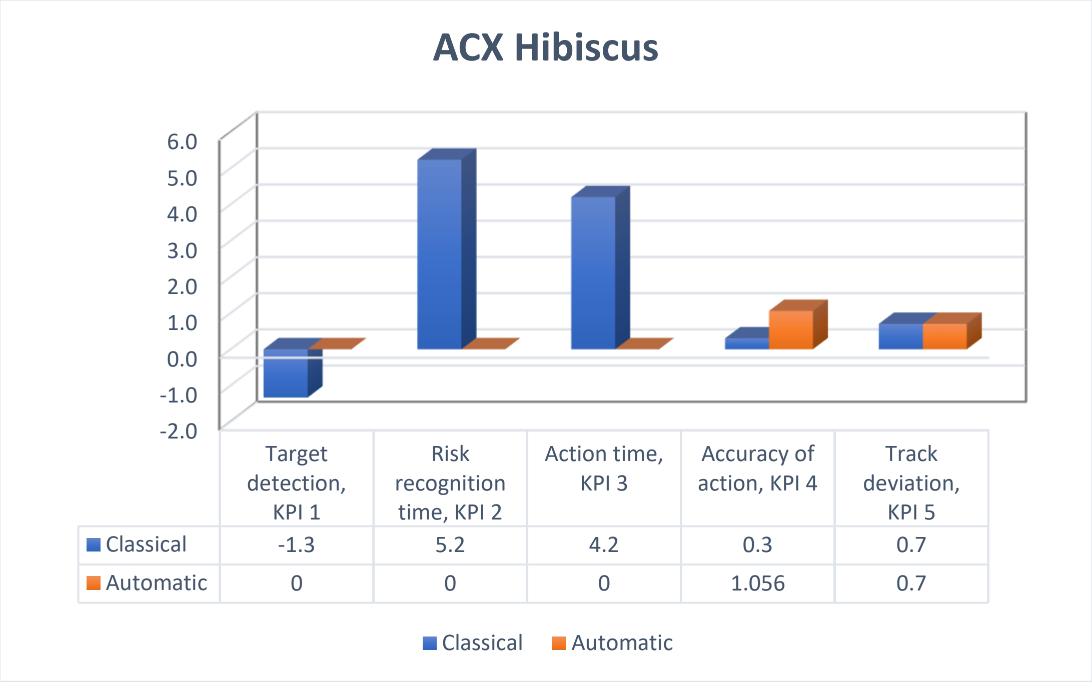


Figure 88 ACX Hibiscus's KPI results for Classical and Automatic approaches. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.2 Scenario 2, (CMA CGM Florida)

Accident report (MAIB, 2014)

This is a collision event that occurred in the East China Sea, between container vessel *CMA CGM Florida* and the bulk carrier *Chou Shan*. This accident happened on the 19th of March 2013, at 0033 and caused severe damage for both ships and the environment, with over 600 tonnes of heavy fuel oil spilt in the sea. No human injuries were recorded in relation to this collision event. Weather and visibility were good at the time of the collision, wind force 4 in the Beaufort scale and 4 NM visibility.

On the *CMA CGM Florida*, the second officer (Filipino officer) was the OOW and he was the responsible officer. Also, a new extra officer was on the watch for bridge familiarisation (Chinese officer). The OOW (Filipino officer) altered course to starboard to avoid fishing boats and a head-on vessel. This alteration resulted in a collision situation with *Chou Shan*, which was crossing from the port side, crossing situation and the *Chou Shan* is the give-way vessel. As the situation developed, the *Chou Shan* OOW started a VHF communication to requested *CMA CGM Florida* to pass his stern. This was against the COLREG rules as the *CMA CGM Florida* is the stand-on vessel, and she should maintain her course and speed, and

Chou Shan is the give-way vessel, and she should take the avoidance action. Additionally, the OOW on *Chou Shan* has used the VHF communication for manoeuvring agreement, which is again prohibited by the COLREG regulation in case of collision. On top of this the communication language, where the extra officer (Chinese officer) on *CMA CGM Florida* was communicating with *Chou Shan* in the Mandarin language, and he agreed on the avoidance manoeuvre by the stand-on vessel *CMA CGM Florida*. The OOW in *CMA CGM Florida* did not understand the conversation in Mandarin language and the extra officer did not translate it correctly. Also, he did not inform the OOW about the agreement of *CMA CGM Florida* taking the avoidance manoeuvre and pass *Chou Shan*'s stern. This left the OOW (Filipino officer) with a lack of situational awareness and actions that all resulted in heading to the collision point.

The event's scenario in the simulator, Classical and Automatic Approaches

In order to reconstruct this event, the original location, the East China Sea, was not available in the simulator database. However, an alternative location was selected, an open sea area. Thus, the scenario has been reconstructed with the same events, directions and details from the original accident report (MAIB, 2014). The picture below (Figure 89) is a capture from the simulator's control station for the *Classical approach* scenario. In the picture, the red dotted line is the own ship's track, and the target ship is approaching from the north to pass the own ship from the port side. Table 21 has detailed actions taken by the own and target ships from the real accident report, and the best action should have been taken according to the point of view of the author and the Automatic Collision Avoidance system's decision for this accident event.

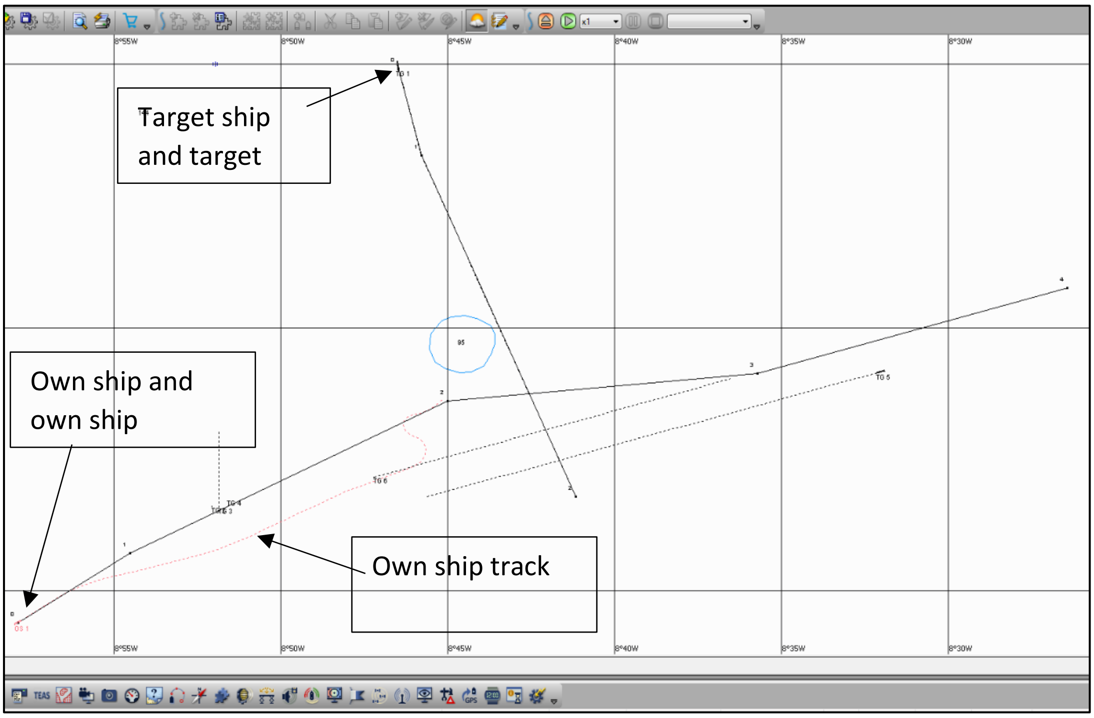


Figure 89 CMA CGM Florida, Classical scenario

The *Automatic approach* scenario is illustrated in the below picture from the simulator's control station (Figure 90). In this *Automatic scenario*, the Automatic Collision Avoidance System has been activated three times to avoid three different targets. Hence, the main target, which own ship has collided within the accident report, is the target approaching from the north, will be labelled as the main target in the picture.

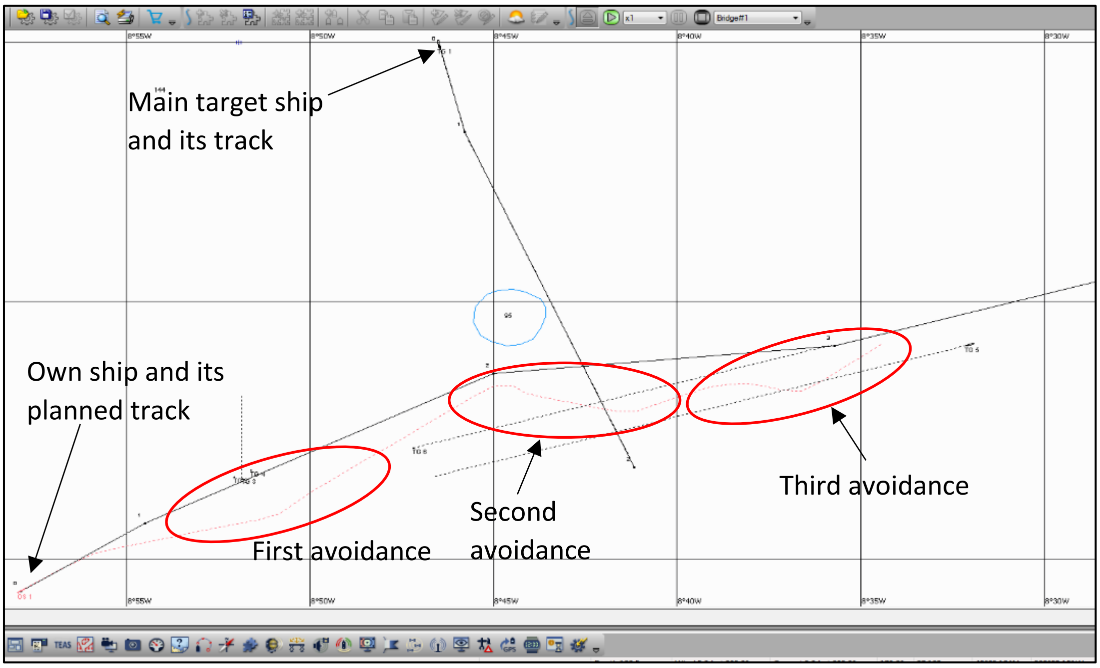


Figure 90 CMA CGM Florida, Automatic scenario

The Classical Approach experiment

In this experiment, the same OOW has performed the *Classical and Automatic Approaches*. In the event, the OOW has taken an early action to avoid the collision with the main target ship (Figure 91). Also, he reduced the speed of his ship. However, he is the stand-on vessel, and the main target ship should have taken the avoidance action. As the main target ship is not taking any avoidance action, then the OOW's decision was correct, yet, it was early action. The OOW was aware and anxious about the other ship that approaching him as a head-on ship (Figure 91). Accordingly, he reduced speed dramatically and unnecessarily. Figure 92 shows the action of the OOW when he realised that the main target ship is becoming clear and he started to change course toward the original planned track. At the time when the own ship has reached the planned track, the OOW started to increase the speed and continue on his planned track (Figure 93). All these events have led to a large passing range from the main target ship (Figures 92 and 93).

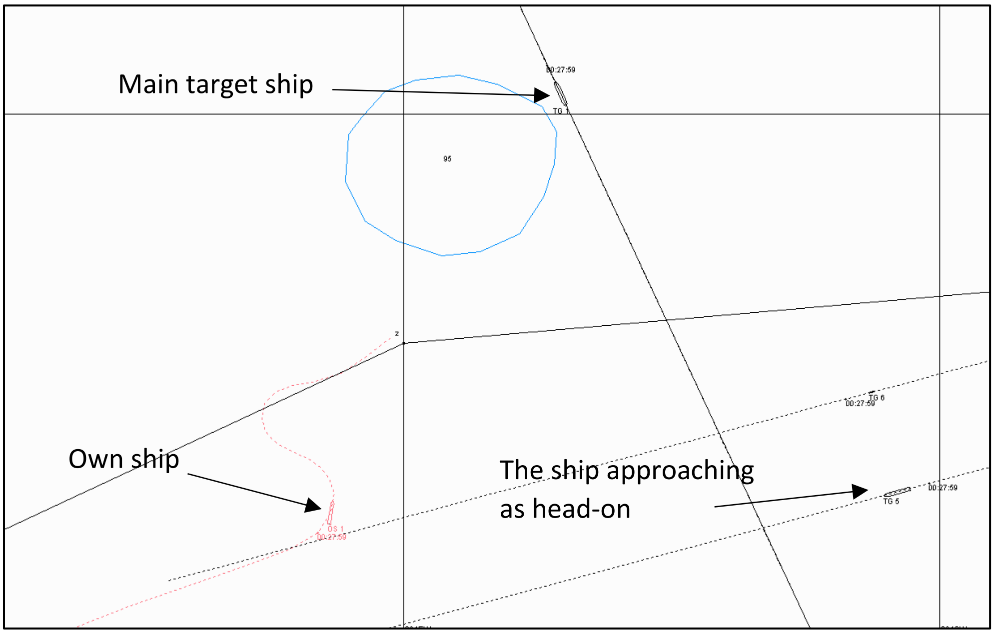


Figure 91 CMA CGM Florida, Classical scenario

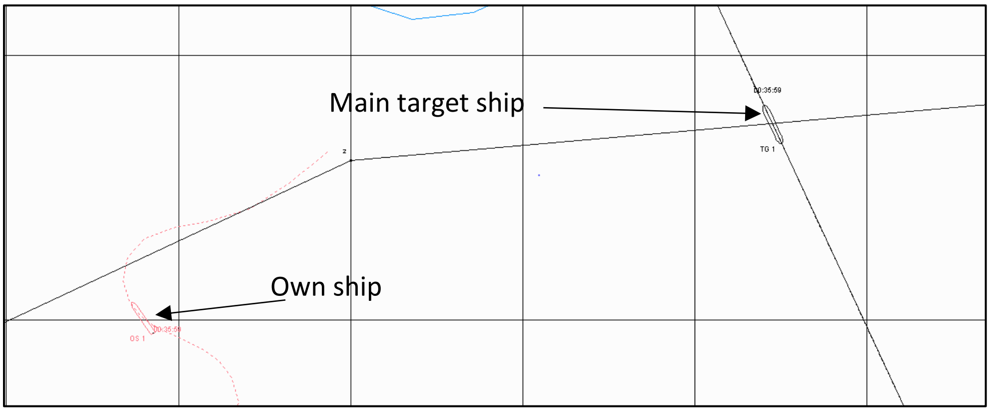


Figure 92 CMA CGM Florida, Classical scenario

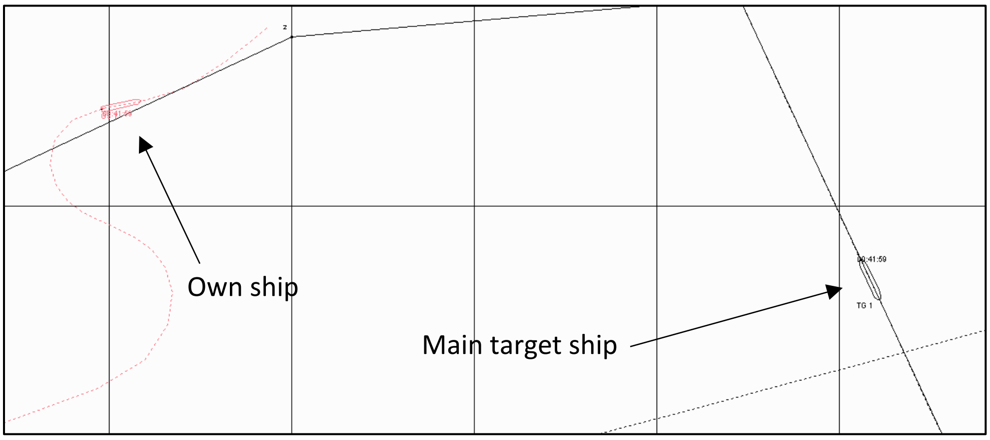


Figure 93 CMA CGM Florida, Classical scenario

The Automatic Approach experiment

In the *Automatic Approach*, the OOW has been trained to utilise the Automatic Collision Avoidance System. In this scenario, there were three targets, which have a CPA that is smaller than the required CPA, 1 NM. In this case, the Automatic Avoidance System has provided decisions to avoid every collision situation separately. In the following figures, the performance of the *Automatic scenario* is illustrated. Here, no speed reduction was needed or instructed by the Automatic system to avoid any of the targets. Also, the passing distance was just above the required CPA. Figure 94 is the illustration of the first action to avoid the fishing boats, then the ship was going back to the planned track. Figure 95 is the action to avoid the main target ship, which was through a course alteration only and no speed reduction was suggested by the Automatic system. Also, Figure 95 shows that there was no conflict with the head-on ship. Figure 96 shows where the own ship passed the main target safe and clear within the required CPA, and clear from the head-on approaching ship. After passing the main target safely, and when the OOW was sailing back to the planned track, the Automatic system detected the risk of collision with the third target and provided the best avoidance manoeuvre to avoid this collision Figure 97.

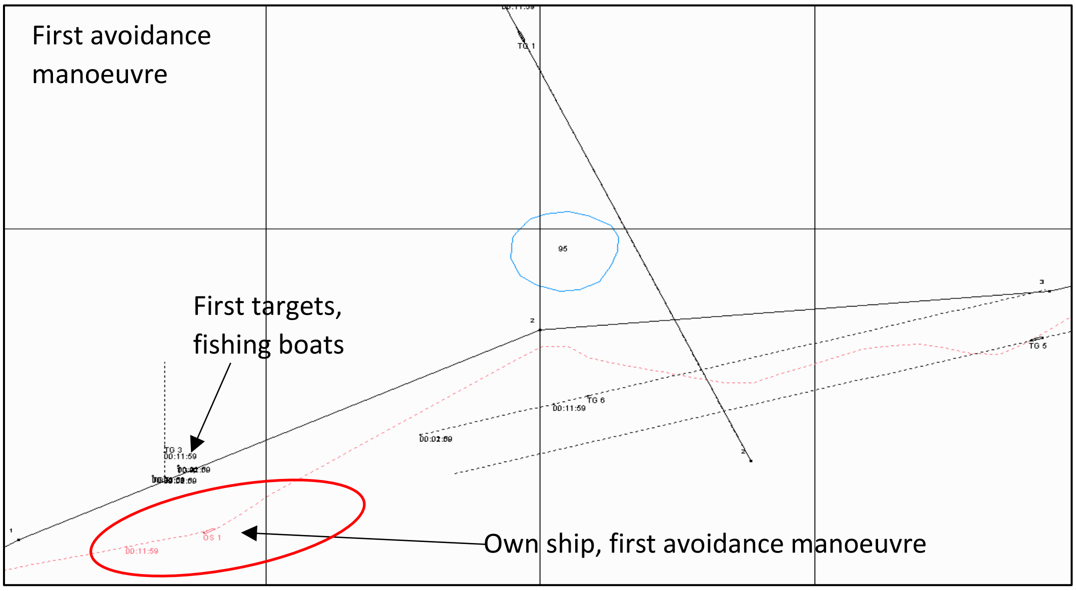


Figure 94 CMA CGM Florida, Automatic scenario

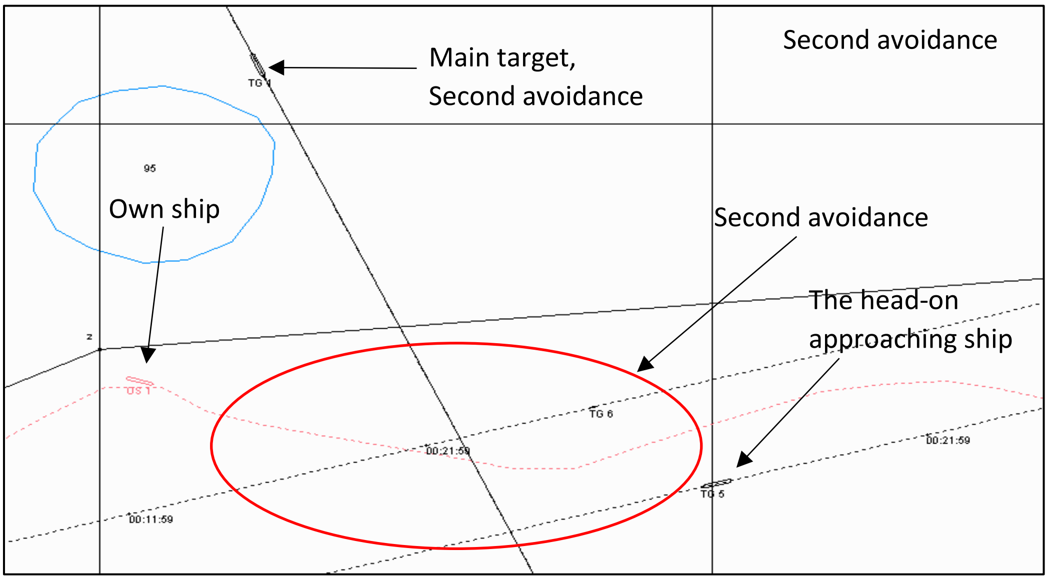


Figure 95 CMA CGM Florida, Automatic scenario

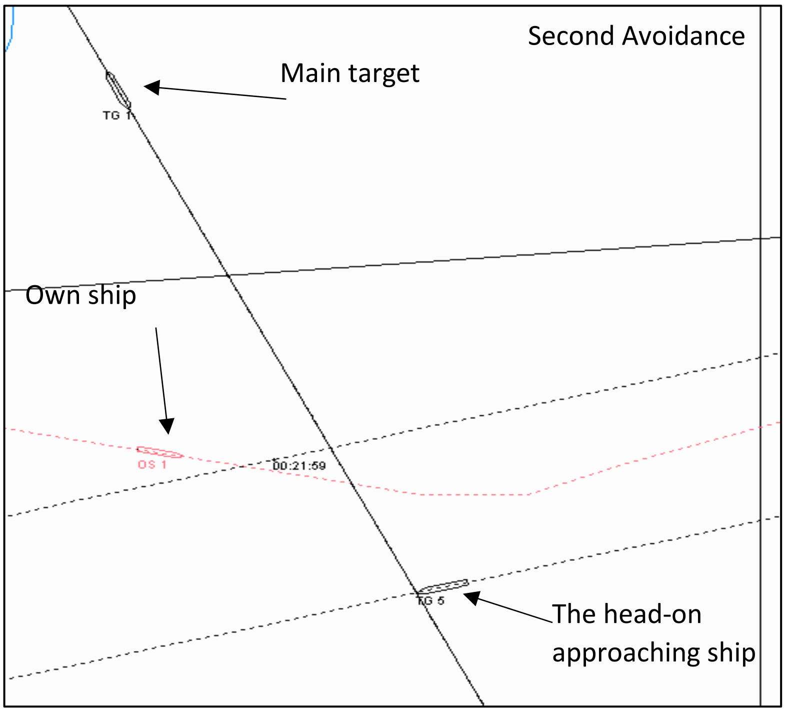


Figure 96 CMA CGM Florida, Automatic scenario

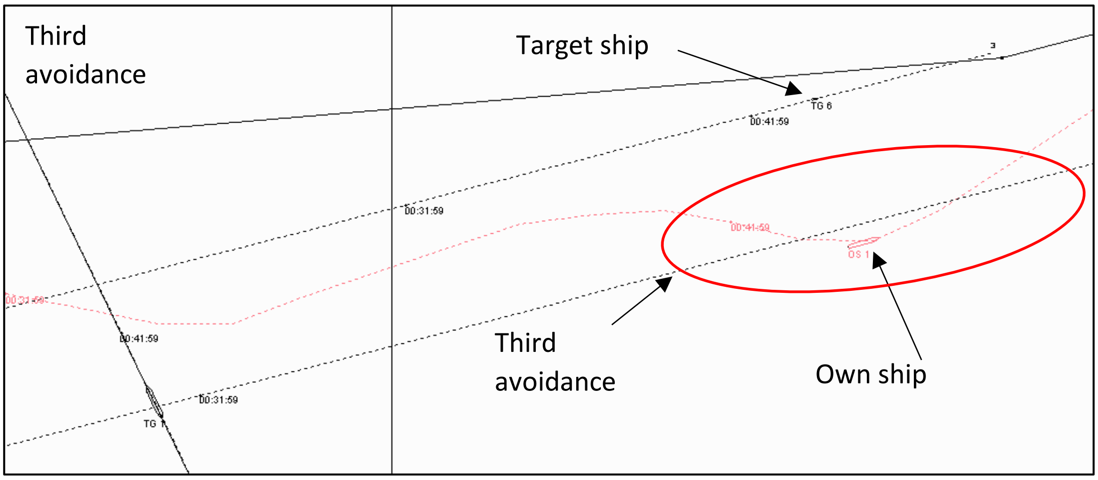


Figure 97 CMA CGM Florida, Automatic scenario

Table 21 The CMA CGM Florida's actions; real event actions, best action and the Automatic system decision

Time of Actions	***CMA CGM Florida* actions**	***Chou Shan* actions**	**Comments**	**Best action by *CMA CGM Florida***	**Best actions by *Chou Shan***	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
2340 (18/03/2013)	3rd off handed over to the Filipino 2nd officer, also the AB has been changed for the new watch. A Chinese trainee 2nd officer soon later arrived in the bridge; his role was to get familiar with the bridge. The Chinese officer did not understand the hand over instruction as it was in the Filipino language.		The ship's official language is English, and in the presence of foreign officers, English should be the only language to be used. The Chinese officer is a trainee officer and he should not interfere in the navigational decisions.				
0000 (19/03/2013)	2nd officer detected a number of fishing vessels on the port bow side on 6 NM. Also, Monte Pascoal was detected on 17.5 NM on the starboard side on a head on situation. And Hong Yun No 1 was ahead on the starboard side and it was an overtaking situation on 9 NM. *Chou Shan* was ahead on the port side in crossing situation on 14NM.	3rd officer handed over to the 2nd officer, and the AB has been changed as well.	The Filipino 2nd officer was using the table of AIS targets on ARPA, he was using the CPA and TCPA to assess the risk of collision. This table sort targets based on their CPA. However, the fishing boats have a CPA of 0.1 NM and they were on the top of the list.	Should have used ARPA properly to see all related information of targets. This would allow for better risk assessment and avoidance actions.			

Time of Actions	***CMA CGM Florida* actions**	***Chou Shan* actions**	**Comments**	**Best action by *CMA CGM Florida***	**Best actions by *Chou Shan***	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0002	6° to the starboard side to 065° to avoid the fishing boats. Also reduced the radar range to 6 Miles.		*Chou Shan* was out of the range of the Radar and could not be seen by Florida.	This was a complicated situation where it was; fishing boat avoidance, overtaking, head-on and stand on for the crossing situation. However, the Filipino officer should have properly assessed the situation and take better action not to put him in a conflict situation with other ships. A large alteration to starboard side could have avoided all the targets, however, the 2nd officer avoided such alteration not to divert far away from the original track.			The system would analyse all the situations and advises one avoidance action to avoid all the targets, which could be a large starboard alteration to avoid all of them.
0007	Another 5° to starboard. This was followed by another three times 5° degrees alteration to starboard side to be clear of the fishing boats. The Monte Pascoal moved to the port side of Florida. 2nd officer asked the Chinese 2nd officer to call fishing boats in Mandarin language and tell them	Manually acquired Florida and got its AIS data. Its CPA was less than 0.5 NM ahead of *Chou Shan*.	The action of multiple small alterations is prohibited by COLREG as it cannot be realised easily by other targets. Also, this was the result of poor assessment of the situation and the Filipino officer was assessing the situation as he alters the course.	Should have taken one significant action to avoid all targets.			The system would advise the OOW for the best action to avoid all the targets.

Time of Actions	*CMA CGM Florida* actions	*Chou Shan* actions	Comments	Best action by *CMA CGM Florida*	Best actions by *Chou Shan*	The developed Auto system actions in the experiment	Collision avoidance system response
	to be clear, fishing boats did not reply.						
0008:24						*Chou Shan* has been detected by the Auto system on the detection zone (10NM).	
0019		Called Florida by VHF, the Chinese 2nd officer answered and was talking in Mandarin. The Chinese officer poorly translated the conversation and agreed to pass astern of *Chou Shan*, and he asked the Filipino officer to pass their stern.	All VHF calls were in Mandarin language and then translated to English for the Filipino 2nd officer		Should not ask for a contrary avoidance action to what COLREG advises in this situation. Instead of asking for Florida to pass her stern, *Chou Shan* should have taken the avoidance action, which is to alter course to starboard and pass port-to-port whit Florida		The system would alert bot ships about the wrong decisions and advised about the best action to be taken by both ships.

Time of Actions	***CMA CGM Florida* actions**	***Chou Shan* actions**	**Comments**	**Best action by *CMA CGM Florida***	**Best actions by *Chou Shan***	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0021	Passed fishing boats and alter 5° to port (075°)	Was monitoring and expected the port alteration.	*Chou Shan* wrongly interpreted Florida's port alteration as an initial alteration to pass her stern.	Should have assessed the situation and not to impede other ships movements, like, *Chou Shan*. Also, the Filipino officer was acting as a stand-on vessel and expected *Chou Shan* to pass his stern.		*Chou Shan* was recognised to be in a collision course with *CMA CGM Florida* at 10 minutes before the collision.	The system would calculate and advised about the best action to avoid the collision. This includes the best time to take the actions (Last Minute Action).
0026	Another 5° to port and mentioned the small CPA with *Chou Shan*, the Chinese officer asked if he is passing its stern. Here the Filipino officer said he is expecting *Chou Shan* to pass port-to-port and from Florida's stern.	Altered course from 165° to 160° then to 155° to support Florida passing his stern.	Teamwork deficiencies, and wrong decisions.	Should have taken an avoidance action, because also stand on vessels in case of not enough action by the give-way vessel still need to take the best action not to collide.	Should have avoided the collision by taking better and safe avoidance action (alter starboard side and pass port-to-port with Florida)	The Auto system has alerted the OOW about the collision situation and provided the best action to avoid the collision. This is to alter course to 101° to avoid the collision. After performing this action *CMA CGM Florida* passed safely from *Chou Shan*.	Would warn and advised both ships about the best actions and times to avoid the collision.
0027	Another 5° to port (065°). Shortly after the alteration, the Filipino officer said, as Hong Yun No1 is ahead, then *Chou Shan* must pass port-to-port. The Chinese officer called *Chou Shan* and asked them	As they accepted the port-to-port passing they asked Florida to alter course to starboard as well. Shortly after the VHF call the 2nd officer					The system would ensure better situational awareness for both ships and that would prevent the situation from getting

Time of Actions	***CMA CGM Florida* actions**	***Chou Shan* actions**	**Comments**	**Best action by *CMA CGM Florida***	**Best actions by *Chou Shan***	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
	to pass port-to-port. *Chou Shan* was 2 NM away and CPA was 0.3 NM. *Chou Shan* refused this, but the Chinese officer insists and said this is the master request, so they accepted. The Chinese officer translated to the Filipino officer that they agreed to pass port-to-port, without telling him to alter his course, as he agreed with *Chou Shan*.	asked for hand steering and ordered 20° to starboard					too complicated by advised and warn about the dangerous situation in advance.
0030	Still concerning about *Chou Shan* alteration and asked the AB to alter 10° to starboard using autopilot. The Chinese officer still asking the Filipino officer if he is passing *Chou Shan*'s stern. The Filipino officer said he is expecting them to pass astern and he is only altering to starboard to support them. Also, the Filipino officer was using the flashing light toward *Chou Shan*. The Chinese officer still suggesting Florida to pass astern of *Chou Shan*.	Was turning to starboard, then asked the AB to sail heading to Florida. The AB put mid-ship to adjust the heading, and he asked the OOW to go hard to starboard. The 2nd officer agreed to this and the AB turned on 0031	Good teamwork as the AB questioned the OOW order and suggested a better order. Very bad teamwork on Florida and the Filipino officer should not engage the Chinese officer in the navigational duties as he is still in the familiarisation period. Also, they all should be using the English language to avoid mistranslating and misunderstanding.				The system would help in enhancing situational awareness in an earlier stage.

Time of Actions	***CMA CGM Florida* actions**	***Chou Shan* actions**	**Comments**	**Best action by *CMA CGM Florida***	**Best actions by *Chou Shan***	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0031	Ordered hand steering and ordered hard to port, shortly he ordered steady then hard to starboard. As they both were getting closer, the Filipino officer was flashing to *Chou Shan*, and called the master to come to bridge about 18 seconds before the collision, the master was reported about the very close vessel.	Master was not called before the collision.					
0033 (Collision time)	Being collided from the port side by *Chou Shan*	Collided with Florida by the bow.					
	Extensive damage on the port side and oil pollution happened.	Serious damage on the bow area.					

General comments about Florida's actions:

- Bad teamwork, which leads to decisions being made by the trainee officer without communicating it with the OOW.
- The first action by the OOW to avoid the fishing boats leads to more complications in further stages.
- The reluctant to deviate from the original track for a long distance.
- Being engaged in multiple collision situations has confused the OOW about the beat action to avoid both of them.

General comments about *Chou Shan* actions:

- Using VHF to negotiate collision avoidance procedures.
- Taking actions against COLREG protocols.

OOW’s opinion about the developed Automatic Collision Avoidance System

The main benefit that was highlighted by the OOW when the Automatic Collision Avoidance system was utilised is the removal of the uncertainty of the decisions that are always associated with the classical procedures for collision avoidance. Additionally, the help of the Automatic system to prevent further conflict situation with other targets was also mentioned by the OOW. He also mentioned that he had to reduce speed in the *Classical scenario* just to ensure the safety of his ship. Where in the *Automatic approach*, the system provides accurate decisions that allowed his ship to pass clear of all targets without reducing the speed.

CMA CGM Florida experiment KPIs

The tables of the collected data, which have been used to calculate the KPIs results are provided in Tables 22 and 23. Moreover, Figure 98 below shows the KPIs result for both the Classical and the *Automatic scenarios*. The chart shows that there is a fluctuation in the *Classical scenario’s* result. First, a slight delay in the detection time, this is due to the fact that the OOW was focusing on the first avoidance manoeuvre. Since the OOW passed the first target clear he detected the main target (second target) and immediately decided to take the avoidance action, which was a very early action. This early action has resulted in a very large passing distance with a hard course alteration and speed reduction. In the last KPI, the track deviation, the ship was away from the original planned track to avoid the first targets. Thus, the OOW’s avoidance decision was toward the planned track, and this shows a very small deviation from the planned track. Still, the OOW's decision was not correct as he unnecessarily reduced the speed and passed far away from the target ship.

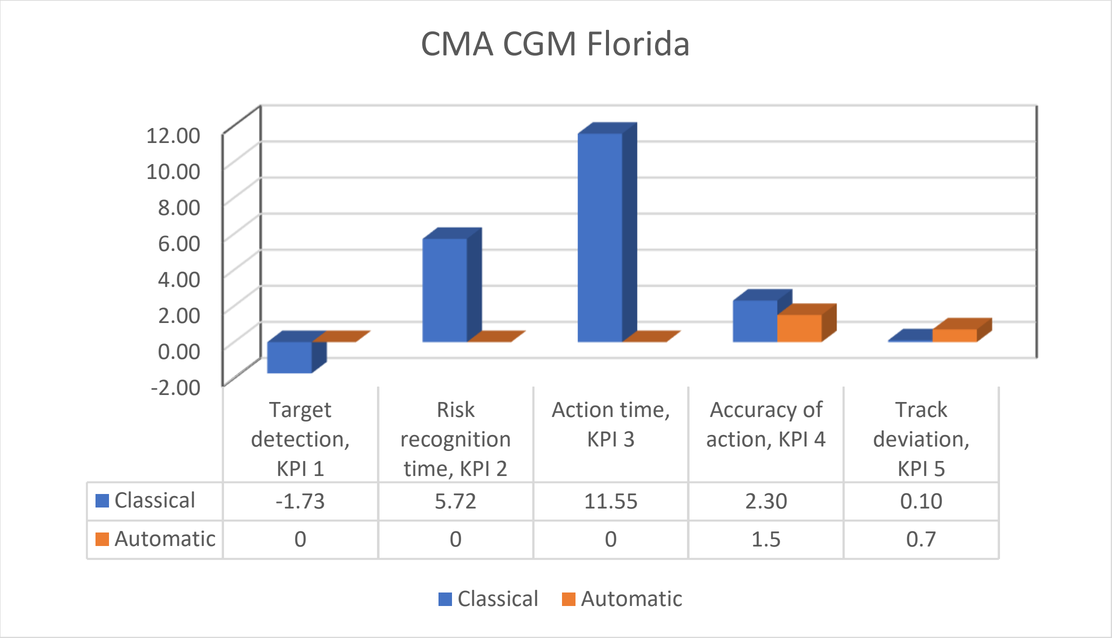
In the *Automatic scenario*, the results show that the times in the first three KPIs were ideally matched with the benchmark, no delay or early ineffective actions. Then, in the passing distance, the Automatic Avoidance System provided a decision that allowed the ship to pass slightly above the required CPA. Still, the own ship was the stand-on vessel, and she should not take any action. Nevertheless, when the give-way (target) vessel did not take any avoidance manoeuvre, the Automatic Collision Avoidance system alerted the OOW about the situation and provided the necessary action to avoid the collision. Finally, track deviation distance was within the allowed limits.

Table 22 CMA CGM Florida Classical scenario data

Classical Approach CMA CGM Florida		
Measures	Data	Unit
Time of appearance	00:11:58	Time
Time of detection	00:13:42	Time
Actual time of risk	00:21:58	Time
time of recognition	00:16:15	Time
required action time	00:30:00	Time
actual action time	00:18:27	Time
required CPA	1	NM
Range	2.3	NM
XTE	1	NM
Actual Deviation	0.1	NM

Table 23 CMA CGM Florida Automatic scenario data

Automatic Approach CMA CGM Florida		
Measures	Data	Unit
Time of appearance	00:08:24	Time
Time of detection	00:08:24	Time
Actual time of risk	00:20:39	Time
time of recognition	00:20:39	Time
required action time	00:25:28	Time
actual action time	00:25:28	Time
required CPA	1	NM
Range	1.5	NM
XTE	1	NM
Actual Deviation	0.7	NM



	Target detection, KPI 1	Risk recognition time, KPI 2	Action time, KPI 3	Accuracy of action, KPI 4	Track deviation, KPI 5
Classical	-1.73	5.72	11.55	2.30	0.10
Automatic	0	0	0	1.5	0.7

Figure 98 CMA CGM Florida, KPIs results. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.3 Scenario 3 (Dutch Aquamarine)

Accident report (MAIB, 2003)

This is a collision accident between the chemical tanker *MV Dutch Aquamarine* and the general cargo ship *MV Ash*. On the 9th of October 2001, at 1620, in Dover Strait TTS heading south-west, both vessels were on the same lane and heading in the same direction when *Dutch Aquamarine* collided with *MV Ash* from the stern. Weather conditions and visibility were good.

Before the collision, *Dutch Aquamarine* was sailing in the Traffic Separation Scheme TTS, where it was a common practice to overtake the slower ships with a small CPA distance in such navigational area. However, *Dutch Aquamarine* speed was 12.5 Knots and was overtaking the slower ships. Among these ships was *MV Ash*, which has a 6.25 Knots speed. *Dutch Aquamarine* was approaching the stern of *MV Ash* as the overtaking vessel. *MV Ash* detected the overtaking vessel *Dutch Aquamarine* in her stern. She is the stand-on vessel and should have maintained her course, yet, the OOW got distracted and did not monitor the development of the collision situation, which requires him to take any avoidance action if the give-way vessel is not avoiding. *Dutch Aquamarine* is the give-way vessel, which should have taken the avoidance action, but she just saw *MV Ash* prior to the collision, despite the efforts has been made to avoid the collision, it collided with the stern of the *MV Ash*.

The event's scenario in the simulator, Classical and Automatic Approaches

In this experiment, the same OOW has performed the *Classical and* Automatic scenarios. For the reconstruction of this scenario, the MAIB accident report (MAIB, 2003) was used to find the details and actions for both vessels that led to the collision event. The following screenshots have been taken from the simulator control station to show the scenarios in both the *Classical and Automatic approaches* of the experiment (Figures 99 and 100). The first picture, Figure 99, shows the *Classical scenario*, where the own ship and its movement track have been labelled, as well as the target ship. The direction of movement is south-west to follow the TTS flow where other ships, which were sailing on the lane were also labelled. In Figure 100, the *Automatic scenario* is illustrated. The own ship and the target ship were labelled in the picture as well as their movement track. As it was a busy traffic area, other ships were labelled in the traffic lane where they were sailing in the same direction. Table 24 has detailed actions taken by the own and target ships from the real accident report, the best action should have been taken according to the author's opinion, and the Automatic Collision Avoidance system's proposed actions to avoid this accident.

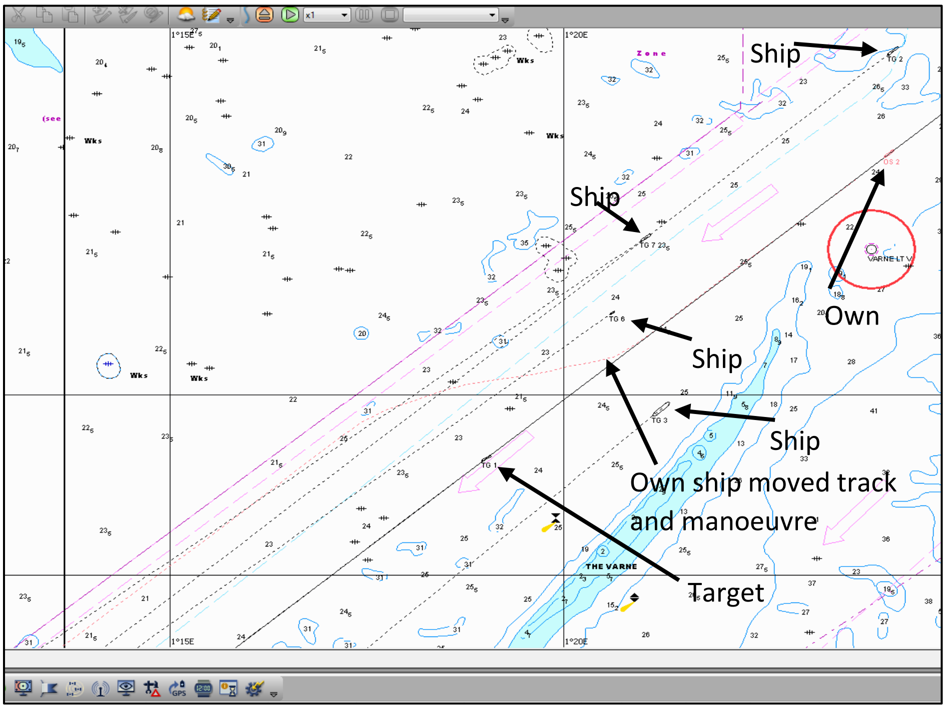


Figure 99 Dutch Aquamarine Classical scenario

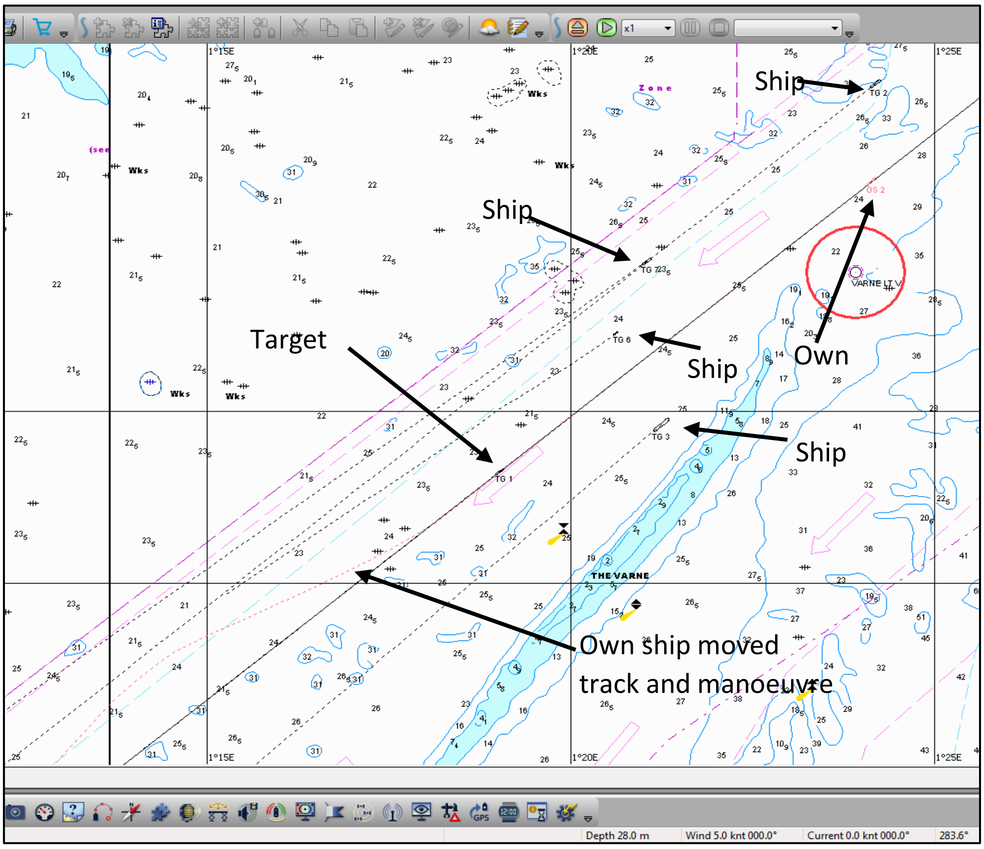


Figure 100 Dutch Aquamarine Automatic scenario

The Classical approach experiment

In this scenario, the OOW has decided to take an early large action to avoid the target in front of his ship, as well as not to engage in any other conflict situation with other ship (Figure 101). This led him to alter the course significantly and to sail near the border of the TTS (Figure 102). As a result, the passing distance from the target ship and the track deviation were to some extent large, especially in such a narrow and dense traffic lane (Figure 103). Also, this led to a long travel time away from the original planned track, which is not recommended to avoid any dangerous restrictions in the water, such as; shipwrecks, shallow water or prohibited areas. Figure 104 shows the own ship sailing back to the planned track after passing the target ship.

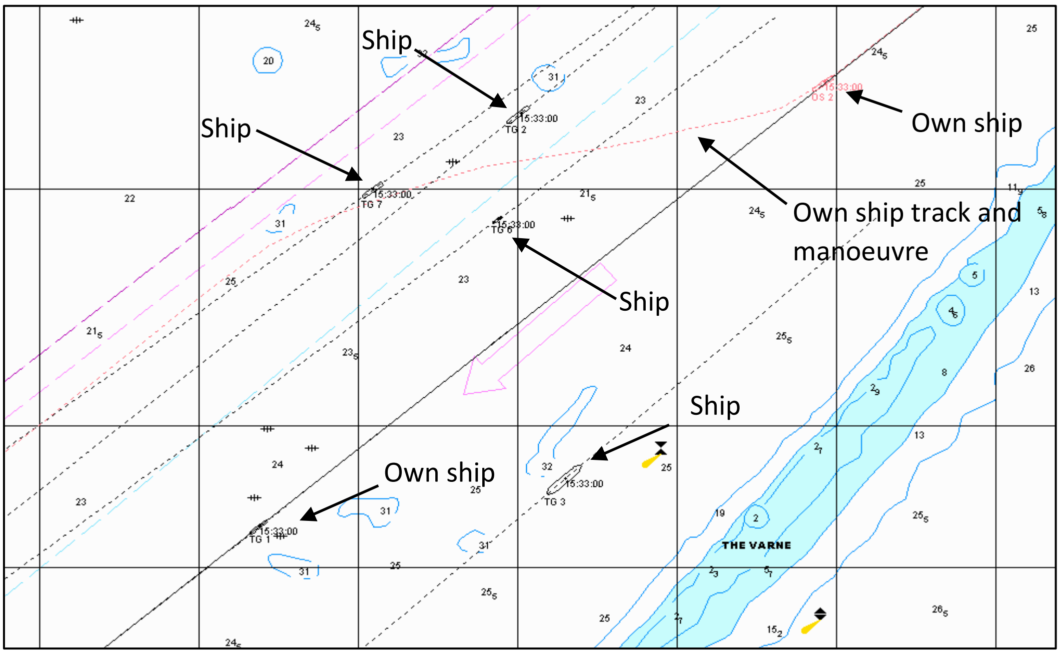


Figure 101 Dutch Aquamarine Classical scenario

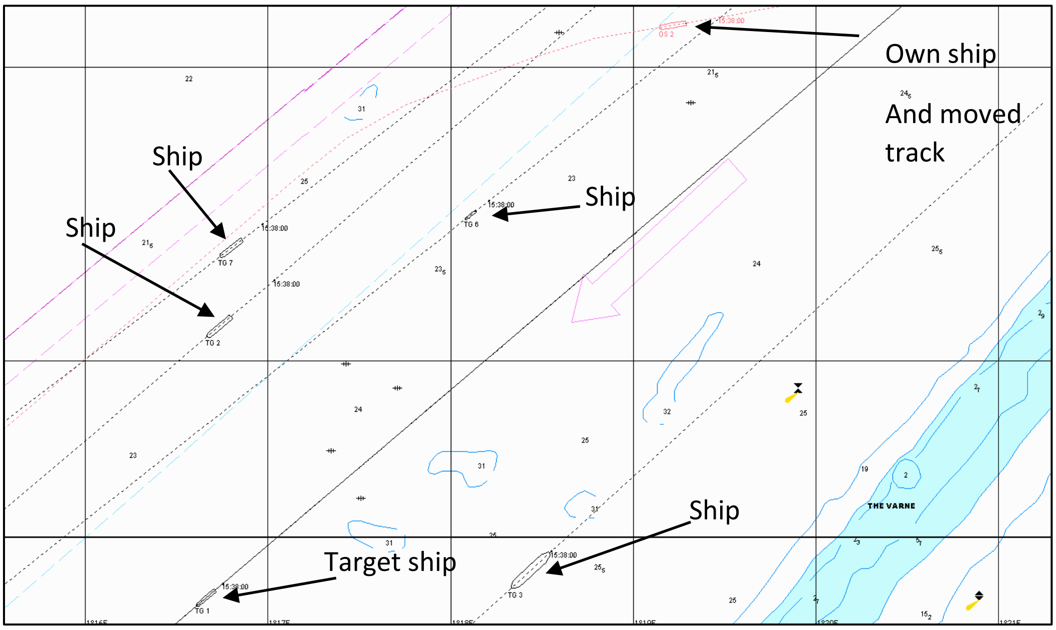


Figure 102 Dutch Aquamarine Classical scenario

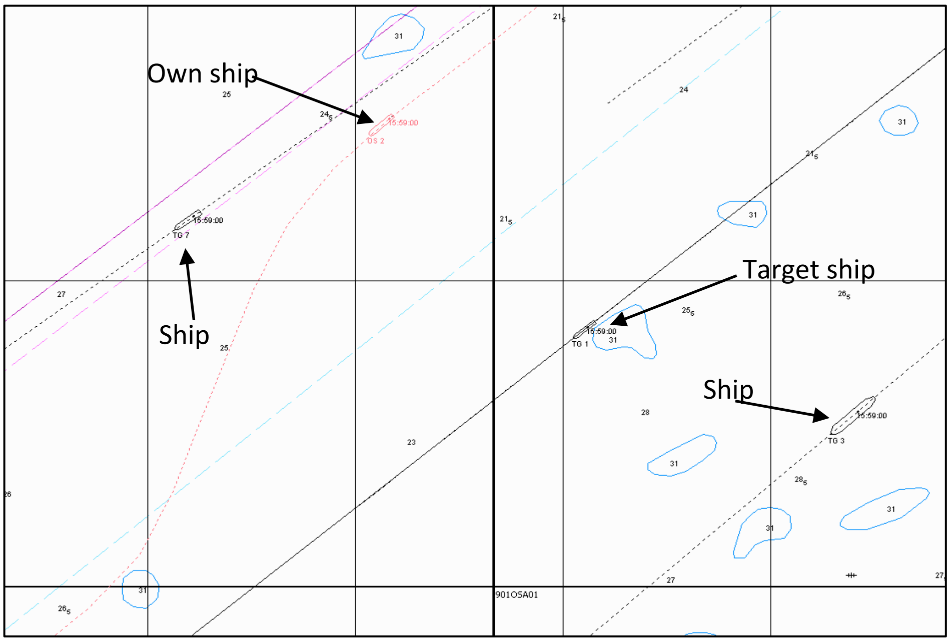


Figure 103 Dutch Aquamarine Classical scenario

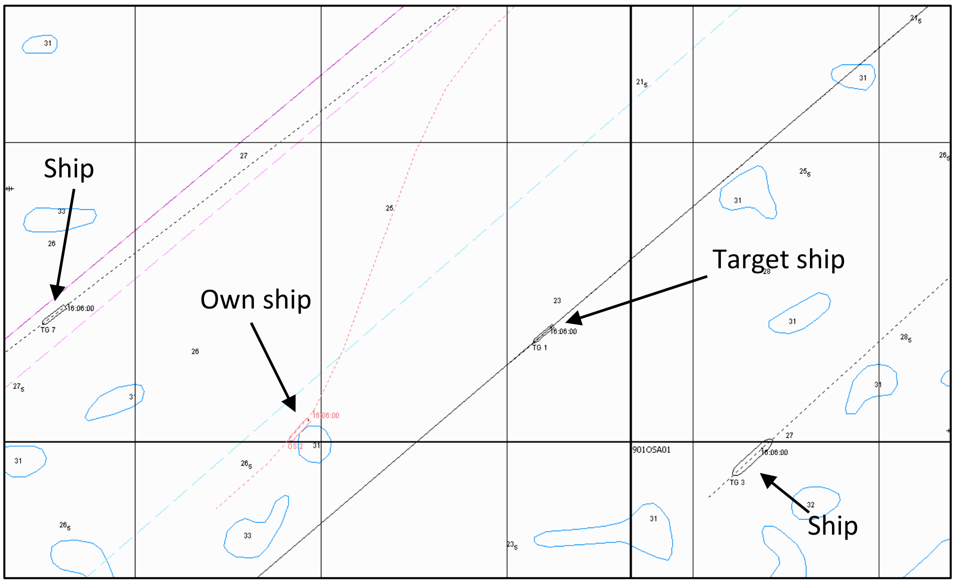


Figure 104 Dutch Aquamarine Classical scenario

The Automatic Approach Experiment

In the *Automatic scenario*, the system has provided an avoidance manoeuvre that allowed the ship to pass between other ships without any violation of the minimum required CPA Figure 105. This has resulted in little diversion from the original track, as well as satisfying the condition of minimum CPA (Figure 106). Figure 107 shows the own ship sailing back to the planned track after passing the target ship safely.

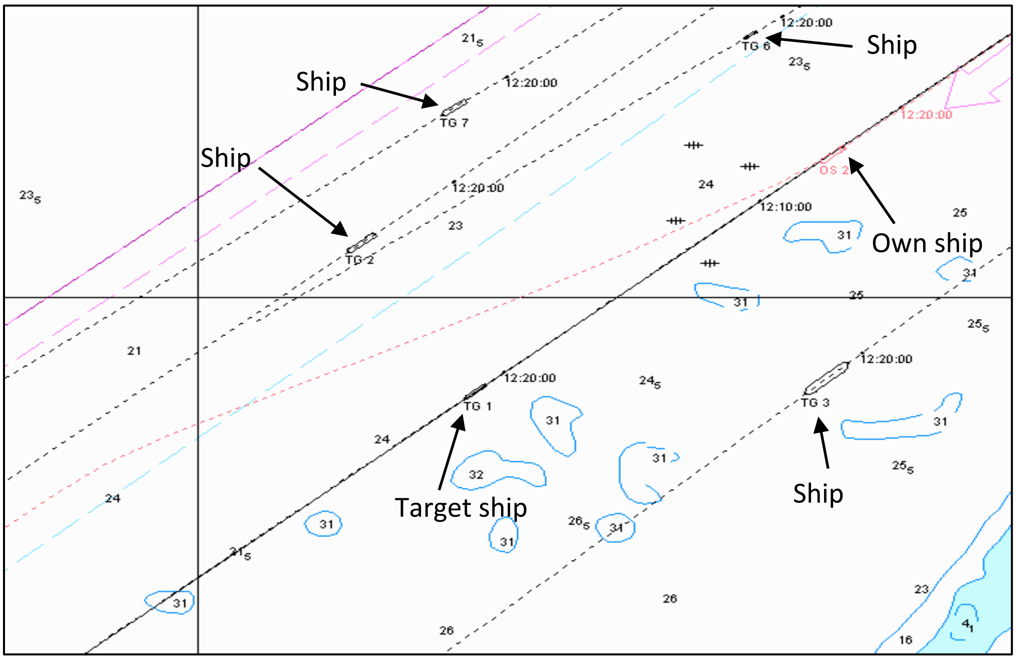


Figure 105 Dutch Aquamarine Automatic scenario

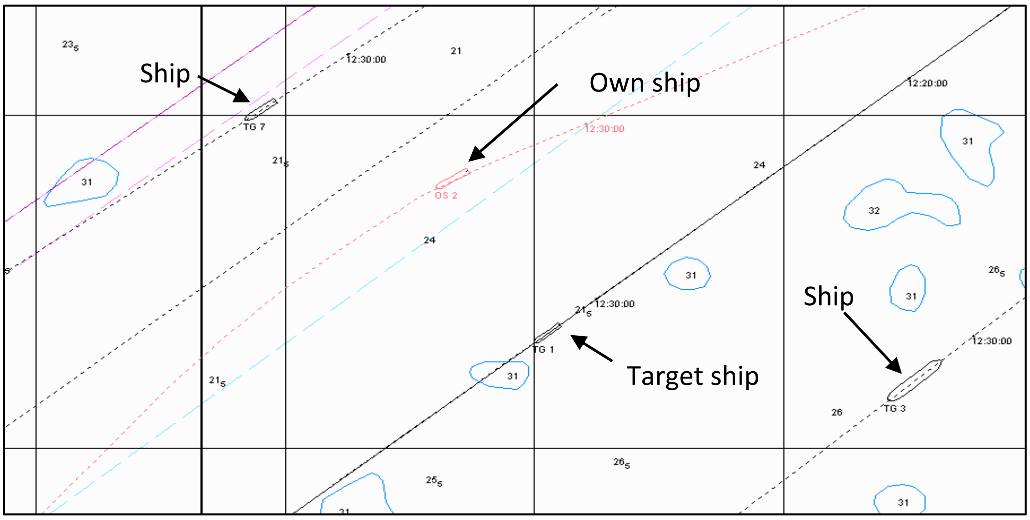


Figure 106 Dutch Aquamarine Automatic scenario

Table 24 The Dutch Aquamarine actions; real event's actions, best action and the Automatic system decisions

Time of Actions	***Dutch Aquamarine* actions (South-west traffic lane)**	**Ash actions (South-west traffic lane)**	**Comments**	**Best action by *Dutch Aquamarine***	**Best actions by Ash**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0210	Left Antwerp berth						
0700	Pilot disembarked						
0800		Entered the TTS					
1200	The chief officer handed the watch over to 2nd officer and entered the TTS		*Dutch Aquamarine* was faster than most of the other ships and was making a lot of close pass overtaking.				
1400		Made a planned course alteration to 235° and kept this course until it collided. Speed was 6.5 knots					
1508	Passed CS3 buoy and kept 235° course and speed 12.8 knots						

Time of Actions	***Dutch Aquamarine* actions (South-west traffic lane)**	**Ash actions (South-west traffic lane)**	**Comments**	**Best action by *Dutch Aquamarine***	**Best actions by Ash**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
1520						The Auto system has detected the target ship (*MV Ash*) once she entered the detection zone (10NM).	
1541:10						The Auto system has recognised the risk of collision 10 minutes before the collision between *Dutch Aquamarine* (own ship) and *MV Ash* (target). Then alerted the OOW about the risk of collision with *MV Ash* and provided the best avoidance action, to alter course to 244°. The ships passed safely after this alteration by *Dutch Aquamarine* (own ship).	
1554	Overtook two vessels and Ash was on 1.5 NM and right ahead. The 2nd officer did not see Ash ahead of him after these overtaking.		2nd officer was using EBL and VRM on the radar to calculate the risk of collision. Then he overtook two vessels and did not see Ash ahead of him after he passed clear of them, it				The system would warn the 2nd officer about Ash, as she is on a collision course, also it would provide the best action to avoid the collision.

Time of Actions	***Dutch Aquamarine* actions (South-west traffic lane)**	**Ash actions (South-west traffic lane)**	**Comments**	**Best action by *Dutch Aquamarine***	**Best actions by Ash**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
			took 12 minutes before he collided Ash. ARPA was not working efficiently on *Dutch Aquamarine*, this why radar was in use.				
N/L	2nd officer **did not see *MV Ash*** until it was very close and just before the collision, she was almost right ahead. About the time of the collision, the 2nd officer put hard to starboard and full astern.	Saw the *Dutch Aquamarine* from the chart table window 1 NM aft of his ship. Then he was engaged on phone call with the vessel's charterer. The chief officer was on call at the collision time, and he knew about it by crew shouting on deck.	The chief officer detected *Dutch Aquamarine* on 5 NM but did not take an action because she is the overtaking vessel and she shall keep clear of him. Also, as an overtaken vessel it is stand-on situation and she shall monitor the situation and avoid the collision if the give-way vessel is not taking good avoiding action.	The lookout was not sufficient in both ships. Proper lookout could help in detecting the collision situation and avoiding it. Seeing *MV Ash* position (right ahead), the collision would be easily avoided by the 2nd officer.	Look out was not sufficient on both ships. Extra lookout could have helped in detecting the collision situation and avoid it. Rule 17 was not applied in the situation, the chief officer should have monitored *Dutch Aquamarine* once he detected it and warn others about the collision situation, if she is not taking action or her action is not enough to avoid the collision, Ash should have taken the best action to avoid the collision.		The system would warn both ships about the collision situation and provide the best action to avoid it. Also, by sharing information and Sharing the decision the situation could have been avoided as the situational awareness would have improved and both ships would have known about the situation and how to avoid it. Also, by Manoeuvre Acknowledgment, Ash would have realised that *Dutch Aquamarine* is not taking any avoiding action, and she should avoid the collision as per rule 17, Last Minute Action.

Time of Actions	***Dutch Aquamarine* actions (South-west traffic lane)**	**Ash actions (South-west traffic lane)**	**Comments**	**Best action by *Dutch Aquamarine***	**Best actions by Ash**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
1620 (collision time)	Collided with the starboard quarter of Ash	Has been hit by *Dutch Aquamarine*'s bow,					
N/L	Started to detach from Ash by the stern engine order	Another contact by *Dutch Aquamarine* in the side					
N/L		Listed to starboard and water entered cargo hold. Master ordered to abandon the ship and jump in the water. The master dead in the water and the ship capsized and sank. The crew *MV Ash* was rescued by the *Dutch Aquamarine* crew.					

General comment:

- The Channel Navigational Information Services (CNIS), which should monitor and manage Dover Strait, did not warn the ships about the situation and it did not take any action to stop the collision. (This is a sign about the poor role of the VTS in collision avoidance procedures).
- Although *Dutch Aquamarine* was not operating ARPA system for collision risk assessment, even though, if ARPA was operating it would not alert the OOW about the collision situation, as it needs a manual question to detect the situation.
- It could be the case that Radar was not able to detect Ash because of the moderate sea and sea clutter in the radar screen. Also, the radar maybe was not able to detect Ash echo because of its small and low structure.
- Rule 17 violations, because the stand-on vessel was assuming that the give-way vessel is aware about the situation and is going to avoid the collision. Where in this situation if the stand-on vessel knew that the give-way one is not taking any action then she should take the best action to avoid the collision.

OOW's opinion about the developed Automatic Collision Avoidance System

In this experiment, the OOW got supported by the utilisation of the developed Automatic Collision Avoidance System to better avoid the target ship with no need for a significant avoidance action. He was uncertain about the avoidance action in the *Classical scenario*, which made him take early and major action. The OOW highlighted the benefit of the Automatic system, which provided an avoidance decision that allowed him to pass the threatening target without the need to hesitate about the consequences of his action for other conflict situation with other ships.

Dutch Aquamarine experiment KPIs

Tables 25 and 26 provide the collected measures for these scenarios, which were used to calculate the KPIs. The chart in Figure 108 illustrates the KPIs results for both the *Classical and Automatic scenarios*. From these results; it appears that in the *Classical approach*, the risk recognition and action time was performed very early. Where the detection time was almost at the right moment. However, early recognition has resulted in an early and large action that was not necessary. Additionally, if the information is retrieved from the original accident reported, it shows that the ship has not detected the target ship until it was too late to avoid the collision. Also, the stand-on vessels did not take any action to avoid the collision.

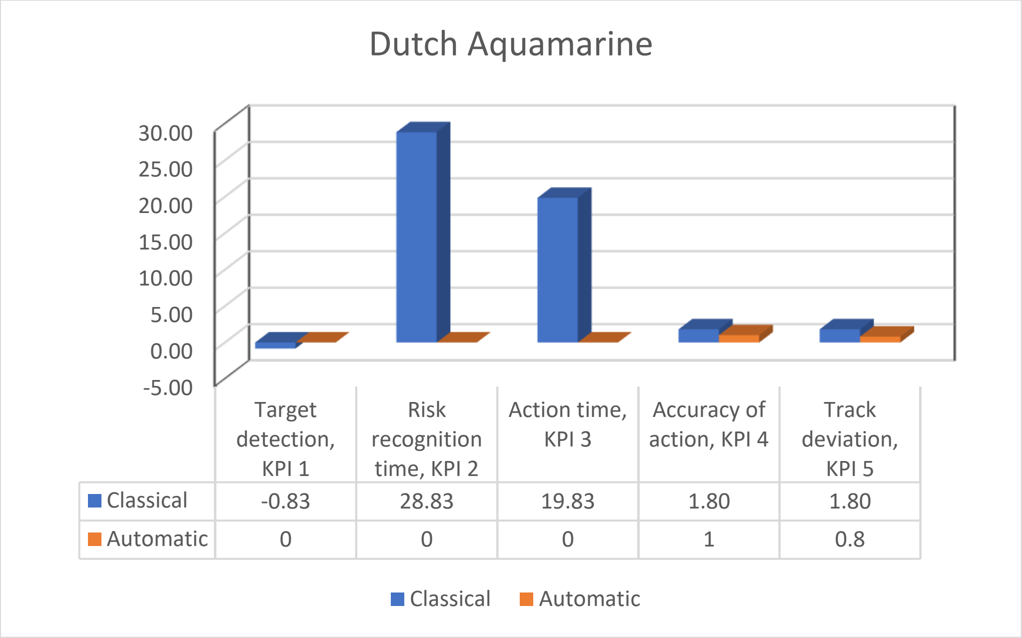
By looking at the *Automatic scenario*, the results were almost in agreement with the benchmark for each KPI. This provides evidence about the performance of the developed new system and how it helps in emergency critical collision situations.

Table 25 The Dutch Aquamarine Classica scenario data

Classical Approach Dutch Aquamarine		
Measures	Data	Unit
Time of appearance	15:20:00	Time
Time of detection	15:20:50	Time
Actual time of risk	15:52:00	Time
time of recognition	15:23:10	Time
required action time	15:52:30	Time
actual action time	15:32:40	Time
required CPA	0.5	NM
Range	0.9	NM
XTE	0.5	NM
Actual Deviation	0.9	NM

Table 26 The Dutch Aquamarine Classica scenario data

Automatic Approach Dutch Aquamarine		
Measures	Data	Unit
Time of appearance	15:20:00	Time
Time of detection	15:20:00	Time
Actual time of risk	15:41:10	Time
time of recognition	15:41:10	Time
required action time	15:41:10	Time
actual action time	15:41:10	Time
required CPA	0.5	NM
Range	0.5	NM
XTE	0.5	NM
Actual Deviation	0.4	NM



	Target detection, KPI 1	Risk recognition time, KPI 2	Action time, KPI 3	Accuracy of action, KPI 4	Track deviation, KPI 5
Classical	-0.83	28.83	19.83	1.80	1.80
Automatic	0	0	0	1	0.8

Figure 108 Dutch Aquamarien KPIs' results. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.4 Scenario 4 (*Ileksa*)

Accident report (MAIB, 2005b)

This accident is the collision accident between the general cargo ship *Ileksa* and the container vessel *Cepheus J*, in Kattegat at the Danish water. This event happened on the 22nd of November 2004, at 0519. At that date, the weather forecasted to be windy and rainy, with wind speed recorded as 7 in Beaufort scale and visibility was from 0.8 to 4 NM. Both vessels were steering in the recommended route as a south-east direction. The *Cepheus J* was approaching from the stern of Ileska, her speed was 16 Knots, and Ileska's speed was 6.5 Knot. This was an overtaking situation, and *Cepheus J* was the give-way vessel. However, the OOW sent the lookout for cleaning, and himself was busy in paperwork. The OOW in *Cepheus J* did not see *Ileksa* until the collision occurred. In *Ileksa*, the OOW detected *Cepheus J* overtaken *Ileksa*, and he recognised the risk of collision. The OOW was assuming that *Cepheus J* will take the avoidance manoeuvre as per the COLREG regulation. When *Cepheus J* was about 0.5 NM, the OOW in *Ileksa* recognised the risk of collision, yet, he did not take immediate action to avoid the collision. He started a VHF call to ask *Cepheus J* about her intention when he received no reply, he started to take action, but the collision was unavertable. In this collision event, both vessels were severely damaged, but no injuries and pollution were reported. Both vessels continued their voyage to the recovery ports.

The event's scenario in Classical and Automatic Approaches

In this experiment, the same OOW has performed the Classical and *Automatic approach*es. Where the location of the collision was not available in the simulator database, an alternative area has been selected to reconstruct the collision scenario. Thus, the same information and details in the accident report have been used to build the scenario (MAIB, 2005b). Figure 109 shows the scenario for the *Classical approach in which* the target and own ships are labelled. Also, the track and manoeuvre of own ship are plotted in Figure 110, which illustrates the *Automatic scenario*. The target and own ships are labelled, as well as the own ship track and manoeuvre. Table 27 has the detailed actions taken by the own and target ships from the real accident report, the best action should have been taken from the author's point of view and the Automatic Collision Avoidance system’s decision for this accident event.

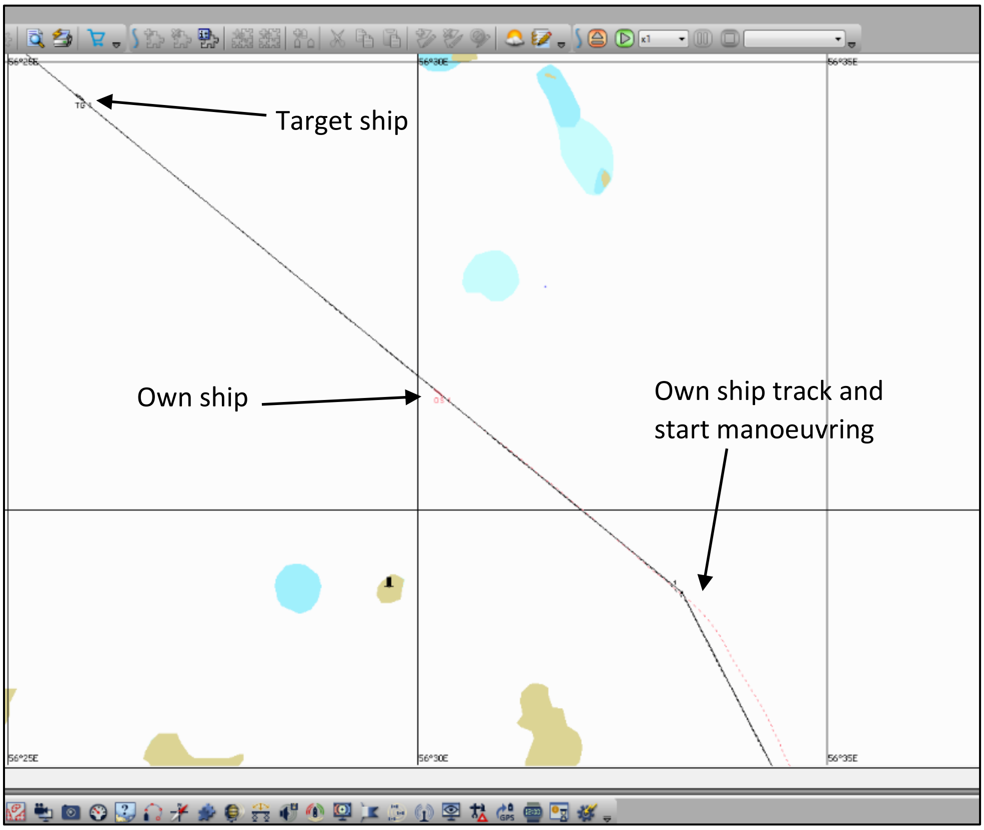


Figure 109 Ileksa Classical scenario

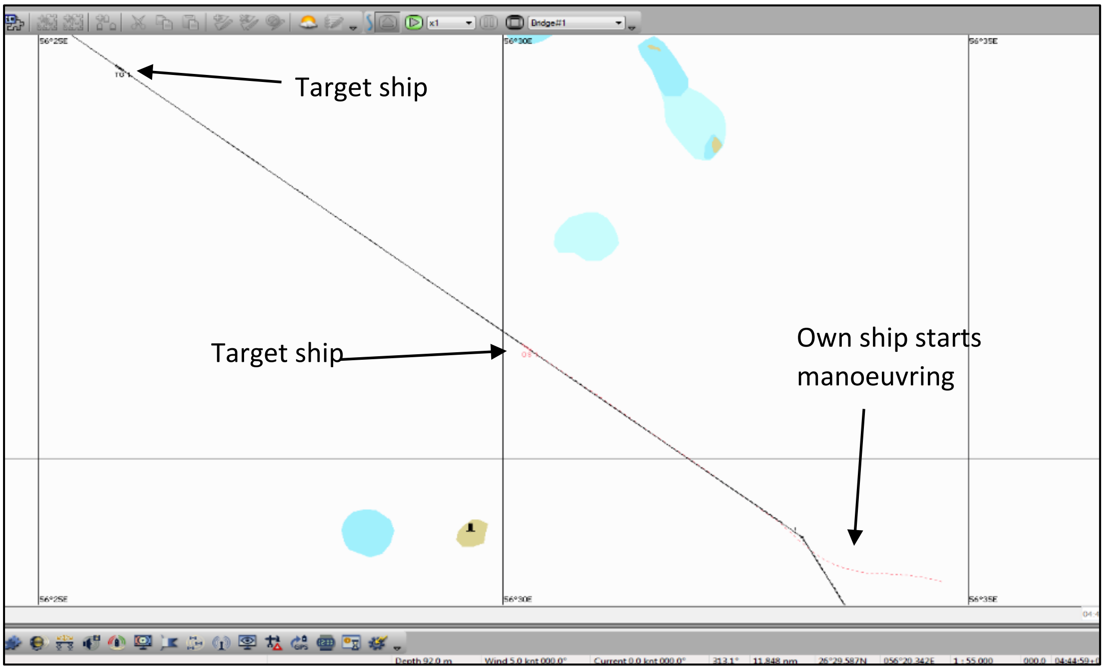


Figure 110 Ileksa Automatic scenario

The Classical Approach experiment

In this scenario, the own ship is the overtaken vessel, and per the COLREG regulation, she should maintain her course, speed and keep away from the overtaking vessel. Therefore, the OOW was late in detecting the target ship approaching from the stern. In general, less priority is usually given to the stern area, and a short distance is being monitored in the radar. This is to enable a long observation distance in the front of the ship. In addition, after the detection (late detection) of the target approaching from the stern, the OOW in own ship (in the front) hesitated to take an avoidance action as he is the stand-on vessel (Figure 111). Therefore, the OOW took a small course alteration just to avoid the immediate risk of collision (Figure 112). Figure 113 shows the result of the late and small action by the OOW, which has led to a small passing range (CPA) from the target ship.

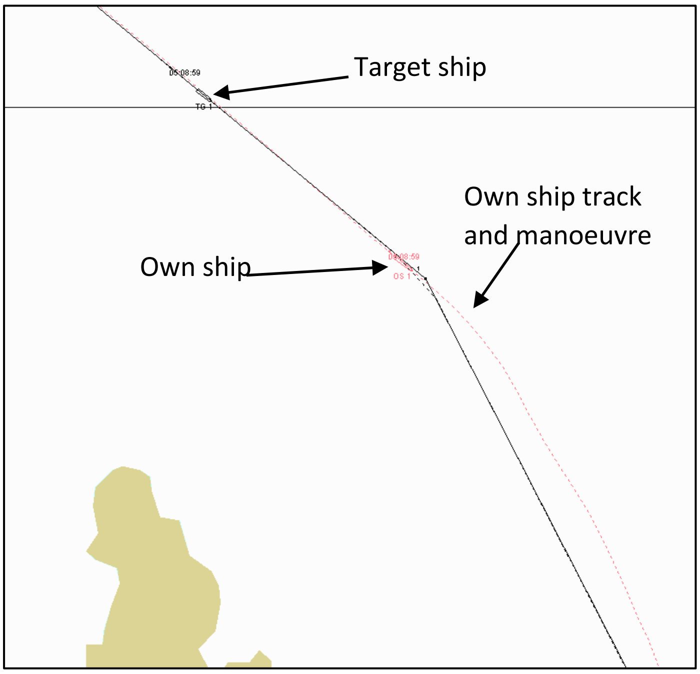


Figure 111 Ileksa Classical scenario

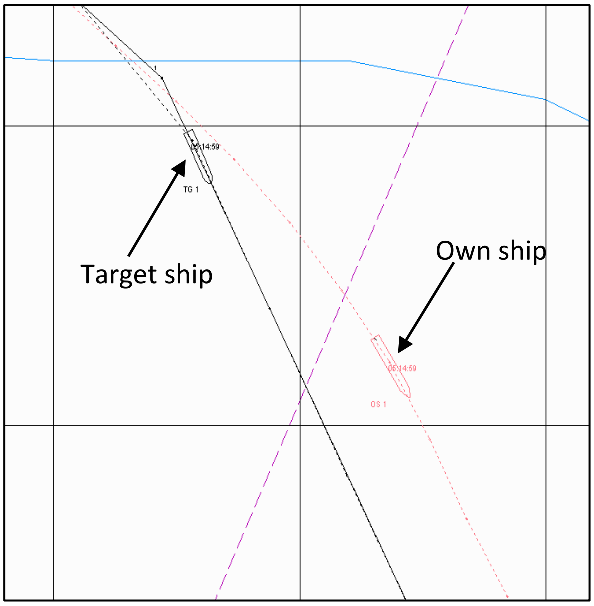


Figure 112 Ileksa Classical scenario

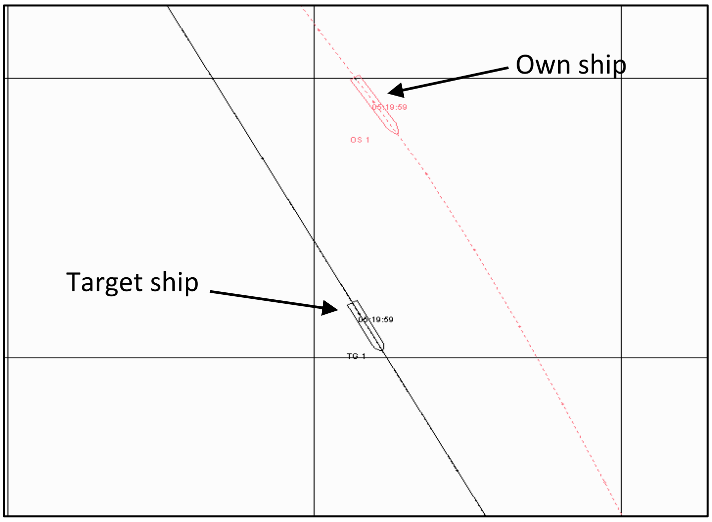


Figure 113 Ileksa Classical scenario

The Automatic approach scenario

In the *Automatic scenario*, the Automatic Collision Avoidance System has detected the target ship approaching from the stern. Therefore, at the time when the target ship became close to the own ship, the Automatic Collision Avoidance System has issued an avoidance action to prevent the accident from happening (Figure 114). In this experiment, the OOW in the training session has been advised (by the author) to alter the course using the autopilot, when the Automatic Collision Avoidance System provided the avoidance decision. The utilisation of the autopilot has resulted in a very slow course alteration, which took a long time to reach the suggested course to steer from the Automatic Collision Avoidance System (Figure 115). Also, with the slow course changing, this caused a large deviation from the original track (Figure 116). However, manual steering is more effective in critical situations to reach the maximum rate of turn. Thus, in order to successfully perform the decisions from the Automatic Collision Avoidance System, it is recommended to use manual steering mode.

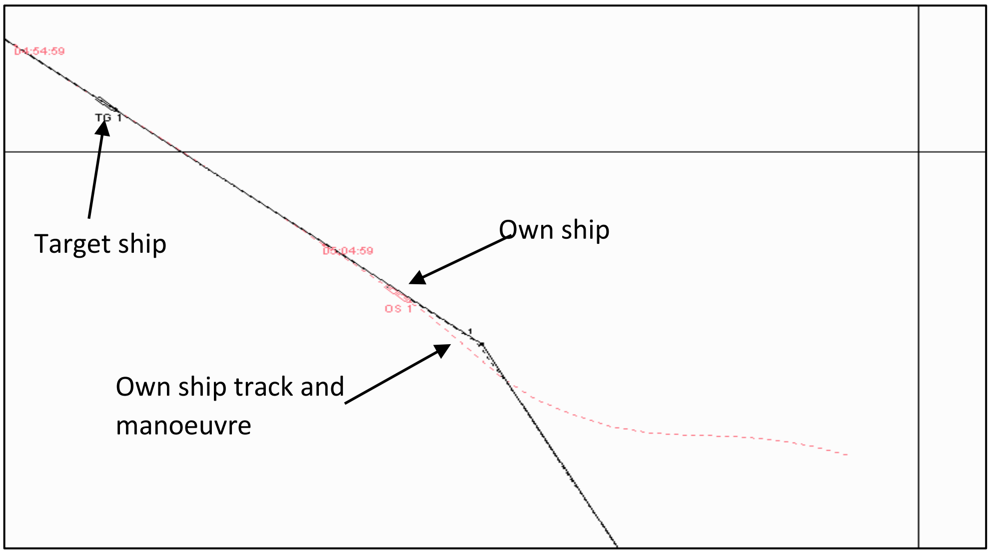


Figure 114 Ileksa Automatic scenario

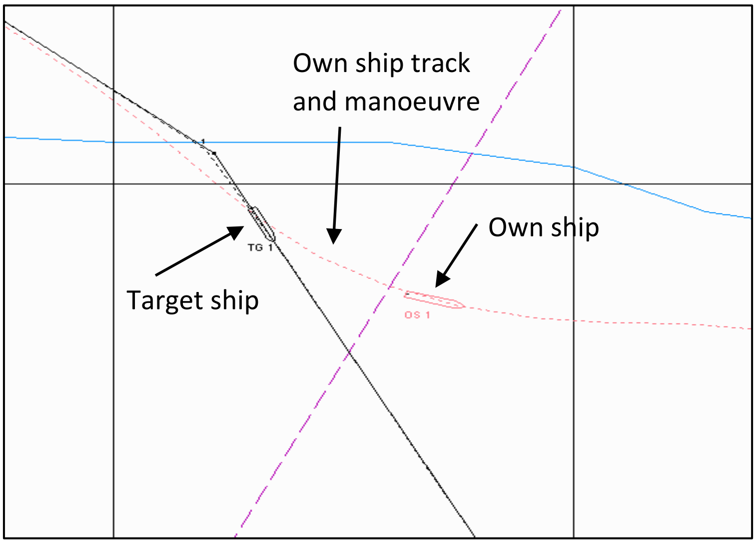


Figure 115 Ileksa Automatic scenario

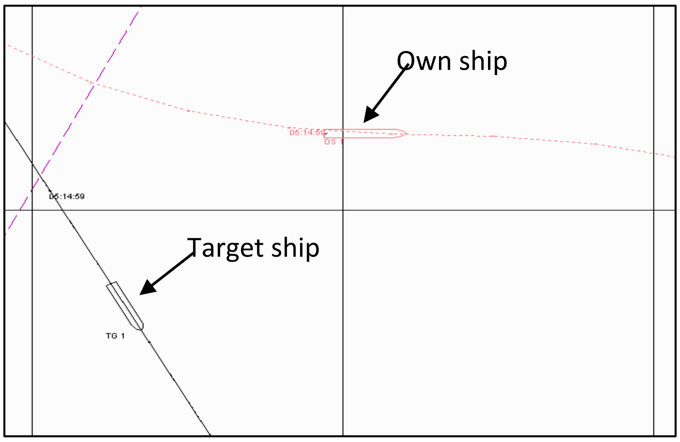


Figure 116 Ileksa Automatic scenario

Table 27 Ileksa actions; real event actions, best action and the Automatic system decision

Time of Actions	***Ileksa* actions (Route T South-easterly)**	***Cepheus J* actions (Route T South-easterly)**	**Comments**	**Best actions by Cepheus J**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0100	The chief officer took over. Speed was 6.5 knots. Entered Route T.					
0300		The chief officer took over from the 2nd officer. Visibility was poor. It was navigating the same track as *Ileksa* on Route T. Speed was 16.5 knots. AB was sent out of the bridge to do some duties. The chief officer was carrying on some paperwork on the chart table.		The AB (look out) should have stayed on the bridge to assist the chief officer in conducting a safe navigational watch. Also, it was night time and by STCW regulation, a sole watchman is prohibited in a night time.		
0445					The Auto system has detected the target ship (Cepheus J) when she came within 10 NM (the detection zone).	
0500	Detect *Cepheus J* on radar at the stern, on the overtaking situation. The chief officer handed over to the 3rd officer and informed the 3rd officer about the overtaking situation.	Tuned the radio to the news channel and was distracted by the paperwork and the news. The heading was 160°.	The chief officer was busy entering the refrigerated container temperature, which needs to keep a record of every 6 hours. The AB read the temperature and give the reading to the chief officer to enter it on the record. This made the chief officer busy on paperwork.			The system could avoid this collision by, first, warn the Chief officer on *Cepheus J* about a threatening target and advise about the best action to avoid the collision.

Time of Actions	***Ileksa* actions (Route T South-easterly)**	***Cepheus J* actions (Route T South-easterly)**	**Comments**	**Best actions by Cepheus J**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
	The heading was 160°. The master was also on the bridge doing some paperwork.					
0506:08					The Auto system has recognised the risk of collision with *Cepheus J* 10 minutes before the collision.	
0509:55					The Auto system has alerted the OOW about the risk of collision and provided the best action to avoid it, to alter course to 091°. After doing this action by Ileska (own ship), the ships have passed safely.	
0516	Call on VHF to ask about *Cepheus J* intention. *Cepheus J* was on 0.7 NM astern of *Ileksa*. *Cepheus J* did not reply to the VHF call. The master switched the helm to manual and put hard to starboard. Because of the wind, the ship did not respond to the rudder order for few minutes, then the master decided to keep the course and	If a good lookout was carried by *Cepheus J* either visually or on the radar, that could prevent the collision from happening.	The 3rd officer did not mention Cepheus J's name on the VHF call, and this could be the reason for not replying. Another attraction method could have been used to warn *Cepheus J* about the situation (whistle or lights). With restricted visibility, still, *Ileksa* was visible for about 9 minutes before the collision, and this is enough time to avoid the			If no action has been taken by the give-way vessel (Cepheus J) the system could remove the uncertainty of the stand on vessel (*Ileksa*) by Sharing information feature, this will ensure that the give-way vessel is not taking any avoiding action and the stand on vessel must avoid it by her manoeuvre. Also, the system could advise about

Time of Actions	***Ileksa* actions (Route T South-easterly)**	***Cepheus J* actions (Route T South-easterly)**	**Comments**	**Best actions by Cepheus J**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
	let *Cepheus J* collide on the stern to avoid being hit in a weak structure area.		collision. Inappropriate lookout by the chief officer on *Cepheus J* was the main cause of the collision in a stand on situation.			the best action to avoid the collision (alter course to any side)
0519 (Collision time)	Being hit from the stern. After the collision, the ship's bow turned to starboard, then to port.	*Cepheus J* collided by the bow on *Ileksa*'s stern.				
N/L			No general alarm and no report about the collision to VTS and coast guard by any of the ships. Also, no mayday message was broadcasted. The vessels were able to continue sailing to berth without aids.			

General Comments:

- The OOW on Cepheus J was busy on other paperwork and not paying attention to the navigational watch.
- The vessel Cepheus J has all the available means for a proper lookout (Radar, AIS and VHF), yet the OOW failed to detect the target right ahead of his vessel, despite Ileksa was apparent for at least one hour on the radar.
- The OOW on Ileksa made a VHF call to Cepheus J to ask about his intention but without mentioning the vessel's name, so the OOW on Cepheus J did not reply to this call and he was listening to the news.
- The OOW on Ileksa did not take an early avoidance action to avoid the collision and was waiting for the OOW on Cepheus J to reply the VHF call.

OOW's opinion about the developed Automatic Collision Avoidance System

Based on the OOW's opinion about this scenario, in the *Classical approach*, he was confused and hesitated about what is the best action he should take and when he should take it. This hesitation was because of the fact that his ship was the stand-on vessel and he should maintain his course and speed, as per the COLREG regulation. However, if the give-way (target) vessel is not taking any avoidance action, then the stand-on vessel must avoid it by her own action. Thus, the OOW was monitoring the target ship carefully waiting for her to start avoiding his vessel, which was approaching his vessel with no avoidance action and that makes him confused about what and when to start to take any action. When the target ship became very close and continue approaching, the OOW decided to start the avoidance manoeuvre.

On the other hand, in the *Automatic approach*, the OOW was relieved from the hassle of what and when to start the manoeuvre when he is the stand-on vessel, if the give-way is not avoiding, where the Automatic Avoidance System will advise the OOW about the best time and action to avoid the collision.

In this scenario, the OOW was advised, by the author, to utilise the autopilot for course alteration, which is provided from the Automatic Collision Avoidance System. In this case, it has been realised that the autopilot is inefficient in critical situations, where the course alteration action should be performed immediately, and the autopilot is not designed to apply for hard turns. This has resulted in a smooth turn by the autopilot that took a long time to reach the required course to steer.

Ileksa experiment KPIs

Tables 28 and 29 below have the collected measures from the playback mode of the scenarios. These measures have been used to calculate the KPIs in these scenarios. In the chart below (Figure 117), the KPIs results for its experiment, classical and *automatic approaches*, have been presented. In the time of detection, the OOW was late by just above 20 minutes. This is due to the fact that the target ship was approaching from the stern of the ship (overtaking). However, the overtaking ship is the responsible ship for taking the avoidance action. Usually, the stern part is given less attention by the OOW, and the radar display is put on off-centre mode, which reduces the display of the stern side to increase the front view. In the risk recognition, also there was a short delay to assist the risk by the OOW. After all, the OOW took a small course change as he was in doubt about the intention of the approaching vessel. Therefore, the track deviation movement was a short distance from the original track.

In the *Automatic approach*, the only issue was the use of the autopilot, which was not responding quickly and caused a small passing distance for the target ship. Apart from this, the time of detection, recognition and action were all on the benchmark results. In this scenario, the author was testing the possibility of utilising the autopilot function to perform the avoidance decision. This will help to examine the performance of a total automatic collision avoidance manoeuvre using the autopilot feature on-board ship. However, in the training session about the Automatic Collision Avoidance System, the OOW has been instructed to implement the system's decisions using the autopilot not the manual steering mode for course alteration. Accordingly, it has been discovered that the autopilot on ships is used to maintain the course of the ship and to implement a small rate of turn to control the ship path. Therefore, this cannot be used in a critical situation.

Table 28 Ileksa Classical scenario data

Classical Approach Ileska		
Measures	Data	Unit
Time of appearance	04:47:00	Time
Time of detection	05:08:20	Time
Actual time of risk	05:07:37	Time
time of recognition	05:11:00	Time
required action time	05:12:05	Time
actual action time	05:10:30	Time
required CPA	1	NM
Range	0.17	NM
XTE	1	NM
Actual Deviation	0.16	NM

Table 29 Ileksa Automatic scenario data

Automatic Approach Ileska		
Measures	Data	Unit
Time of appearance	04:45:00	Time
Time of detection	04:45:00	Time
Actual time of risk	05:06:08	Time
time of recognition	05:06:08	Time
required action time	05:09:55	Time
actual action time	05:09:55	Time
required CPA	1	NM
Range	0.3	NM
XTE	1	NM
Actual Deviation	1	NM

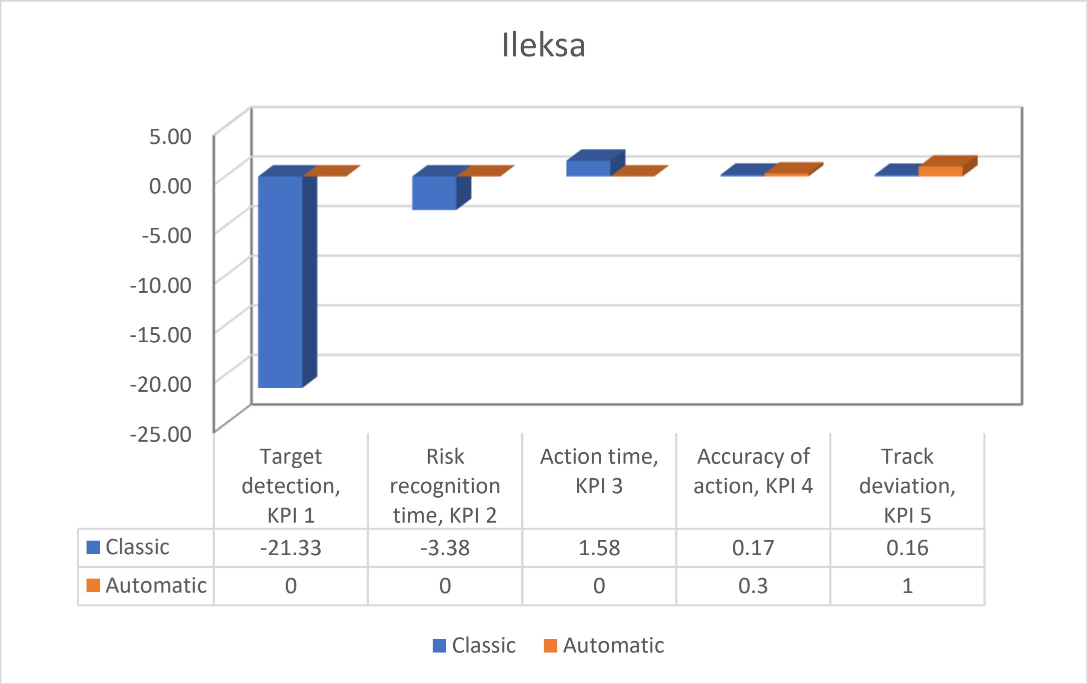


Figure 117 Ileksa KPIs' results. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.5 Scenario 5 (Hyundai Dominion)

Accident report (MAIB, 2005a)

This accident is a collision event between container ships *Hyundai Dominion* and the *Sky Hope*. These two vessels collided on the 21st of June 2004, at 0738, in the East China Sea. This was a crossing situation where *Sky Hope* is the give-way vessel and *Hyundai Dominion* is the stand-on vessel. However, in *Sky Hope*, the OOW has misinterpreted the collision situation and wrongly assumed that the *Hyundai Dominion* is overtaking him, which means *Hyundai Dominion* is the give-way vessel. This makes the *Sky Hope* an overtaken vessel (stand-on) and she should only maintain his course and speed, which was the wrong assumption of the OOW on *Sky Hope*. The OOW in *Hyundai Dominion* has assisted the situation (correctly) as a crossing situation, and his ship was the stand-on vessel. Due to this misunderstanding of the situation, the OOW in *Sky Hope* wrongly assumed himself an overtaken vessel (strand-on) and did not take any avoidance action. The OOW in *Hyundai Dominion* was correct in his decision, where it was a crossing situation and he was the stand-on vessel and did not take any avoidance action. When both vessels realised that the risk of collision was becoming higher, instead of taking an avoidance action, they started a VHF call to discuss the situation. Also, the OOW on *Hyundai Dominion* had delayed the action by sending a text message via the AIS asking *Sky Hope* to keep clear of him. At the time when both vessels started to take the avoidance actions, it was too late to avoid the collision, and they both collided. *Sky Hope* has sustained severe damage, where *Hyundai Dominion* had minor damages. No injuries or pollution were reported in this accident. The weather condition was good with wind speed scaled 5 in Beaufort, visibility was good, and the sea state was moderate.

The event's scenario in Classical and Automatic approaches

In this experiment, the second experimental method has been applied. An OOW has performed the *Classical scenario*, and another OOW has been trained and performed the *Automatic scenario*. Hereafter, the following experiments were performed in this second experimental method to see if it has any differences in the results.

The actual area of this accident happened in the East China Sea, which is not available in the simulator database. Therefore, an alternative area has been used to reconstruct the scenario. The same details and parameters have been collected from the accident report to build up the scenario (MAIB, 2005a). The *Classical scenario* and the OOW performance in this experiment are represented in the following (Figures 118) where own and target ships are labelled. The

Automatic scenario is illustrated in the below pictures, with the performance of the OOW in this experiment (Figures 119). Table 30 has detailed actions taken by the own and target ships from the real accident report, and the best action should have been taken from the author's opinion and the Automatic Collision Avoidance system's decision for this accident event.

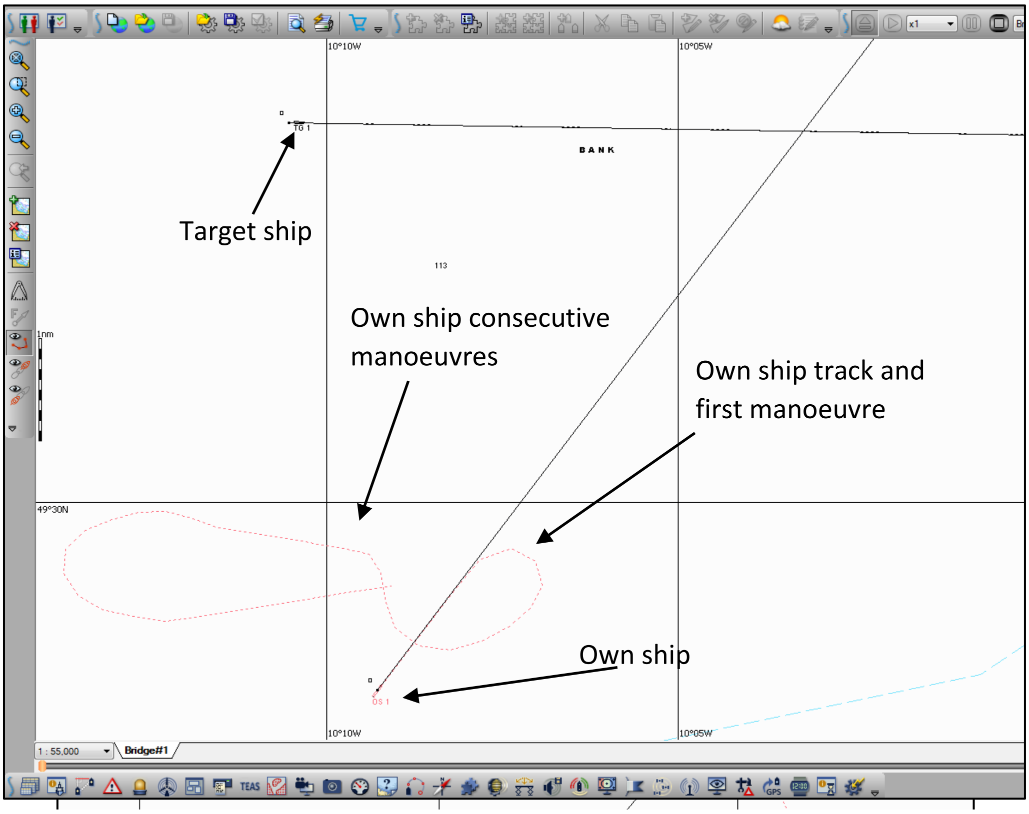


Figure 118 Hyundai Dominion Classical scenario

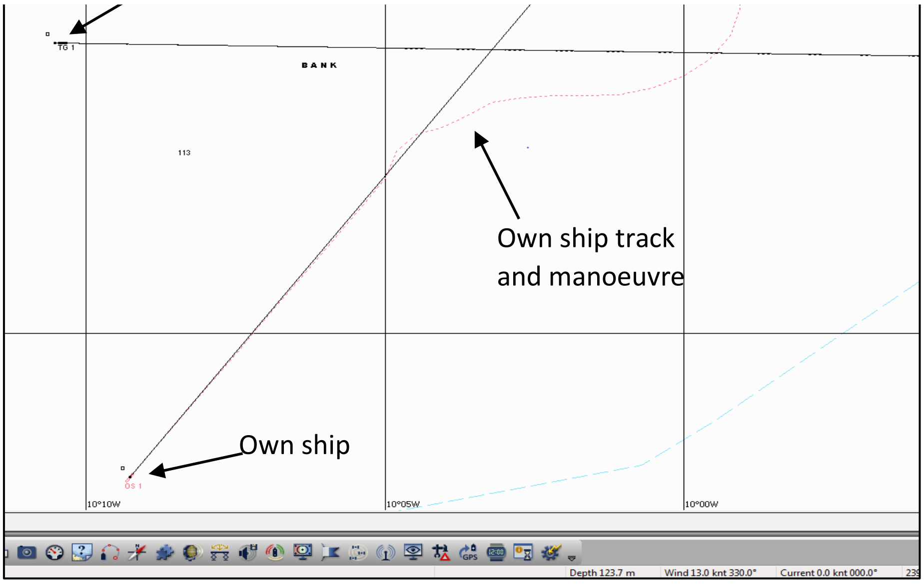


Figure 119 Hyundai Dominion Automatic scenario

The <u>Classical Approach</u> experiment

In this scenario, the visibility was clear, and there were no other targets in the vicinity. Thus, the OOW was aware of the target ship from the beginning of the exercise. Additionally, he was suspecting a risk situation to arise from that only target in the vicinity. Moreover, the OOW was operating under monitoring in the simulator environment, which motivated him to perform well. All these factors have affected the OOW decision-making process, where he was rushing to make an early action to avoid the situation from developing.

This has led him to start a VHF communication with the target ship immediately. Once the target ship did not respond to the VHF call, the OOW decided to start taking action. At this point, he did not consider all the available information and parameters. Nonetheless, he started to turn the ship hard to starboard, for a complete circle to avoid the risk of collision with the target ship (Figure 120). However, the OOW did not take into consideration the distance of the target ship, she was 4 NM away, in open water, and no other targets were in the area.

Consequently, additional targets have been added to the scenario, by the instructor (the author), to restrict the OOW from returning to his original planned track Figure 121. Nevertheless, the OOW has moved away from the collision situation with the intended target and avoided the collision. Thus, the passing range and the track deviation were much greater than the allowed limits.

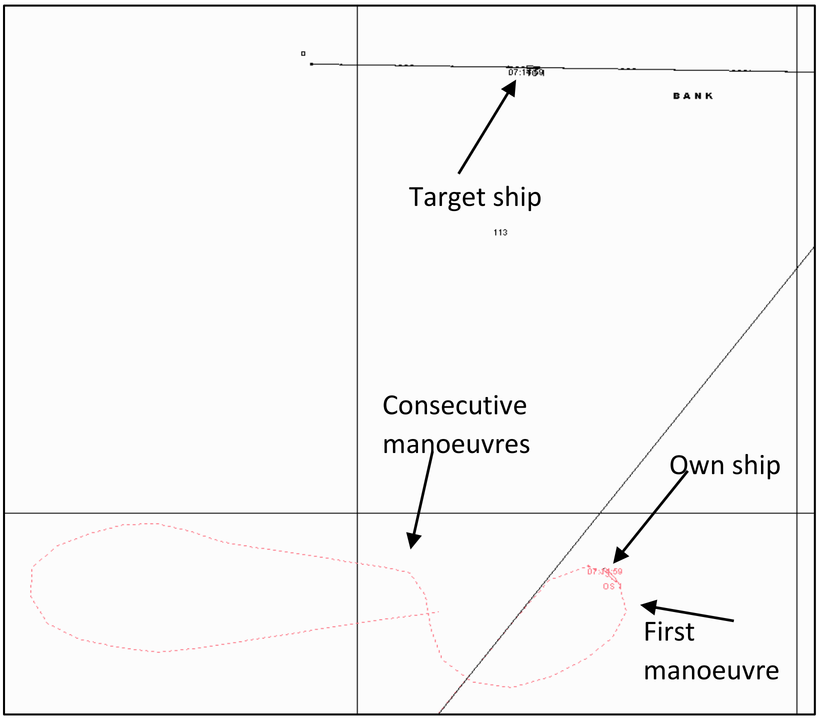


Figure 120 Hyundai Dominion <u>Classical scenario</u>

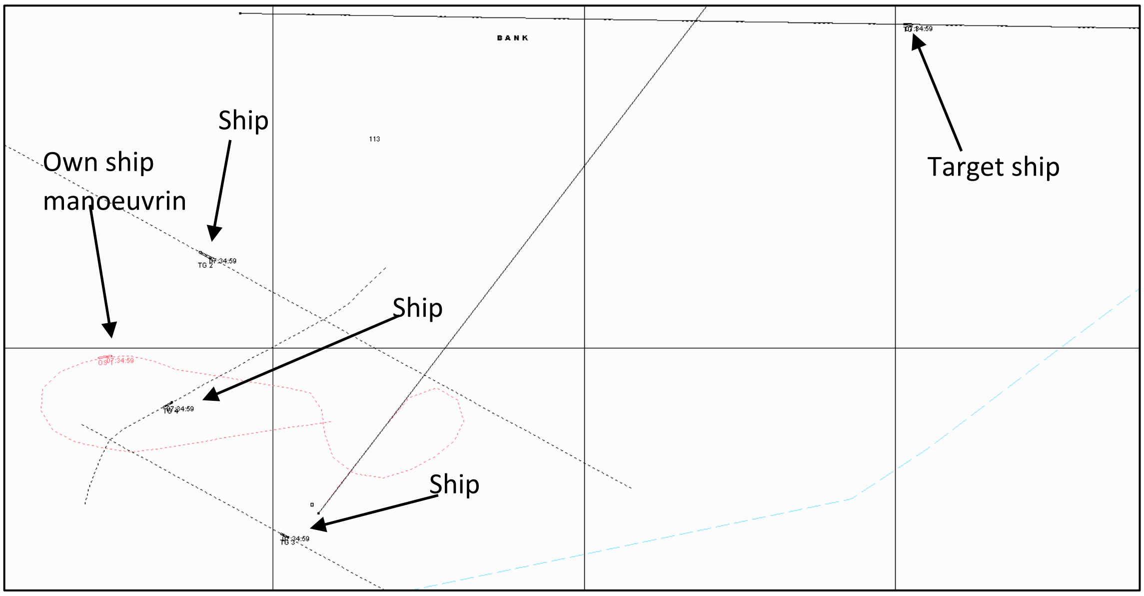
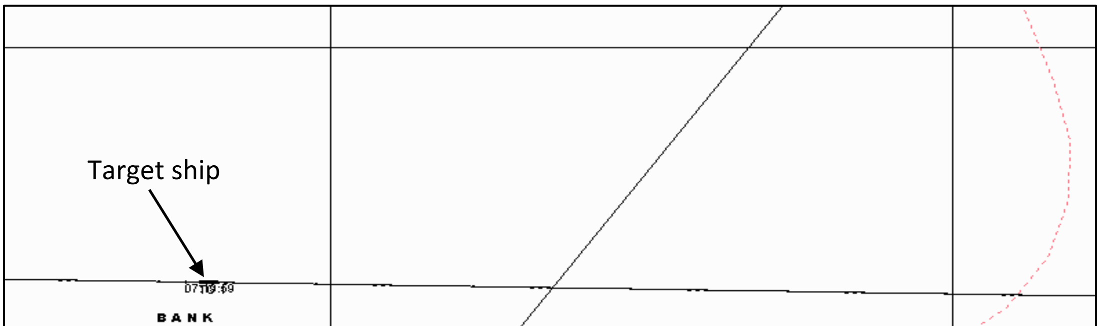


Figure 121 Hyundai Dominion Classical scenario

The Automatic approach scenario

In the *Automatic scenario*, the developed Automatic system has evaluated the risk situation correctly, where the situation was a crossing situation, and the own ship was the stand-on vessel. Although the own ship was the stand on the vessel, the target ship did not take any avoidance action. However, the system recognised that and provided the OOW with the required decision to allow him to avoid the collision situation within the allowed limits. In Figure 122 the two ships were getting closer to each other and there was no action taken by the target ship, which is the give-way vessel, to avoid the collision. Thus, Figure 123 shows the action that has been taken by the own ship, the stand-on vessel, to avoid the collision situation. The own ship has taken the avoidance action and passed ahead of the target ship, as it is shown in Figure 124. Figure 125 shows the own ship after crossing the bow of the target ship and passed it in a safe and clear distance.



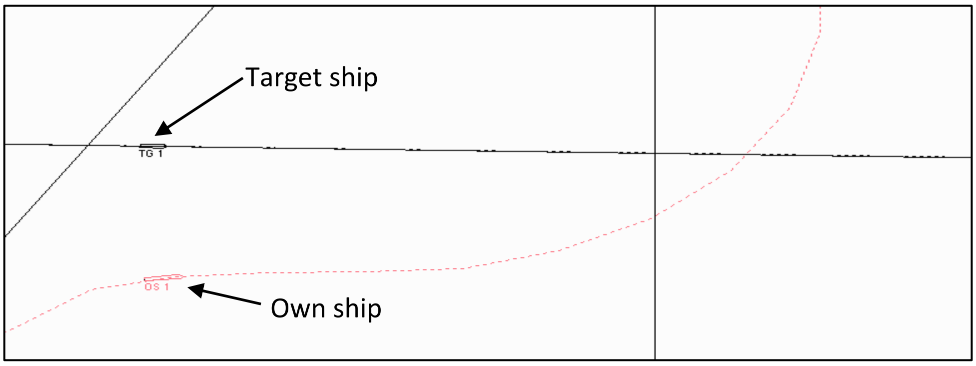


Figure 123 Hyundai Dominion Automatic scenario

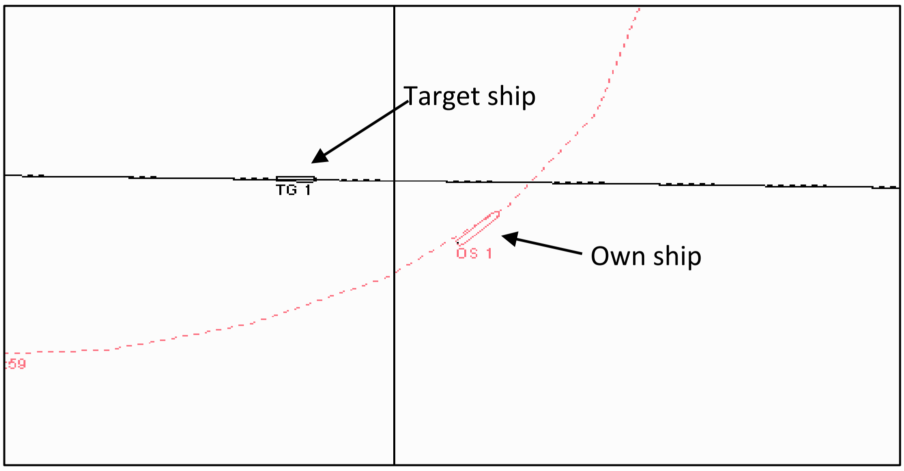


Figure 124 Hyundai Dominion Automatic scenario

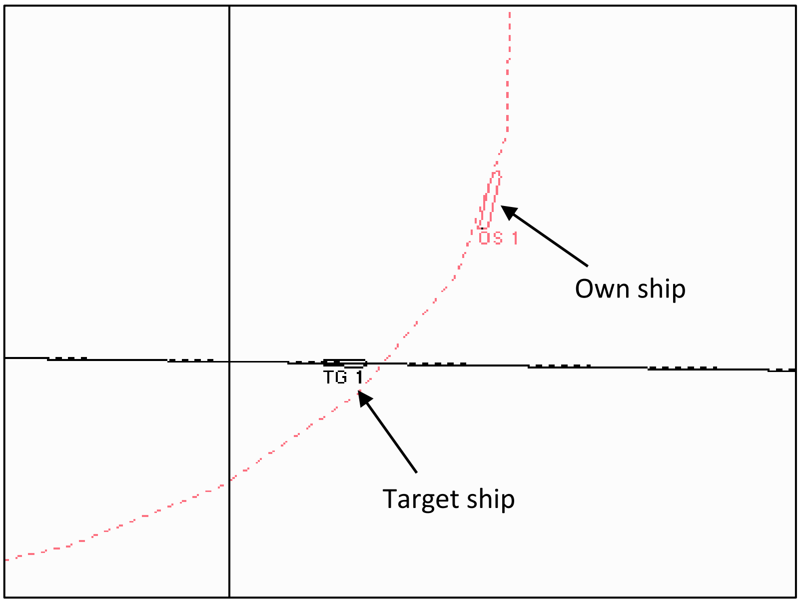


Figure 125 Hyundai Dominion Automatic scenario

Table 30 Hyundai Dominion action; real event action, best actions, and the Automatic system decisions

Time of Actions	*Hyundai Dominion* actions	*Sky Hope* actions	Comments	Best action by *Hyundai Dominion*	Best actions by *Sky Hope*	The developed Auto system actions in the experiment	Collision avoidance system response
0700	AB left the bridge temporarily.						
0710-0720	OOW detected the *Sky Hope* by radar and then visually on his port bow at 5 NM. *Hyundai Dominion* was doing 22 Knots. The OOW assessed the situation as crossing where his ship is the stand-on vessel and *Sky Hope* is the give-way vessel and she should alter course and keep clear.	At 0715, *Hyundai Dominion* was detected on the starboard quarter. Course and speed were 091° and 15.3 Knots. At 0720, *Hyundai Dominion* was at 6 NM and bearing was wrongly assumed to be 210°. The OOW assessed the situation as an overtaking and did not take any action where *Hyundai Dominion* should keep clear as an overtaking vessel.	Wrong collision risk assessment by the OOW on *Sky Hope*, where he assessed the situation as an overtaking and assumed that *Hyundai Dominion* should keep clear. The real situation was a crossing situation, and the *Sky Hope* is the give-way vessel and *Hyundai Dominion* is the stand-on vessel.			At 0710 the Auto system has detected *Sky Hope* on the detection zone (10 NM). At 0717:10 the system has recognised *Sky hope* to be a risky target on a collision course (10 minutes before the collision).	The system would have processed all the available data to correctly and accurately evaluate the collision risk and assign every ship with her situation, whether stand on or give way.
0725-0730	Range to *Sky Hope* became 2.5 NM, and CPA was 0.3 NM. The OOW called *Sky Hope* by VHF to warn her about the situation and ask her to alter the course, but she did not answer. OOW sent an alerting message via AIS saying “PLS KEEP	At 0725 the OOW switched to manual steering as *Hyundai Dominion* was not taking any action. At 0730 *Hyundai Dominion* was about 3 NM away and approaching. The OOW called *Hyundai Dominion* on VHF at 0730, 0732 and	A human error was the reason for the collision as the OOW, wrongly assessed the situation as an overtaking and did not cross-check the navigational situation or reassess the safety of his ship. Also, at this time, an avoidance action by any	Instead of tacking an avoidance action, The OOW on *Hyundai Dominion* kept calling on VHF and sending text messages by the AIS. However, he did not consider rule 17 where the stand-on vessel should take	Take any avoidance action instead of calling on VHF.	At 0722:40 the system has warned the OOW about the collision situation (1 NM before the collision) and provided the best action to avoid the collision. The decision is to alter the course to 090°. After the performance of the action by the OOW	The system would have advice every vessel with the best action to avoid the collision inadequate time.

Time of Actions	***Hyundai Dominion* actions**	***Sky Hope* actions**	**Comments**	**Best action by *Hyundai Dominion***	**Best actions by *Sky Hope***	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
	CLEAR", again no reply to the message.	0734 to ask her to keep clear.	vessel could have avoided the collision.	action if the give way one is not taking an appropriate action to avoid the collision.		*Hyundai Dominion* has passed *Sky Hope* safely.	
0732	Call again on VFH, and *Sky Hope* replied and intended to cross ahead. The OOW did not accept the bow crossing intention and asked *Sky Hope* to alter course to starboard and pass astern of his ship as it was crossing situation and *Sky Hope* is the give-way vessel. The AB returned to the bridge and the OOW asked for manual steering. After the *Sky Hope* call, the OOW asked for hard to starboard wheel and sounded on short blast and he was monitoring the situation visually and then by the CCTV on the port side.	This time *Sky Hope* replied immediately and acknowledges the AIS message and mentioned his intention to pass ahead of *Hyundai Dominion* as it was an overtaking situation. After the disagreement of bow crossing by Hyundai Dominion, the OOW agreed to alter course to starboard and pass astern. After a moment the OOW on *Sky Hope* called again and stated that it is too late to avoid the collision by starboard alteration, and he is altering to the port side.	Although it was too late to take any avoidance action, both OOWs was discussing the situation rather than taking any actions, even to reduce the impact of the collision.				The system would have automatically shared the information and decisions between both ships to prevent any wrong interpretation and misunderstanding of the situation, also to enhance the overall situation awareness.
0736		CPA was 0.2 NM, the OOW changed course to 065° trying to avoid the collision.					The System would have automatically stopped the engine at the moment when the collision is not avoidable to reduce the impact of the collision.

Time of Actions	***Hyundai Dominion* actions**	***Sky Hope* actions**	**Comments**	**Best action by *Hyundai Dominion***	**Best actions by *Sky Hope***	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0738 (Collision Time)	Both vessels collided	Both vessels collided					

General comments:

- The OOW on Sky Hope misjudged the collision situation and was (wrongly) assuming the situation to be an over-taking situation and his intention was to cross Hyundai Dominion from the bow.
- The collision situation was crossing, and Sky Hope was the give-way vessel, bud she did not take any action to avoid the collision until it was too late to avoid it.
- The OOW on Hyundai Dominion recognised the crossing situation and his ship was the stand-on vessel, also, he recognised that the give-way vessel (Sky Hope) was not taking any avoidance action but instead of taking avoidance action he was sending a text message via the AIS to the Sky Hope to keep clear of his way.
- Both vessels initiated a VHF call, Hyundai Dominion asked Sky Hope to take and avoidance action, but it was too late to prevent the collision.

OOWs' opinions in both scenarios

In the *classical approach*, the OOW has performed and early and major action to avoid the risk of collision situation from developing. His decision has been influenced by the nature of the simulator exercise, where usually the trainees perform under the pressure of being monitored, and they try to act perfectly and in ample time. When the OOW was asked about his action, he said that he was suspecting the risk of collision with that only target and thought it would be better if he reacts immediately to avoid any further conflicts.

In the *Automatic approach*, the OWW saw feeling nervous about the intention of the target ship. When he realised that the target ship was not taking any action, the OOW knew he needs to avoid the collision. When the Automatic Collision Avoidance System provided the action to avoid the collision, the OOW immediately took action to prevent the accident. Thus, the avoidance action led to avoid the target ship within the minimum allowed limit of the CPA; the OOW had confidence in the system and started to trust its capabilities.

The Hyundai Dominion scenarios KPIs

Tables 31 and 32 provide the collected measures for these scenarios, which have been used to calculate the KPIs. In Figure 126, the KPI results are presented to show the OOW performance in these scenarios. As a result of the immediate detection of the target in the *Classical approach*, consequently, the OOW assumed it is a risk situation and started to take avoidance action. The avoidance action was taken almost 10 minutes before it actually should have been taken. Moreover, the passing distance was extremely large, 4 NM away from the target, which is far from being a dangerous situation.

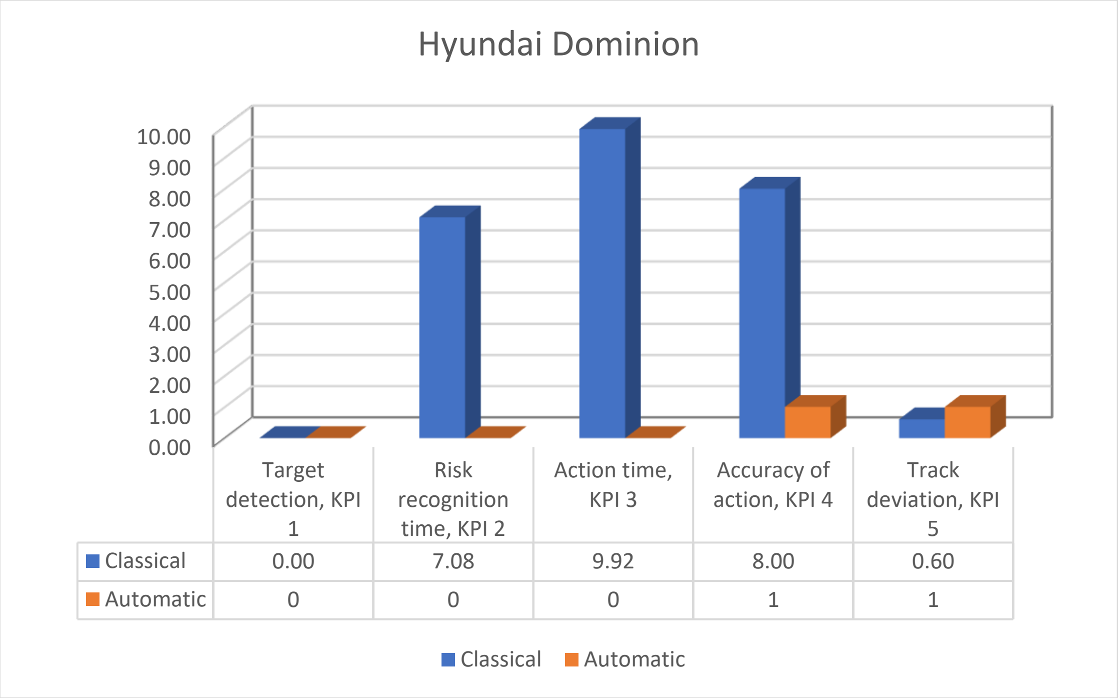
In the *Automatic approach*, the system has been operated perfectly; all the KPIs results have been exactly matching with the benchmarks that show the ideal performance.

Table 31 Hyundai Dominion Classical data

Classical Approach Hyundai Dominion		
Measures	Data	Unit
Time of appearance	07:10:00	Time
Time of detection	07:10:00	Time
Actual time of risk	07:17:05	Time
time of recognition	07:10:00	Time
required action time	07:23:25	Time
actual action time	07:13:30	Time
required CPA	0.5	NM
Range	4	NM
XTE	1	NM
Actual Deviation	0.6	NM

Table 32 Hyundai Dominion Automatic data

Automatic Approach Hyundai Dominion		
Measures	Data	Unit
Time of appearance	07:10:00	Time
Time of detection	07:10:00	Time
Actual time of risk	07:17:10	Time
time of recognition	07:17:10	Time
required action time	07:22:40	Time
actual action time	07:22:40	Time
required CPA	0.5	NM
Range	0.5	NM
XTE	1	NM
Actual Deviation	1	NM



	Target detection, KPI 1	Risk recognition time, KPI 2	Action time, KPI 3	Accuracy of action, KPI 4	Track deviation, KPI 5
■ Classical	0.00	7.08	9.92	8.00	0.60
■ Automatic	0	0	0	1	1

Figure 126 Hyundai Dominion KPIs' results. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.6 Scenario 6 (*Ever Smart*)

Accident report (MAIB, 2015)

This accident is a collision event between the container ship *Ever Smart* and the tanker *Alexandra 1*, at Jebel Ali port entrance, United Arab Emirates. On the 11th of February 2015, at 2342. After the departure of *Ever smart* from the port, with the pilot on board, she was sailing outbound the channel to leave the port. The pilot has steered the ship to the middle of the channel and then gave the steering instruction to the master of the ship and disembarked the vessel. While *Ever Smart* was leaving the channel, the VTS has advised the tanker vessel *Alexandra 1* to wait for the pilot at the pilot station who will disembark from *Ever Smart* and embark his vessel to bring her in. During the waiting time, *Alexandra 1* heard a broken conversation with another vessel instructing it to pass clear from Alexandra 1's stern. The master in *Alexandra 1* assumed that ship to be *Ever Smart* and moved ahead to give her space to pass his stern. *Ever Smart* was instructed to maintain her course and the pilot will be steering *Alexandra 1* inside the channel. This conflicted understanding has put both vessels in a collision course, and by the time they were assisting the situation and starting the VHF calls to discuss the situation, it was too late to avoid the collision. This was a crossing situation and the tanker vessel was the give-way vessel while weather conditions and visibility were good.

In this accident, no injuries or pollution were reported, but bows of both vessels were severely damaged.

The event's scenario in <u>Classical and Automatic approaches</u>

In these scenarios, the second experimental method is implemented. An OOW has performed the *<u>Classical scenario</u>*, and another OOW has been trained to utilise the Automatic Collision Avoidance System and performed the *<u>Automatic scenario</u>*.

The scenario's details and information that have been used to reconstruct this experiment are obtained from the accident report (MAIB, 2015). The screenshot from the simulator control station has been used to illustrate the performance of the scenarios. Figures 127 and 128 show the scenarios of this experiment and explain the performance of the *<u>Classical and Automatic scenarios</u>*. Table 33 has detailed actions taken by the own and target ships from the real accident report, and the best action should have been taken from the author's opinion and the Automatic Collision Avoidance system's decision for this accident event.

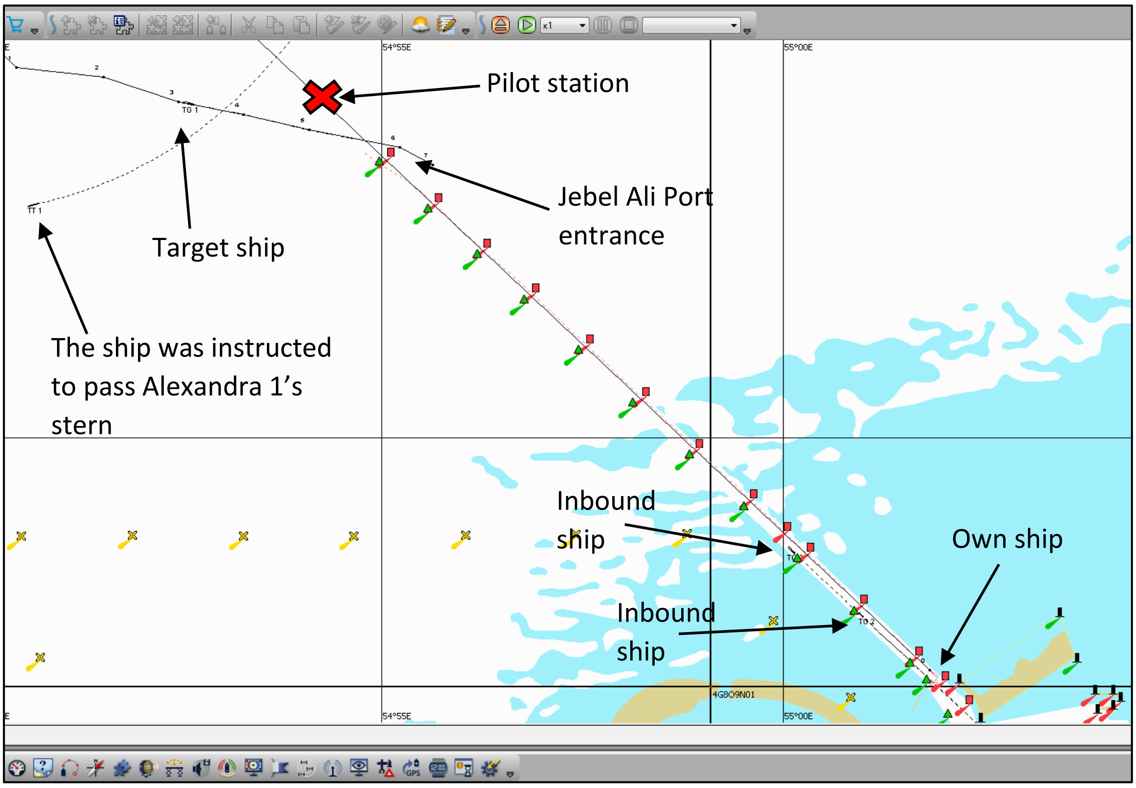


Figure 127 Ever Smart <u>Classical scenario</u>

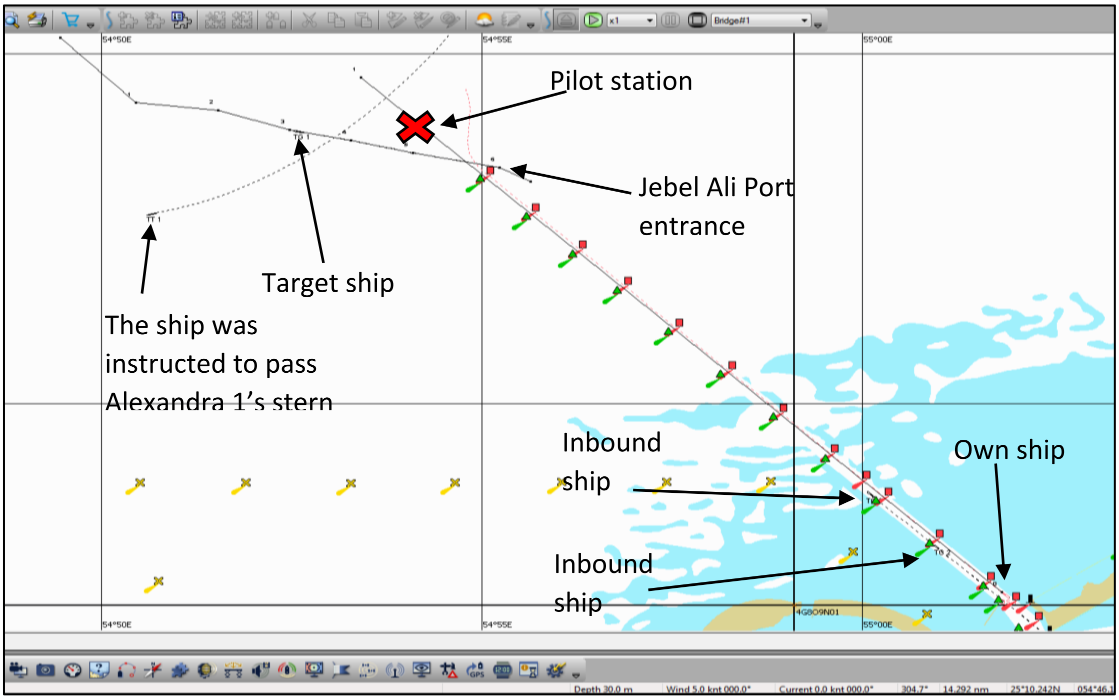


Figure 128 Ever Smart Automatic scenario

The Classical Approach experiment

In this scenario, the pilot (the author) was on the bridge with the OOW. Before the disembarkation of the pilot, he instructed the OOW about the steering directions and action, as well as the inbound vessel. The OOW was following the pilot's instruction, and he was waiting for the inbound vessel to be clear as the pilot was going to bring that ship in. When the target vessel was very close, and the risk of collision was excessive, the OOW took an avoidance action to pass astern of the inbound vessel Figure 129. The action of the OOW took the ship straight to the channel's buoy; the ship slightly touched the buoy Figure 130. To move away from the buoy, the OOW took an opposite action to starboard to avoid the buoy, and that action moved the ship to the target ship again Figure 131. The OOW misjudged the distance of the target ship and collided on its starboard side accommodation area (Figure 132). Additional pictures were taken from the bridge when it was dark, from the real scenario (Figure 133) and then, in the playback mode, the searching light has been switched on to evaluate the situation and see the distance to the target ship (Figures 134).

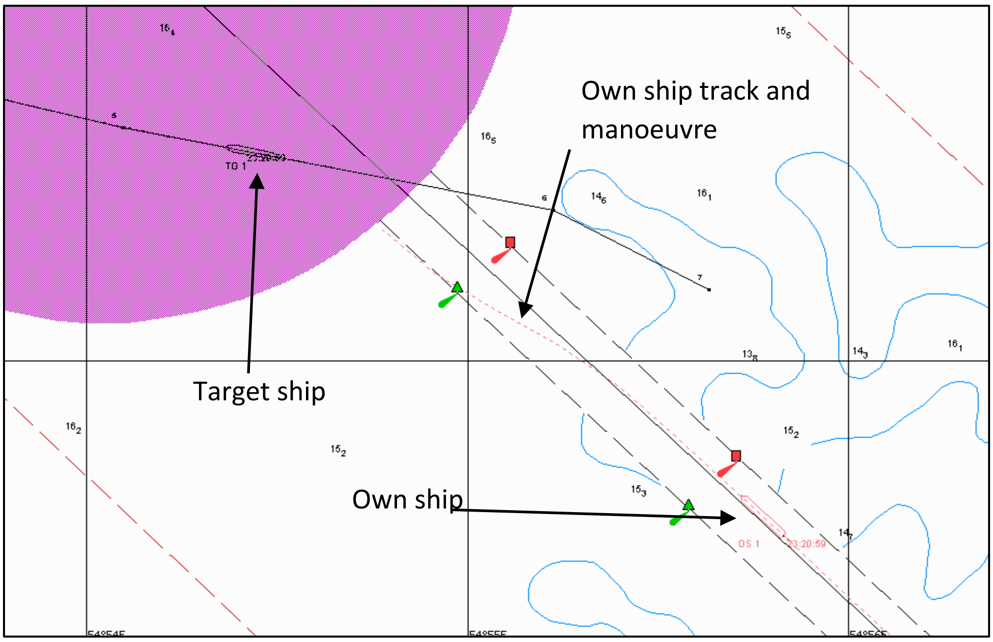


Figure 129 Ever Smart Classical scenario

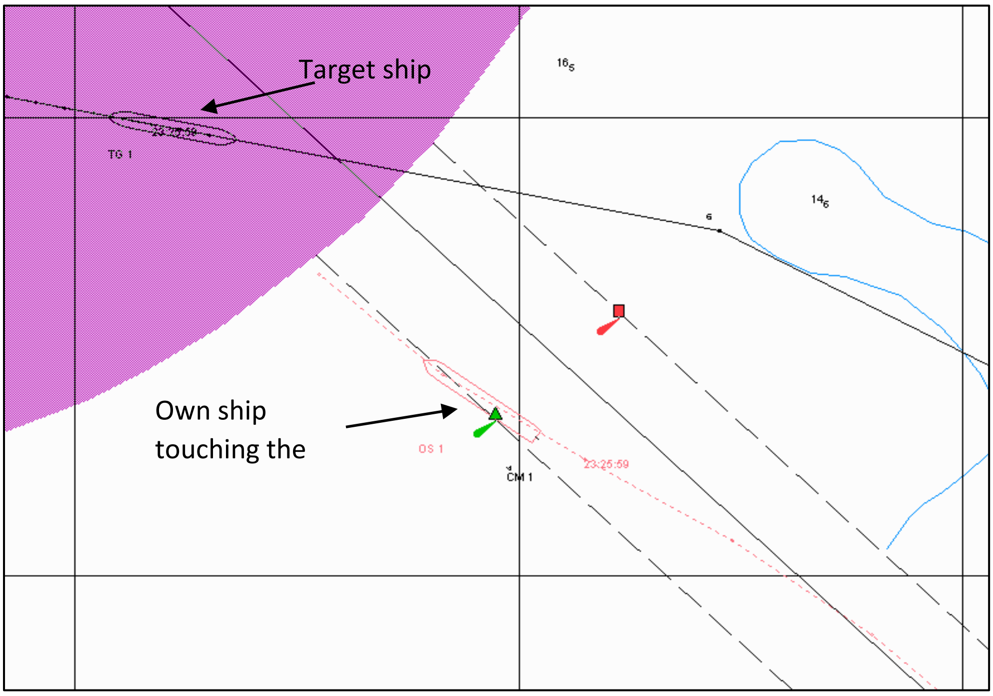


Figure 130 Ever Smart Classical scenario

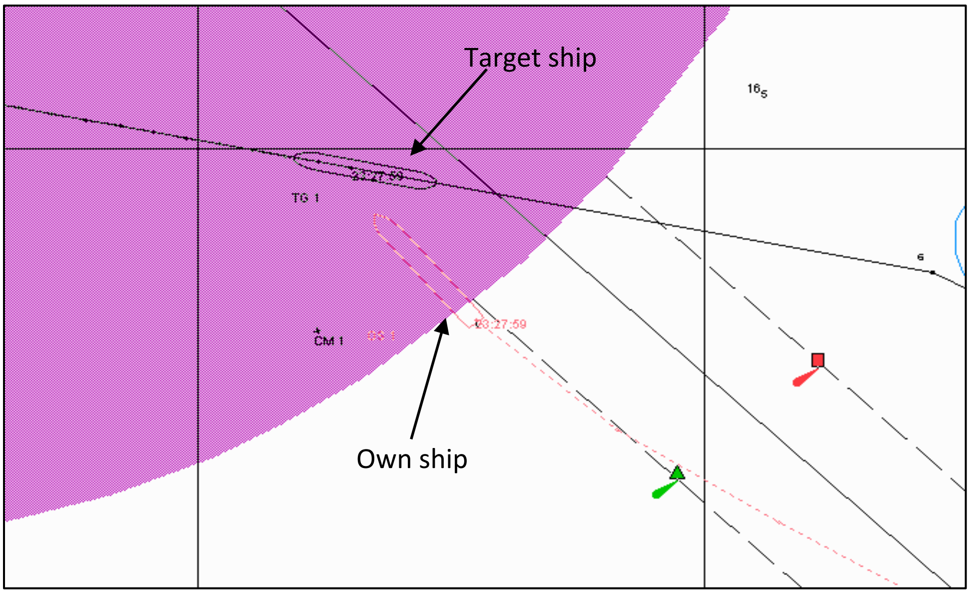


Figure 131 Ever Smart Classical scenario

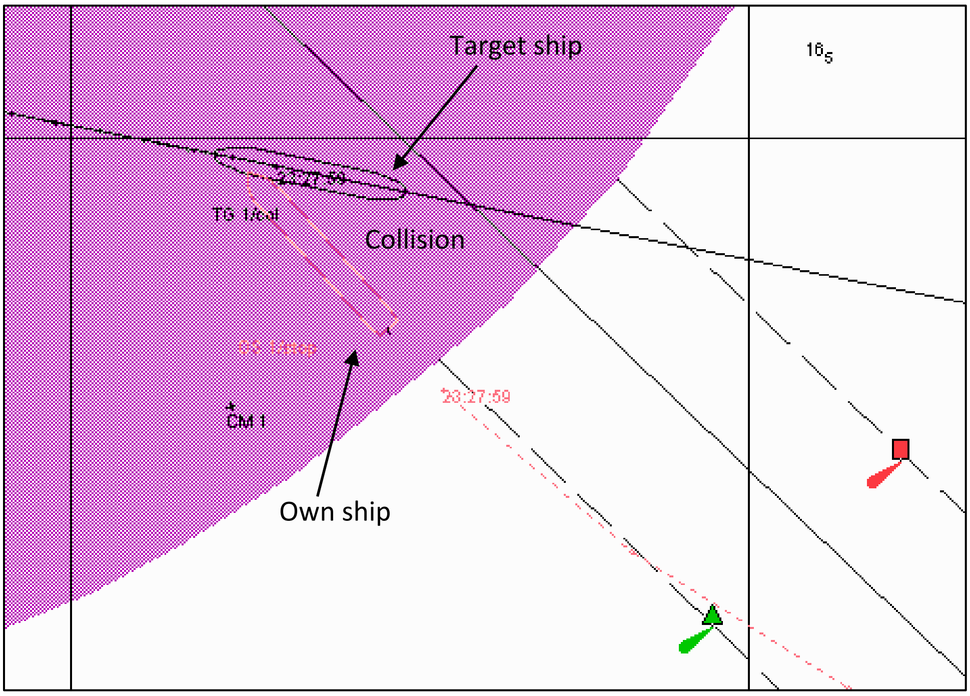


Figure 132 Ever Smart Classical scenario

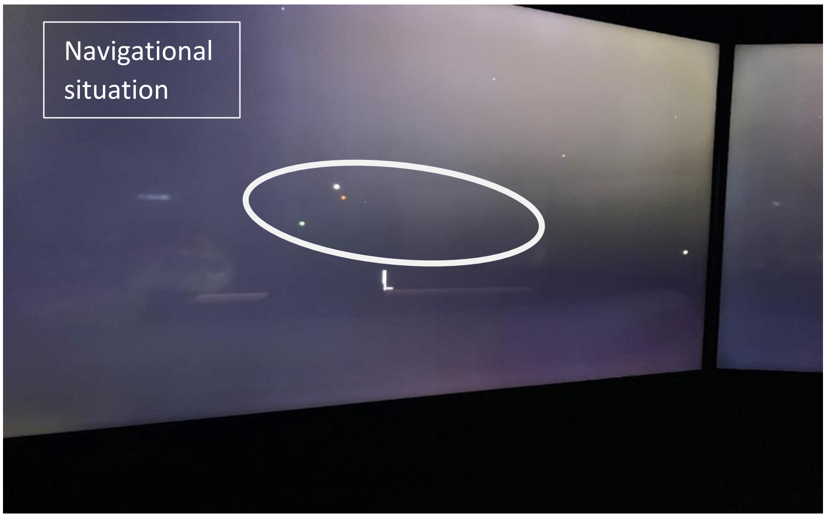


Figure 133 Ever Smart Classical scenario, real bridge view

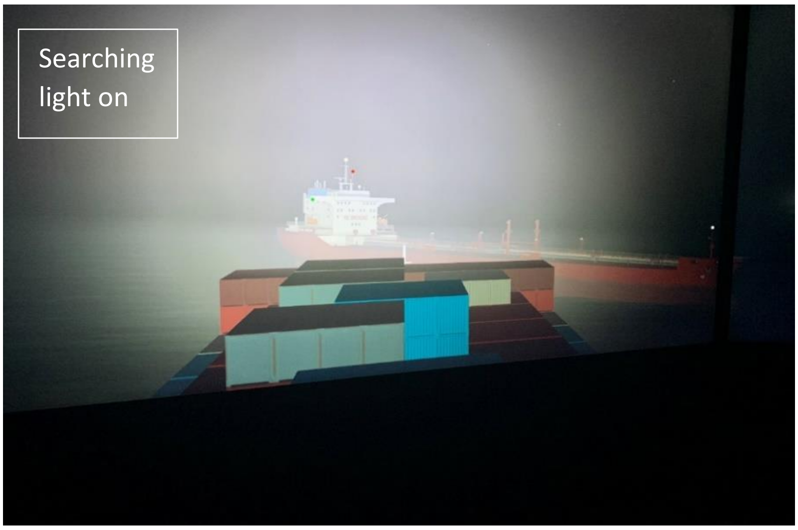


Figure 134 Ever Smart Classical scenario Searching light on

The Automatic Approach experiment

In the Automatic Collison Avoidance scenario, the ship was moving on her planned track. The target ship was detected, and the risk was evaluated on time. Whereas, the narrow navigating channel has restricted the possibility to manoeuvre at the required time (Figure 135). However, the Automatic Collision Avoidance System has evaluated the situation and decided to delay the avoidance action to be clear of the channel and then start the course alteration, Figure 136. This decision has allowed the ship to pass clearly ahead of the target ship (Figure 137). The decision of action delay has been made by the intervention of the human (the author) involved in the operation of the developed Automatic Collision Avoidance System. If the system was operating fully automatically, it would have suggested an avoidance action that does not lead to violation of any navigational limits and the time of action in this scenario. The system would have considered the speed change in this situation. This would have been either; by increasing the speed and pass ahead of the target ship or by reducing the speed and pass astern of that target ship. In both conditions, no violation would have happened if speed was considered.

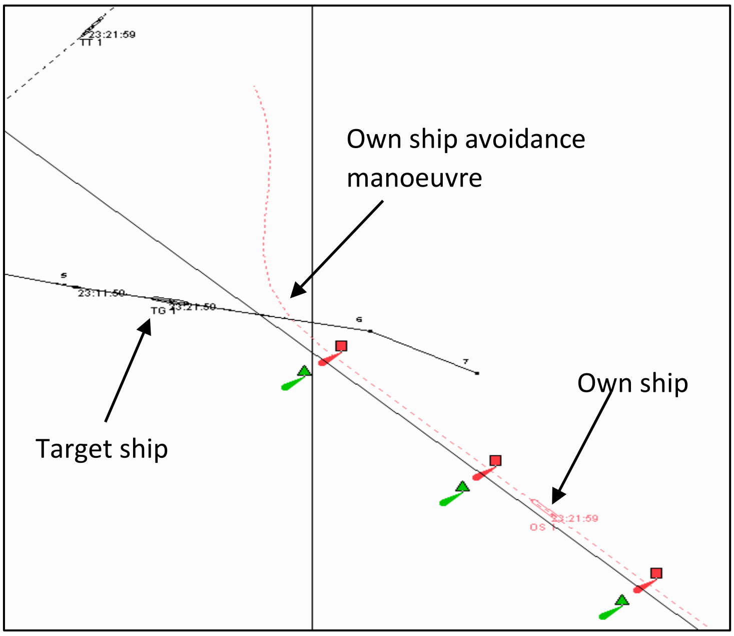


Figure 135 Ever Smart Automatic scenario

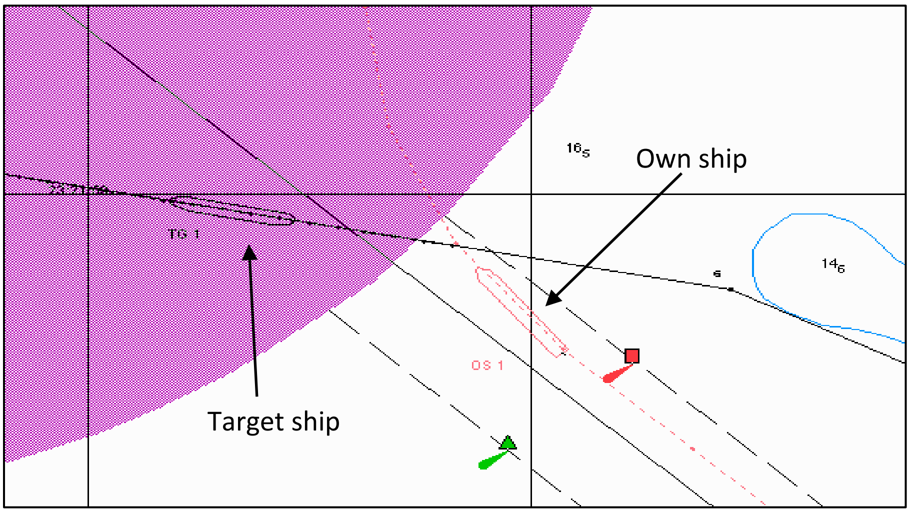


Figure 137 Ever Smart Automatic scenario

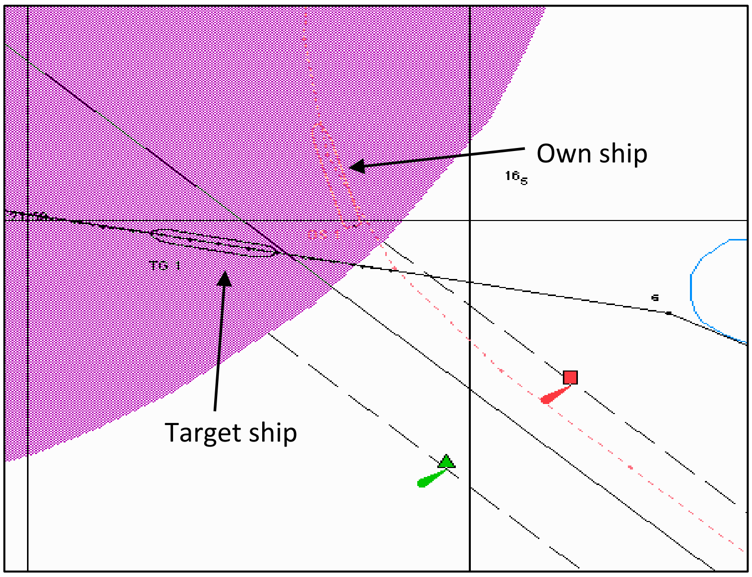


Figure 136 Ever Smart Automatic scenario

Table 33 Ever Smart actions; real event actions, best actions and the Automatic system decisions

Time of Actions	***Ever Smart* actions**	***Alexandra 1* actions**	**Comments**	**Best action by *Ever Smart***	**Best actions by Alexandra 1**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
2230	Casted off (unberthed) from Jebel Ali berth with three tugs. The master, 3rd officer and pilot were on the bridge.						
2242	Tugs released and manually steered to the main channel.					The Auto system has detected *Alexandra 1* (target) on the detection zone (10 NM).	
2248		Anchor away and underway to enter Jebel Ali port through the main channel. The master, 3rd officer and AB were on the bridge.					
2253	VTS informed the pilot about two inbound vessels, in which *Alexandra 1* is one of them. Also, the VTS instructed the pilot to proceed to *Alexandra 1* after *Ever Smart* to pilot her to its berth. The pilot informed the VTS that *Ever Smart* will remain	VTS informed the vessel that the pilot will disembark from *Ever Smart* and board *Alexandra 1* to berth. Also, the VTS authorised her to enter the channel once *Ever Smart* is clear.					

Time of Actions	*Ever Smart* actions	*Alexandra 1* actions	Comments	Best action by *Ever Smart*	Best actions by Alexandra 1	The developed Auto system actions in the experiment	Collision avoidance system response
	on the channel until she is clear of buoy No. 1.						
2314		*Ever Smart* was still on the channel and needs time to clear out, so the master stopped the engine 1.3 NM away from buoy No.1					
2319:45						The Auto system has recognised the risk of collision with *Alexandra 1* (target) 10 minutes before the collision.	
2327						The Auto system has alerted the OOW about the collision situation and provided the best action to avoid it. The action is to alter course to 342°, and when the OOW applied this, the ships passed safely. In this experiment, the action has been delayed for two minutes to allow the ship to be clear of the channel entrance buoy.	

Time of Actions	***Ever Smart* actions**	***Alexandra 1* actions**	**Comments**	**Best action by *Ever Smart***	**Best actions by Alexandra 1**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
2328		The engine sets to dead slow ahead. The VTS instructed another tug about passing 1 NM astern of Alexandra 1, the master wrongly assumed this instruction to be for *Ever Smart*. However, he assumed her to alter course to the port side after clearing the channel to pass his stern.	The VTS did not attract *Alexandra 1* about the tug that is passing his stern. Also, the master assumed that was *Ever Smart* and did not confirm with the VTS before taking actions based on scanty VHF information.		Should have contacted the VTS and clarify the situation of which ship is passing his stern.		
2334	The pilot advised the master to reduce speed to 10 Knots, and maintain COG as 314°. Also, the pilot reminded the master about the inbound tanker on the west of the channel and left with the 3rd officer. The master ordered helms to be 319°and visually assumed the *Alexandra 1* to pass 1.5 cables on the port side.		The master on *Ever Smart* confirmed and accepted all the instruction from the pilot, however, he was not aware of the situation around his ship and did not assess the situation of Alexandra 1.	Should have monitored the situation around his ship and allocate a good lookout duty. Also, the master and the 3rd officer were not aware of the situation until 3 seconds before the collision.			The system would have alerted the master about the risk of collision with *Alexandra 1* and advice about the best action to avoid the collision. In general, enhance the situational awareness on *Ever Smart*.

Time of Actions	***Ever Smart* actions**	***Alexandra 1* actions**	**Comments**	**Best action by *Ever Smart***	**Best actions by Alexandra 1**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
2337	Pilot disembarked and pilot boat cleared of the ship heading to Alexandra 1. The master increased speed.			Should not increase the speed in the channel.			
2340	Passed the channel buoy No. 1, speed was 11 Knots. The master instructed the 3rd officer to go full ahead. Helms still steering 319°.	Engine set to slow ahead and making the speed of 2 Knots. The master saw *Ever Smart* passing buoy No.1 and not altering course to the port side to pass his stern.	The master on *Alexandra 1* should have confirmed and shared his perception with involved parties, *Ever Smart*, VHF, and pilot. Especially in the case of crossing situation, where *Alexandra 1* was the give-way vessel and *Ever Smart* is the Stand on. However, both ships did not take the COLREG rules into consideration with the involvement of the pilot and VTS in the manoeuvre. Where the masters are the only responsible person of the safety of their ships.		Should have contacted *Ever Smart* and agree on leaving the channel plan.		On the event of a collision with other ship, the system will alert the OOW about the collision situation and advice about the best action to avoid the collision. After this, the system will share the avoidance decision with the other ship, and this would have warned *Alexandra 1* about *Ever Smart* decision, to avoid the collision or the lack of any avoidance action. However, *Alexandra 1* could have known earlier about that *Ever Smart* is not taking any avoiding action and she could start taking actions earlier to avoid

Time of Actions	***Ever Smart* actions**	***Alexandra 1* actions**	**Comments**	**Best action by *Ever Smart***	**Best actions by Alexandra 1**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
							the collision by herself.
2341:28		The master called the VTS on VHF to inform them that *Ever Smart* is not altering course to port and it is going to collide with them. Then the VTS called *Ever Smart* to notify them about the inbound Alexandra 1. The pilot from the pilot boat intervened in the call and ordered *Ever Smart* to go hard to starboard. Also, the master set the engine to full astern.	Lack of coordination between all parties to confirm the awareness of all of them about the situation.				Enhance the situational awareness among all parties by automatically sharing the intentions of each ship. This is a conceptual function that is proposed in the system architecture. However, to enable this option, all targets must be fitted with the Automatic Collision Avoidance System.
2342:12	The master answered and ordered the helms hard to starboard and was wondering about the situation.		It is too late to avoid the collision by any action from both ships. Also, to this moment, the master on *Ever Smart* was not aware bout the risk of collision with Alexandra 1.				

Time of Actions	***Ever Smart* actions**	***Alexandra 1* actions**	**Comments**	**Best action by *Ever Smart***	**Best actions by Alexandra 1**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
2342:19 (Collision time)	Collided with *Alexandra 1* bow to bow.	Collided with *Ever Smart* bow to bow.					

General comments:

- The master on Alexandra 1 was making a very slow approach to the pilot station waiting for the pilot to come on-board, he responded to a VHF call that was not for his ship and assumed that he was instructed to pass astern of Ever Smart, which was leaving the port's channel.
- Ever Smart was following the pilot's instruction to maintain course and speed all the way to leave the channel and that Alexandra 1 will be clear and under the command of the pilot.
- At the time both vessels recognised the risk of collision, it was too late to avoid the collision, despite the actions were taken by both vessels.

OOWs' opinion in both scenarios

The narrow area of navigation stressed the OOW in the Classical approach. He took the first action turning to port to avoid the target ship in front, and when he saw the buoy very close to his ship, he tried to avoid the buoy, which put him on a collision course with the target ship again. He tried to avoid it again, but it was too late to prevent the collision. The OOW said that he panicked when he saw the buoy, and that made him take aggressive action to avoid it, and he forgot about the target ship. He also said that he evaluated the distance to the target to be enough to avoid the collision, but it was not.

In the *Automatic approach*, the OOW was seeing the target ship getting closer in a collision course, and the Automatic Collision Avoidance System is not providing any avoidance manoeuvres, yet. This has created confusion for the OOW as he was unsure about the capability of the Automatic system to provide efficient action that enables him to avoid the collision situation. Accordingly, when the ship has reached the best moment to start the manoeuvre, the Automatic system immediately provided the avoidance decision to the OOW. Therefore, once the system has provided him with the avoidance decision, he directly performed the action, which took him away from the target ship and avoided the collision, without any breach to the safety parameters. However, no early action was needed to avoid the collision, as OOW's action will move the ship for a long distance from the planned track, unnecessarily. The OOW gave good feedback about the performance of the system, and he said it is a life-saving system if it is installed on ships.

The Ever Smart scenario KPIs

Tables 34 and 35 provide the collected data for these scenarios, which were used to calculate the KPIs. The KPIs result in Figure 138 shows that in the *Classical scenario*, the OOW was late in target detection and risk recognition. Thus, the OOW took an early action that led him to touch the buoy. By trying to avoid the buoy, the OOW steered toward the target ship and eventually collided on it.

In the *Automatic scenario*, the system was operating as planned for target detection and risk recognition. Yet, the action has been delayed avoiding the collision with the channel's buoy. However, when the buoy was cleared, the system directly advised the OOW to change course to the starboard side to avoid the collision. The passing distance from the target ship was small but still clear. In this situation, if the speed was utilised, this would allow the ship to pass within the required limit for action performance. In this case, the target ship was waiting for the pilot at the channel's entrance and her speed was very slow, less than 2 Knots. If manoeuvring by speed change was implemented by own ship, this would have helped by, either; increasing speed and pass faster ahead of target ship and this will increase the range (distance to target), or reduce the speed and pass from the stern of the target. If speed was utilised combined with course alteration, this would have helped in avoiding the target ship within the required CPA distance. However, the speed change is not recommended by the COLREG regulation for collision avoidance, and it is preferable to avoid collision situations by course alteration. Thus, in this scenario, no speed change has been taken to examine the capability of the Automatic System in providing an avoidance decision in such a critical situation by course alteration only.

Table 34 Ever Smart Classical scenario data

Classical Approach Ever Smart		
Measures	Data	Unit
Time of appearance	22:52:20	Time
Time of detection	22:56:00	Time
Actual time of risk	23:18:30	Time
time of recognition	23:19:00	Time
required action time	23:23:50	Time
actual action time	23:20:40	Time
required CPA	0.5	NM
Range	0	NM
XTE	0.5	NM
Actual Deviation	0.09	NM

Table 35 Ever Smart Automatic data

Automatic Approach Ever Smart		
Measures	Data	Unit
Time of appearance	22:42:00	Time
Time of detection	22:42:00	Time
Actual time of risk	23:19:45	Time
time of recognition	23:19:45	Time
required action time	23:25:05	Time
actual action time	23:27:05	Time
required CPA	0.5	NM
Range	0.15	NM
XTE	0.5	NM
Actual Deviation	0.7	NM

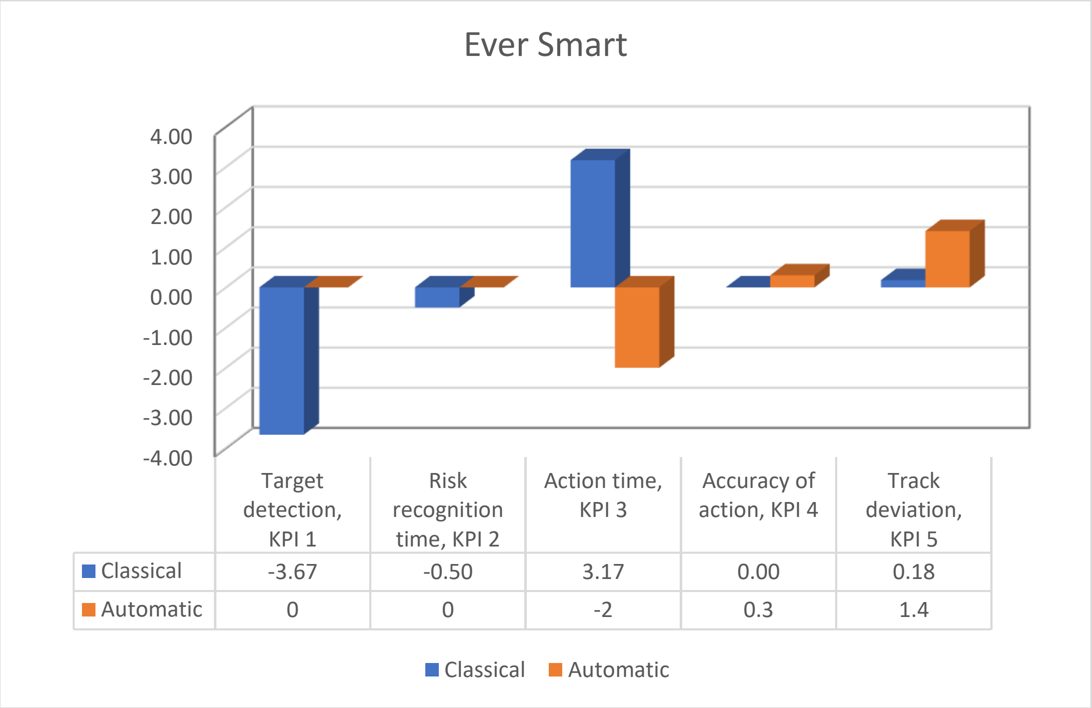


Figure 138 Ever Smart KPIs' results. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.7 Scenario 7 (*Lykes Voyager*)

Accident report (MAIB, 2006)

This accident is the collision event between the container ships *Lykes Voyager* and *Washington Senator*, in Taiwan Strait, at 0938. This was a head-on situation in restricted visibility; the visibility was less than 200 m in fogy condition. The OOW in *Lykes Voyager* was being overtaken by another ship on his starboard side, and *Washington Senator* was detected ahead of his ship. The OOW decided to alter course to the starboard side to avoid Washington Senator, which is in head-on situation (port to port, as per COLREG regulation). In the meanwhile, *Washington Senator* started a VHF call to ask about the intention of the ship in front of him. A conflicting reply has been heard, and the OOW in *Washington Senator* assumed that was *Lykes Voyager* and assumed an agreement to pass starboard to starboard (against COLREG regulation) had been made. The OOW in *Washington Senator* started to alter the course to the port side to pass starboard to starboard with *Lykes Voyager*, and this put both ships in the collision course. At the time when they realised the risk of collision, it was too late to prevent the accident. Both vessels had been damaged but continued their voyage to Hong Kong for repair. No injuries or pollution were reported in this accident event.

The event's scenario in Classical and Automatic approaches

In this experiment, the second method has been applied. Two different OOWs were used for each scenario, one for the *Classical* and another one for the *Automatic approaches*. This accident was in the Taiwan Strait, which is not available in the simulator database; thus, an alternative area has been used to reconstruct the scenario (MAIB, 2006). Moreover, in the accident report, there was no detailed information about the other targets around the ship. However, a slight change has been done to build the scenario and make it similar to the collision that happened.

In Figure 139, the reconstruction and targets of this scenario are explained, while the performance of the scenario in the *Classical approach* is presented. Figure 140 illustrates the reconstruction of the *Automatic scenario*, which has all targets and own ship labelled and elaborated. Table 36 has the detailed actions taken by the own and target ships from the real accident report, the best action should have been taken according to the author and the Automatic Collision Avoidance system's decision for this accident event.

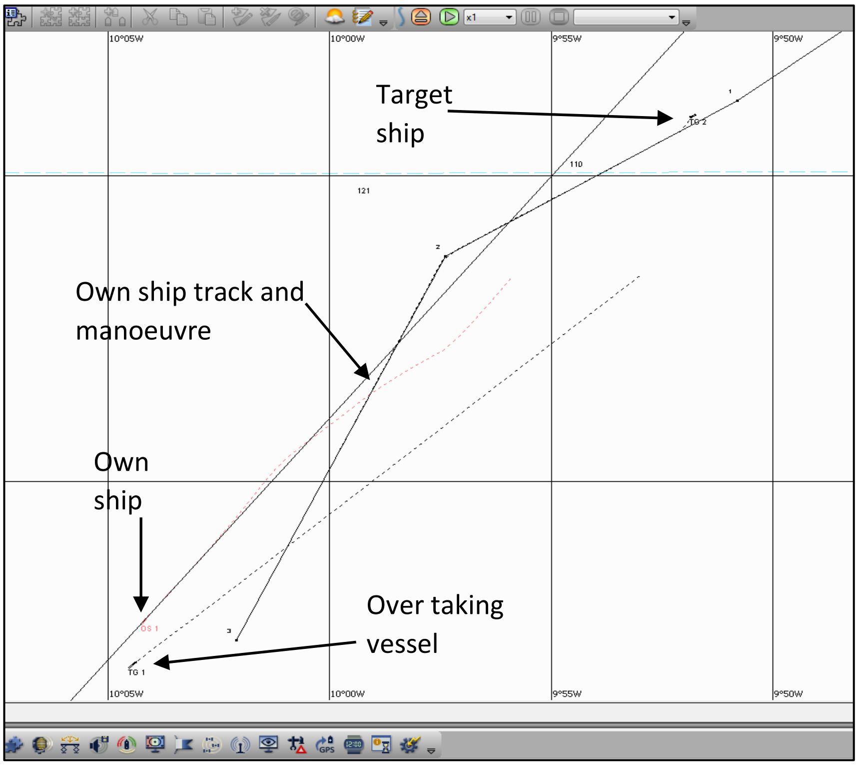


Figure 139 Lykes Voyager *Classical scenario*

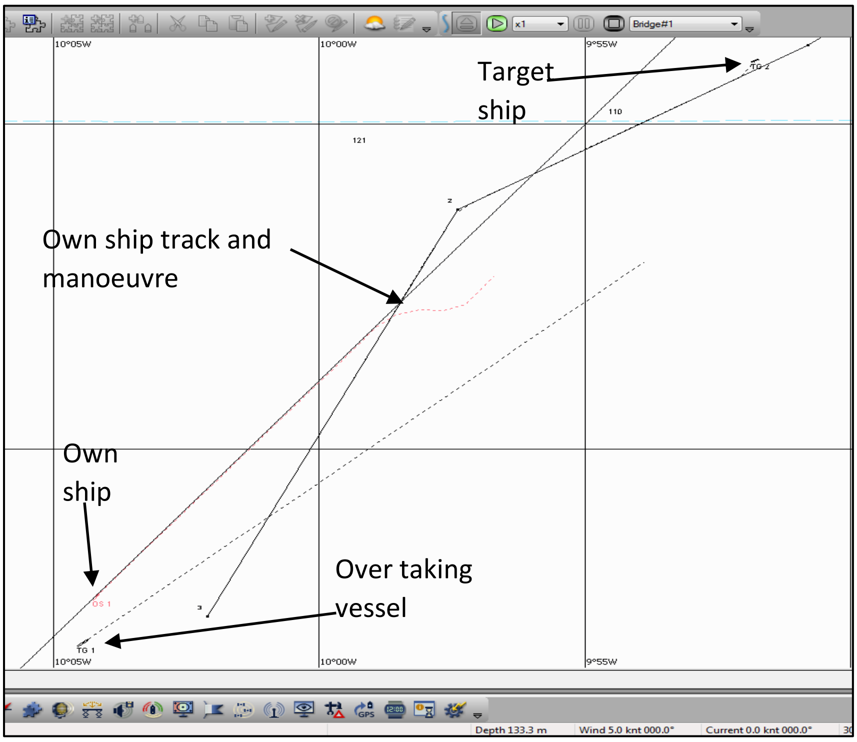


Figure 140 Lykes Voyager *Autoamtic Scenario*

The Classical Approach experiment

In this scenario, the visibility was the factor that affects the navigational condition, which was reduced to about 200 m. thus, the OOW is totally dependent on the radar to ensure the safety of the navigation. The performance of the OOW was good. Yet, he passed the target ship in a distance that is about 5 cables, which is less than the required CPA (1 NM). Figure 141 shows the own ship when she started to alter course to the starboard side to avoid the collision. This was a head-on situation and course alteration to the starboard side is the correct action by the COLREG regulation. After this action, the own ship passed the target clearly from the port side Figure 142.

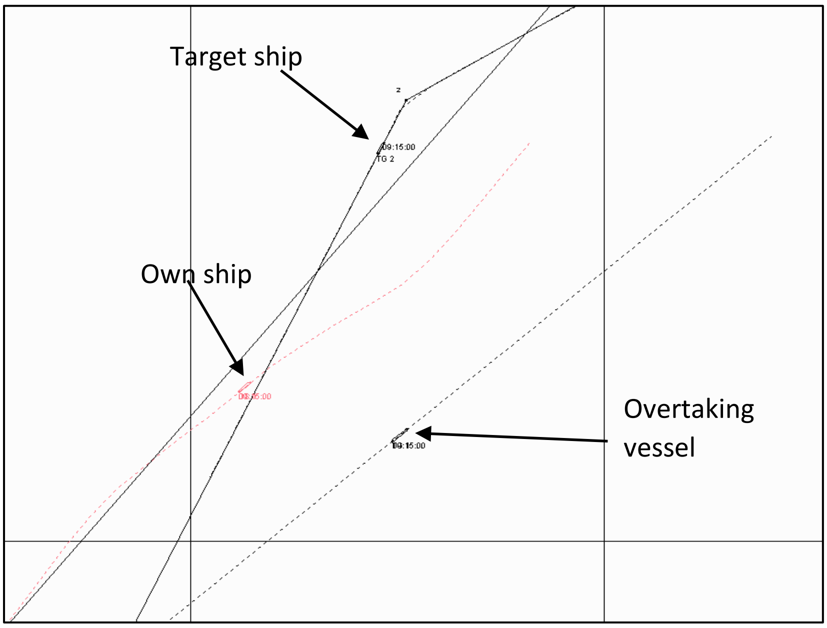


Figure 141 Lykes Voyager Classical scenario

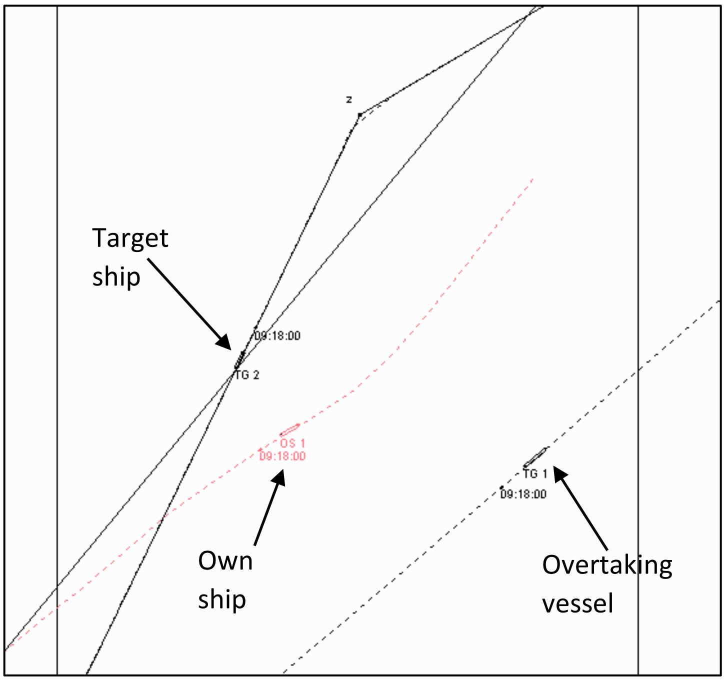


Figure 142 Lykes Voyager Classical scenario

The Automatic Approach experiment

In the *Automatic scenario*, an important issue was identified about the operation of the Automatic system. This point has revealed the necessity to utilise time for risk recognition, which is a fixed unit that does not get affected by the speed of the ships and/or the direction of movement. In this scenario, it was a head-on situation Figure 143, and the own and target ships had a fast approaching rate to each other. Figure 144 shows the time when the own ship started to alter her course to the starboard side to avoid the collision, also, it shows the small distance between the two ships at the time of taking action. This has resulted in a small passing distance from the target ship (Figure 145). This was due to the fact that the time it takes to collect the data from the simulator, then enter it into the developed system to find the avoidance decision was a considerably long time in this scenario, because of the fast-approaching rate.

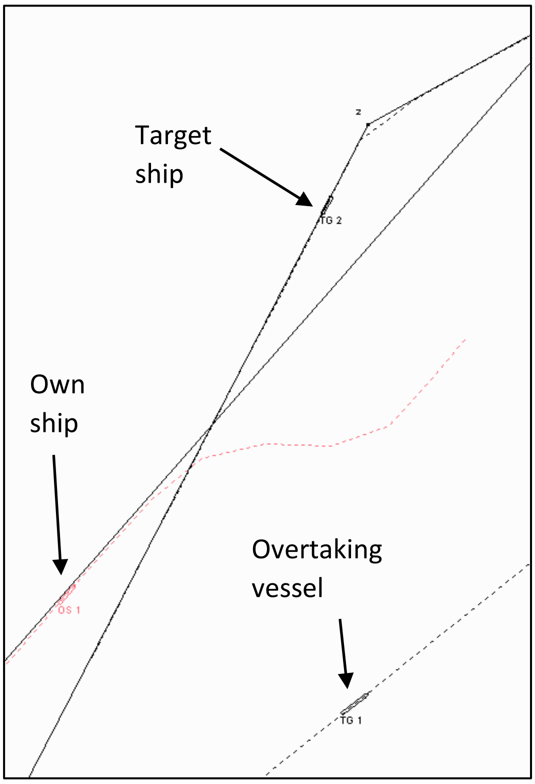


Figure 143 Lykes Voyager Automatic scenario

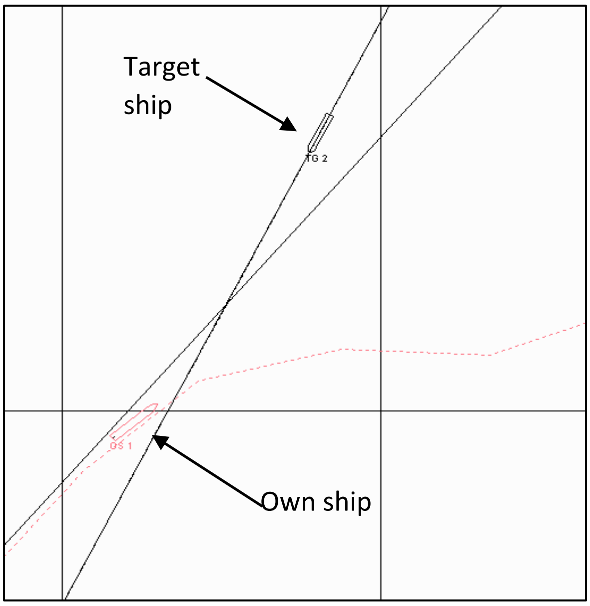


Figure 144 Lykes Voyager Automatic scenario

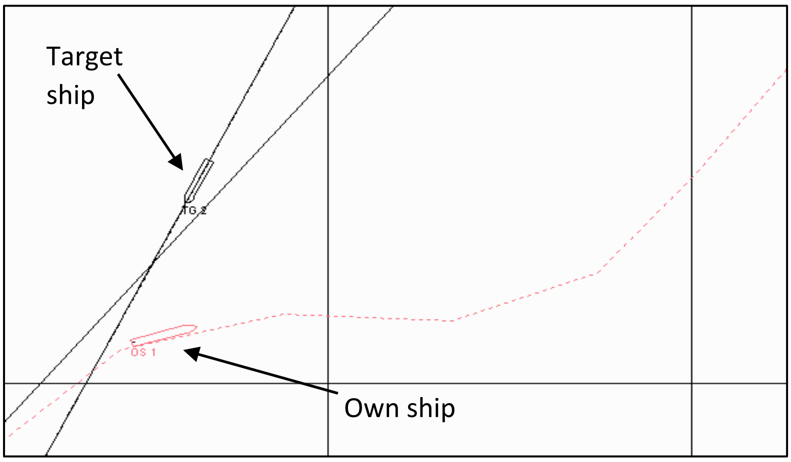


Figure 145 Lykes Voyager Automatic scenario

Table 36 Lykes Voyager actions; real event actions, best actions and the Automatic system decision

Time of Actions	***Lykes Voyager* actions**	***Washington Senator* actions**	**Comments**	**Best action by *Lykes Voyager***	**Best actions by Washington Senator**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0755	The situation was as the following; the 3rd officer relieved the chief officer, and the master came on the bridge to assess the OOW who just joined the ship also, the AB lookout was there. The ship was on autopilot and course of 039° and speed of 19 Knots. It was very poor visibility (less than 1 NM).		None of the ships has reduced speed as a result of poor visibility.				
0800		3rd officer relived the chief officer. The ship's course was 233° and speed about 17 Knots.					
0900		Visibility reduced to 0.5 NM and the ship's whistle was sounded.					

Time of Actions	***Lykes Voyager* actions**	***Washington Senator* actions**	**Comments**	**Best action by *Lykes Voyager***	**Best actions by Washington Senator**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0902:30						The Auto system has detected the *Washington Senator* (target) on the detection zone (10NM).	
0905		The master heard the whistle and arrived on the bridge at 0905. At that time the ship was overtaking another ship on her port bow slowly. Before the arrival of the master, the AB heard a fug signal, which was assumed to be the ship overtaken. A second target was detected ahead as well. The OOW decided to pass between these two targets, but the master has advised him to alter course to the starboard side and pass both targets on the port side. Thus, the course was changed to 243°. After the alteration, the OOW informed the master of detecting two radar targets on the port bow. In a short time, these two targets were on 8 and 7 NM. the target on the left side was passing clear and	As a result of the poor visibility, it was hard and confusing to detect targets and to cross check them on what is appearing on the radar and the AIS. However, neither the master nor the OOW had made any effort to confirm the targets name before the VHF call or within the conversation. This leads to the wrong assumption being made, and the wrong target to make a collision avoidance agreement with. However, the VHF should not be used for collision avoidance arrangement, as per the regulation.		Could have confirmed the target's name from the AIS, and the correct target acquisition on ARPA. The OOW did not follow the right VHF Calling procedures and did not make sure about the ship which answered his call and made the passing agreement with.		The system has helped to correctly identify the target with its correct location. Moreover, the system allowed the OOW to have a better and correct interpretation of the situation, which helped in better decision making. This is by providing the location of the target ship and the collision situation, head-on situation.

Time of Actions	***Lykes Voyager* actions**	***Washington Senator* actions**	**Comments**	**Best action by *Lykes Voyager***	**Best actions by Washington Senator**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
		the one on the right side had a CPA of 2.5 cables to port. the master instructed the OOW to bring the right-side target's information from the AIS. Then it has been found it is the *Lykes Voyager* target. The OOW was instructed to call them on VHF. In his call, he said all the target's information form ARPA without mentioning the ship's name. A female OOW answered that call, and immediately after her, a male replied as well. Also, the male OOW requested *Washington Senator* to pass starboard to starboard. The master and the OOW assumed that was an agreement for *Lykes Voyager* on the manoeuvre. Then the master decided to change course to 40° to port, the male voice agreed. Finally, the master ordered a port side alteration to the helmsman and claimed these actions were taken around 0930.					

Time of Actions	*Lykes Voyager* actions	*Washington Senator* actions	Comments	Best action by *Lykes Voyager*	Best actions by Washington Senator	The developed Auto system actions in the experiment	Collision avoidance system response
0908:32						The Auto system has recognised the risk of collision with *Washington Senator* 10 minutes before the collision	
0915-0930	Visibility increased to 1.5 NM and a ship was seen to being overtaken, this vessel was recognised after the accident to be Notori Dake. At the same time, a target was acquired on the radar to be at 8 NM and course of 235°. At 0930 the OOW altered the course from 030° to 022° to increase the CPA of Notori Dake. After this alteration, a VHF call was heard once calling ship's information without her name or call sign. The OOW responded to this call by replying her name and position. After her reply another ship replied, now the OOW assumed that call was not for her ship (*Lykes Voyager*). No farther action was taken in response to this VHF call as they assumed it to be intended to another ship. Soon the master realises the target that acquired by the		Again, no proper listening on VHF channel 16 was maintained the VHF calling procedures were not followed correctly. Also, the use of VHF in Collision avoidance is contrary to the regulation.	Could have confirmed the name of the ship calling and ensure a proper call is in places		At 0917 the Auto system has alerted the OOW about the collision situation and provided the best action to avoid it to the OOW. The action is to alter course to 096°.	The system could have enhanced the level of situational awareness and the correct interpretation of the situation for the OOWs. Also, the system will alert and advise the ships about the dangerous situation and the best actions to avoid collisions. The system would also share the data, information and decisions with the ships in the vicinity to share the same mental model and avoid the wrong interpretation of the situations.

Time of Actions	***Lykes Voyager* actions**	***Washington Senator* actions**	**Comments**	**Best action by *Lykes Voyager***	**Best actions by Washington Senator**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
	OOW and ordered a course change to 070° to pass this target and Notori Dake as well. The result of this alteration leads to 5 cables CPA.						
Two minutes later	That target was about 5 cables CPA, and its radar vectors show a turn to the port side towards *Lykes Voyager*. The master ordered starboard 20 and sounded one long blast. Moments later that ship became visible with its bow almost reciprocal and a distance of about 50 m. Also, her stern was swinging towards *Lykes Voyager*, so the master ordered hard to port trying to swing his ship's (*Lykes Voyager*) stern away from that target, which appears to be Washington Senator. This last action failed to avoid the collision and Washington Senator's stern struck on *Lykes Voyager*'s No.2 crane.		No action by any vessel could have stopped the collision from happening at this late stage.				The system would have stopped the engine to reduce the impact of the collision.

Time of Actions	***Lykes Voyager* actions**	***Washington Senator* actions**	**Comments**	**Best action by *Lykes Voyager***	**Best actions by Washington Senator**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0935		The result of the master alteration brought the ship on 200° course and this put her on a reciprocal course with *Lykes Voyager* and this increased the CPA to 8 cables on the starboard side. Soon after the master saw *Lykes Voyager* altering course to starboard side by radar. The master felt he cannot go more to the port side because of Notori Dake and ordered hard to starboard. Soon later *Lykes Voyager* became visibly, and the master ordered hard to port to swing the stern away but that did not help and they collided.	The master on *Washington Senator* has based his decisions on scanty information from the radar and did not make any effort to confirm this information.		Could have checked the information by better awareness and monitoring on the ARPA and AIS systems. Also, use better procedures on VHF usages to avoid more confusion. However, this is contrary to the collision avoidance regulation		

Time of Actions	***Lykes Voyager* actions**	***Washington Senator* actions**	**Comments**	**Best action by *Lykes Voyager***	**Best actions by Washington Senator**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
			After the collision Notori Dake was questioned about the accident. The master and the OOW mentioned that they did not see, acquire or plot the targets in that time, and they did not know about the accident until the 13 of April, five days after the accident.				The system could have identified these targets correctly and remove the misunderstanding and wrong identification of the targets.

General comments:

- The vessels had restricted visibility and Lykes Voyager detected vessels on a head-on situation.
- The master on Washington Senator has made an avoidance manoeuvre based on the VHF call, he was assuming that was made with Lykes Voyager.
- The use of VHF for collision avoidance has prevented the master on Washington Senator from following the proper instruction of the COLREG in a head-on situation and he made his action based on the VHF agreement to act against the COLREG.
- The OOW on Lykes Voyager was taking the correct action and altered his course to starboard to avoid the collision, also, he did not respond to VHF call, and Washington Senator called other vessels and based his action to that call.
- Based on the wrong call, Washington Senator has altered course to the port side, which put took her directly to Lykes Voyager and they collided.
- The collision happened because of the wrong use of the VHF in collision situations and not following the COLREG instructions.

OOW's opinion about the developed Automatic Collision Avoidance System

In the *Automatic approach* scenario, the OOW has mentioned the issue of the late decision from the Automatic Collision Avoidance system, where he was stressed because of fast-approaching speed to the target ship and the ships passed each other in a very close range. The OOW suggested if the Automatic Collision Avoidance system has provided the avoidance decision earlier where that would have allowed a larger distance from the target ship.

The Lykes Voyager KPIs

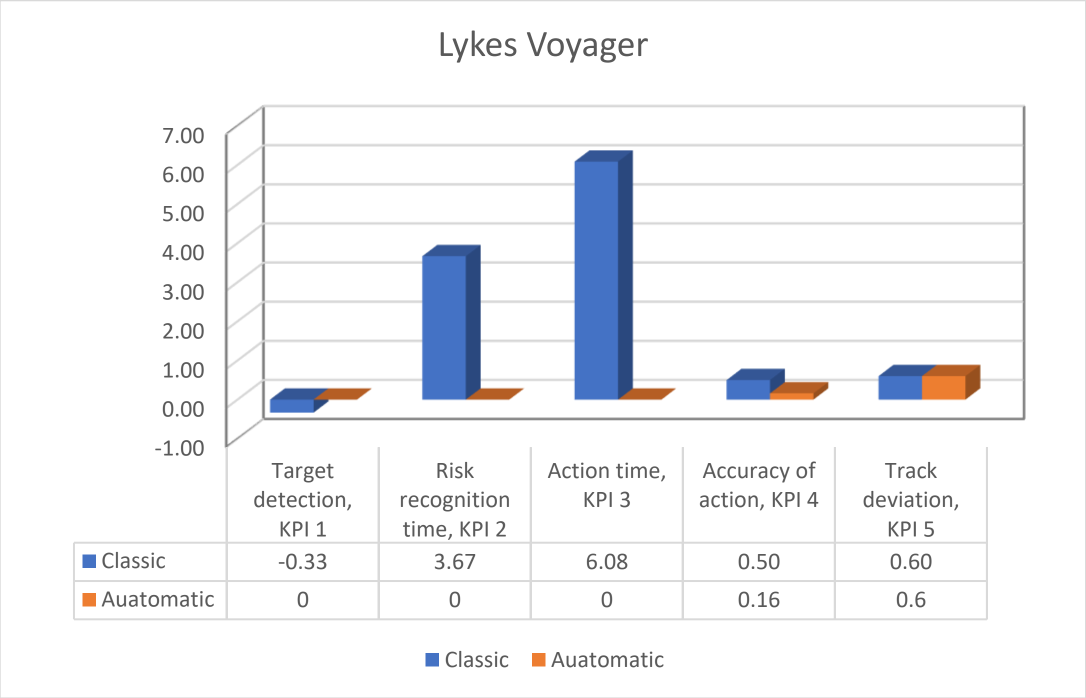
Tables 37 and 38 show the collected data for these scenarios, which were used to calculate the KPIs. The graph in Figure 146 presents the results of the KPI calculations for this scenario. The KPI results in the experiment have shown good performance in both the *Classical and Automatic scenarios*. Whereas, the risk recognition and action time were a little earlier than the benchmark. Also, the CPA results are below the required limit, in the *Classical scenario*, it was 0.5 NM, and 0.16 NM in the automatic one. This is a result of the system being operated by a human, where if it was fully automatic, it would have calculated and provided the decision much faster and that would have shown a better result. Moreover, this supports the fact that utilising the time for risk assessment is more accurate than using the distances.

Table 37 Lykes Voyager Classical Scenario data

Classical Approach *Lykes Voyager*		
Measures	Data	Unit
Time of appearance	09:00:00	Time
Time of detection	09:00:20	Time
Actual time of risk	09:08:40	Time
time of recognition	09:05:00	Time
required action time	09:15:20	Time
actual action time	09:09:15	Time
required CPA	1	NM
Range	0.5	NM
XTE	1	NM
Actual Deviation	0.6	NM

Table 38 Lykes Voyager Automatic scenario data

Automatic Approach Lykes Voyager		
Measures	Data	Unit
Time of appearance	09:02:30	Time
Time of detection	09:02:30	Time
Actual time of risk	09:08:32	Time
time of recognition	09:08:32	Time
required action time	09:17:00	Time
actual action time	09:17:00	Time
required CPA	1	NM
Range	0.16	NM
XTE	1	NM
Actual Deviation	0.6	NM



	Target detection, KPI 1	Risk recognition time, KPI 2	Action time, KPI 3	Accuracy of action, KPI 4	Track deviation, KPI 5
■ Classic	-0.33	3.67	6.08	0.50	0.60
■ Auatomatic	0	0	0	0.16	0.6

Figure 146 Lykest Voyager KPIs' results. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.8 Scenario 8 (*Scot Isles*)

Accident report (MAIB, 2009)

This is the event between the general cargo ship *Scot Isles* and the bulk carrier Wadi Halfa, in Dover Strait, on the 29th of October 2008, at 0449. At the time of the accident, the weather was slight to moderate with wind force 3 on the Beaufort scale and good visibility. The *Scot Isles* was crossing the TTS from north to south towards Antwerp. The *Wadi Halfa* was sailing in North East traffic lane. Both vessels had no lookout person on the bridge at the time of the collision. *Scot Isles* has not seen *Wadi Halfa* until they collided with each other. *Wadi Halfa* detected *Scot Isles* just before the collision, the avoidance action did not help to prevent the collision. Both vessels were damaged, but no injuries were reported. 60 tonnes of fuel oil were spilt in the water from Scots Isles.

The event's scenario in Classical and Automatic approaches

In this experiment, the details and information have been collected from the accident report (MAIB, 2009). The scenario shows that the own ship is crossing the Traffic Separation Scheme TTS. However, she should have kept clear of all ships transiting in the lanes, cross in the right angle and as fast as she can. Despite the high number of passing vessels, the situation was good, and the OOW was able to cross without any problems. Figures 147 and 148 below illustrate the performance of the scenarios in both *Classical and Automatic approaches.* Table 39 has detailed actions taken by the own and target ships from the real accident report, the best action should have been taken from the author's point of view and the Automatic Collision Avoidance system’s decision for this accident event.

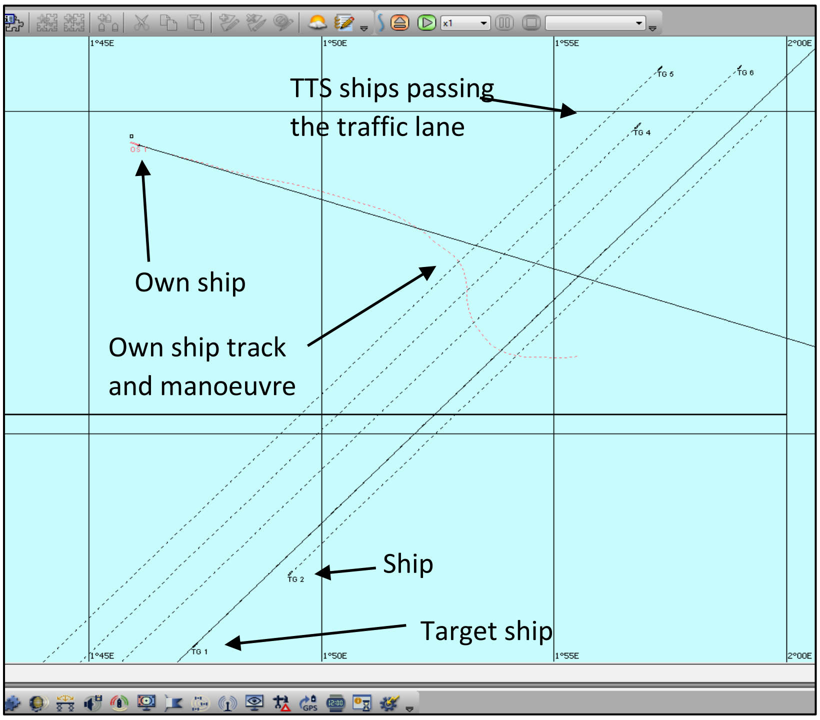


Figure 147 Scot Isles Classical scenario

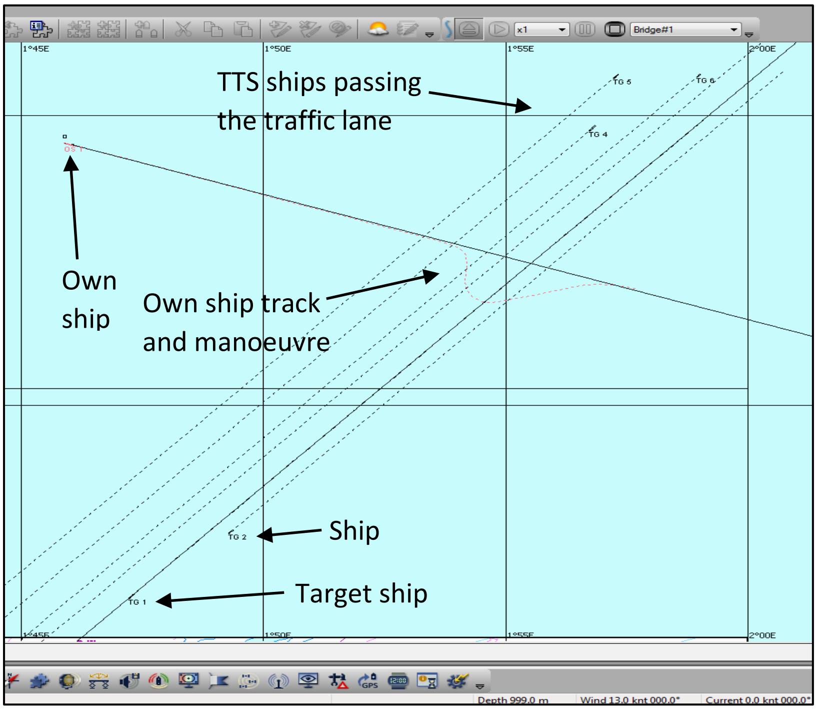


Figure 148 Scot Isles Automatic Scenario

The Classical approach experiment

In this scenario, the OOW initially turned little to port to pass clear from the ships sailing south. After passing the southbound ships, he started altering course to starboard to increase the CPA for the ships coming from north Figure 149. The OOW was late in detecting the risk of collision with the target ship. Thus, when he saw the ship, he started immediately taking an avoidance action to pass her stern (Figure 150). The OOW's action was early and major, which led him passing in long distance from the target Figure 151.

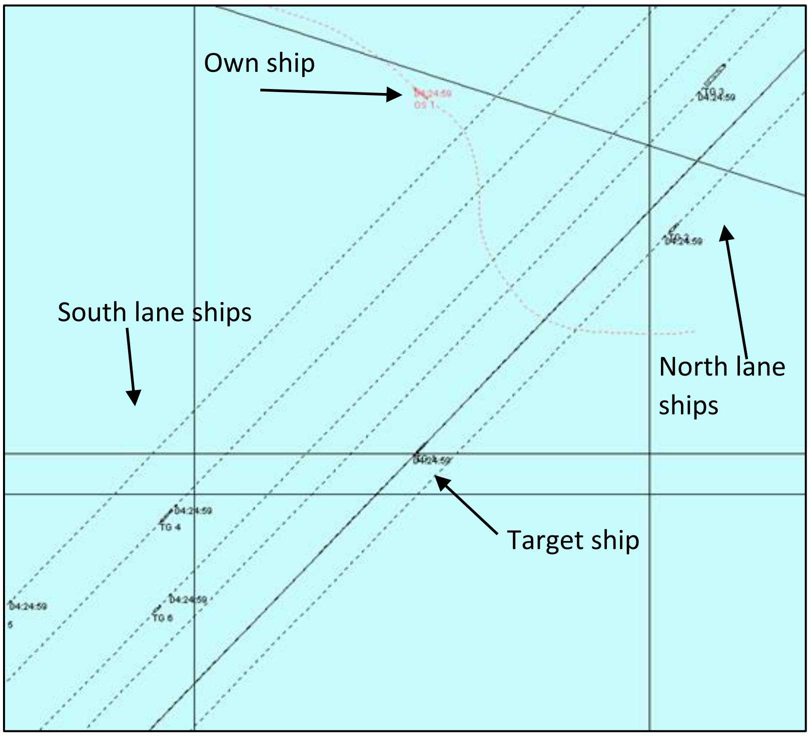


Figure 149 Scot Isles Classical scenario

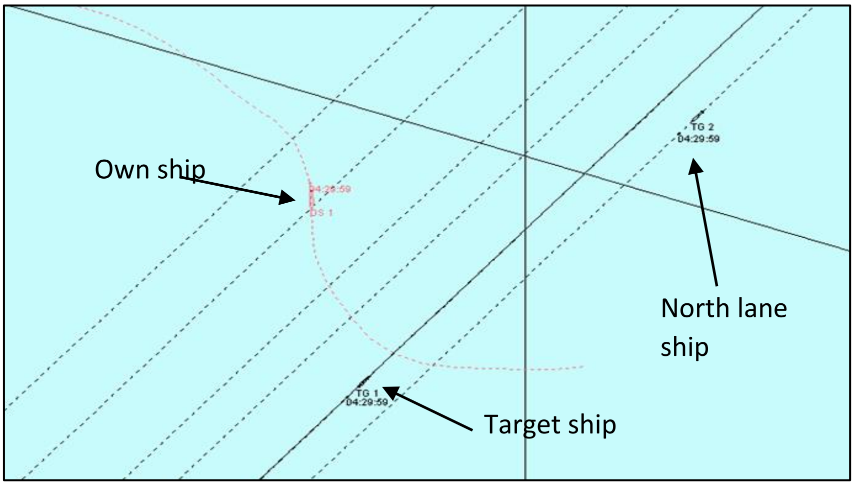


Figure 150 Scot Isles Classical scenario

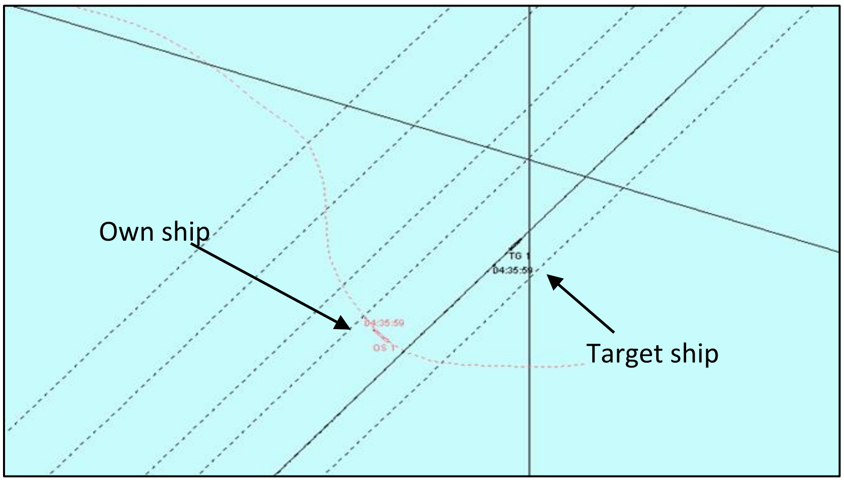


Figure 151 Scot Isles Classical scenario

The Automatic Approach experiment

In the *Automatic scenario*, the Automatic Collision Avoidance System has detected the risk at the right time. Figure 152 shows the own ship sailing in a collision course with the target ship in a crossing situation, and the own ship is the give-way vessel. Moreover, the system provided a precise decision for course alteration to the starboard side to pass astern of the target ship (Figure 153). The avoidance decision has allowed the own ship to pass the target ship within the limits of the passing distance and just above the deviation limit Figure 154.

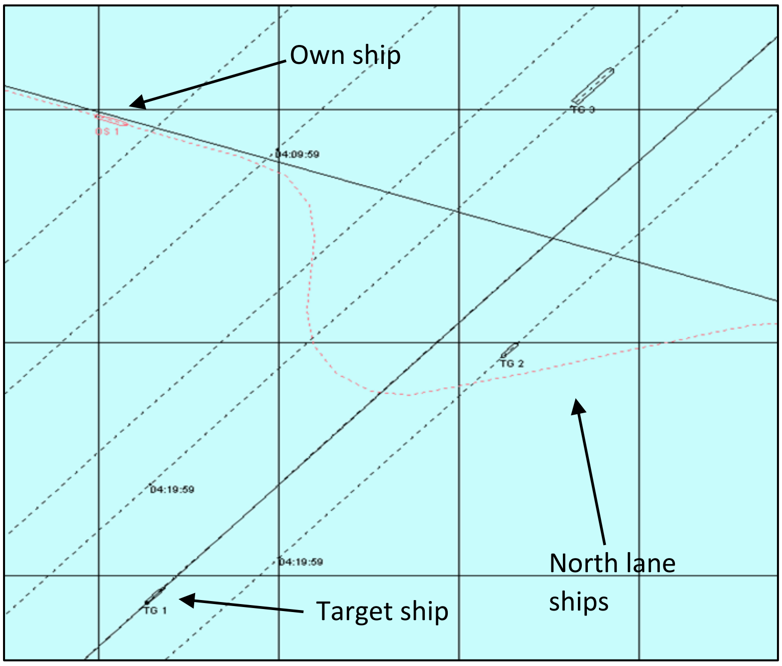


Figure 152 Scot Isles Automatic scenario

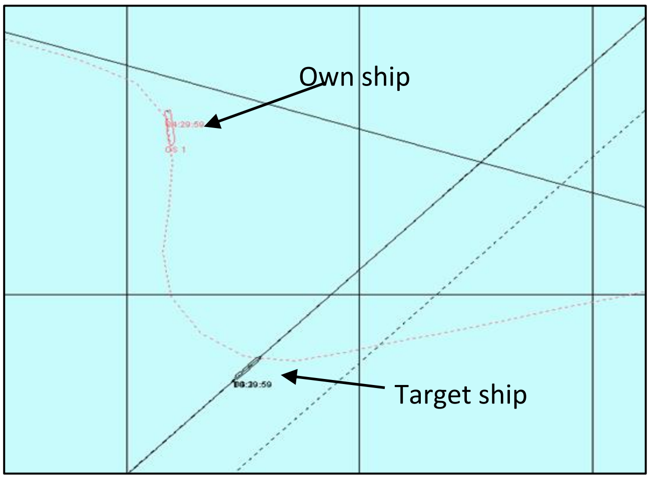


Figure 153 Scot Isles Automatic scenario

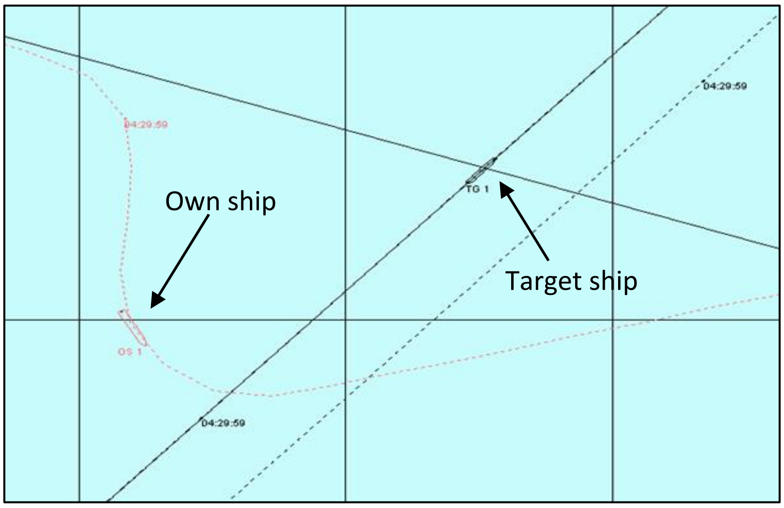


Figure 154 Scot Isles Automatic scenario

Table 39 Scot Isles actions; real event actions, best actions and the Automatic system decisions

Time of Actions	***Scot Isles* actions**	***Wadi Halfa* actions**	**Comments**	**Best action by *Scot Isles***	**Best actions by Wadi Halfa**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0400	The Chief Officer took over the watch and an AB was on watch for the look-out. The ship was 4 NM from the SW traffic lane. No targets were acquired for collision risk assessment. However, there were a number of them on the radar screen. And no monitoring on the AIS system as well.	The Chief Officer took Over the watch with a cadet and a look-out AB.		Should have acquired the targets on the radar for good collision risk assessment.		The Auto system has detected *Wadi Halfa* (target) on the detection zone (10NM)	The system would have processed all the data and targets and alert the OOW about any dangerous situation.
0410	Alter course to 109° from 105°.						
0421	Started to cross the SW lane. No position plotting was on the chart after 0400.		NO proper look-out and radar monitoring were conducted in the navigational watch.	Should confirm that it is clear to cross the traffic lanes before crossing.			It would alert the OOW about any collision situation and advice about the best action to avoid it.
0424						The Auto system has recognised the risk of collision with *wadi Halfa* 10 minutes before the collision.	

Time of Actions	*Scot Isles* actions	*Wadi Halfa* actions	Comments	Best action by *Scot Isles*	Best actions by Wadi Halfa	The developed Auto system actions in the experiment	Collision avoidance system response
0427						The Auto system has alerted the OOW about the risk of collision with *wadi Halfa* and provided the best action to avoid it. The action is to alter course to 186°.	
0430		Alter course to 041° from 035°.	NO proper look-out and radar monitoring were conducted during the navigational watch.				
0435	Red navigational light has been reported by the look-out on the vessel's starboard side. The OOW did not comment on the report and the look-out went for the safety check.	The look-out went for a break, and the cadet was in the charts room and plotting positions every 10 minutes. The OOW was monitoring ARPA and did not acquire any targets to assess the risk of collision.	No targets were acquired in both ships for proper collision risk assessment. Especially in *Scot Isles* before they crossed the traffic lanes. The OOW ignored the look-out report about the red light on the starboard side, which was Wadi Halfa's sidelight.	Listen to the look-out report and take the best actions to identify the target and avoid the collision.	Targets acquisition and monitoring for collision risk assessment.		After alerting both ships about the dangerous situation, it would monitor the situation and share the information and decisions with both ships to ensure collision avoidance manoeuvres are applied by the give-way vessel. However, if the give-way vessel is not taking any action or her action is not enough to the void the collision, the system would advise the stand-on vessel about the best action to take to avoid the collision.

Time of Actions	***Scot Isles* actions**	***Wadi Halfa* actions**	**Comments**	**Best action by *Scot Isles***	**Best actions by Wadi Halfa**	**The developed Auto system actions in the experiment**	**Collision avoidance system response**
0443	Stared to cross the NE lane.		No collision risk assessment was conducted before crossing the lanes.				The engine will stop **a**utomatically to reduce the impact of the collision when it comes to the point of no action can stop the collision from happening.
0448		The masthead light and green sidelight of *Scot Isles* was seen by the OOW on the port bow very closely.	Too late to take any avoiding action by both ships.				
0449 (Collision time)	The OOW saw the accommodation's lights of *Wadi Halfa* very close to his starboard quarter. He tried to put a hard to port rudder when the collision happened.	The OOW put the helms hard to starboard and asked the cadet to call the master.					

General comments:

- The master of Scot Isles has left the OOW alone and assumed the VTS will advise him in case of any collision situation, which is not the role of the VTS to relieve the OOW form the COLREG obligations.
- The master did not leave any night standing orders, which was required by the SMS and it could warn the OOW about dangerous areas of navigation.
- In Wadi Halfa, the Chief Officer took over the watch and dismissed the lookout.
- The Chief Officer was not focusing on navigational duty.
- In both vessels there was no proper lookout and they did not see each other until it was too later to avoid the collision.

The OOWs' opinion about the developed Automatic Collision Avoidance System

The OOW was commenting on the precision of the system, where it provides decisions that avoid the collision situation in the minimum course alteration. Moreover, the ability to provide the decisions at a late stage of the collision situation, and still avoid the collision. This can be very useful as a safety measure to prevent a collision from happening. Additionally, the precision of the system's action helped the OOW to avoid any other conflicting situation with other targets passing the traffic lanes.

The Scot Isles KPIs results

Tables 40 and 41 provide the collected measures for these scenarios, which have been utilised to calculate the KPIs. Figure 155 presents the KPIs results to show the performance of the OOW in this scenario. The KPIs results for the *Classical scenario* show that the OOW was late in the target detection. Additionally, it shows that the OOW's decision led to a large passing distance from the target ship, as well as a long sailing distance from the original planned track. Nevertheless, the OOW's decision was taken in ample time before the collision, which would have allowed a smooth avoidance manoeuvre, with less sailing and passing distance. This shows the tendency of OOWs to take earlier and larger deviation that results in unnecessary longer movement just as extra safety precautions. Due to the uncertainty of the avoidance action's effectiveness, OOW prefers to take early and large deviation, which is considered an inefficient decision.

In the *Automatic scenario*, the system has detected the target once it has entered into the detection zone (10 NM). Also, the risk recognition time was captured on time, 10 minutes before the collision. For the action time, the system was capable of providing the decision that allowed the ship to pass the target exactly on the required benchmark, 0.5 NM. Moreover, the sailing distance from the original planned track was just above the tolerance XTE for this scenario which will enable the own ship to quickly return to the original track. Thus, in this scenario, the Automatic Collision Avoidance System has proven its unique advantage to remove the uncertainty of the collision situation and the best action to avoid it, as it provides an avoidance decision that allows the ship to better fulfil the navigational requirement.

Table 40 Scot Isles Classical scenario data

Classical Approach Scot Isles		
Measures	Data	Unit
Time of appearance	04:06:45	Time
Time of detection	04:17:25	Time
Actual time of risk	04:26:15	Time
time of recognition	04:26:00	Time
required action time	04:29:35	Time
actual action time	04:26:40	Time
required CPA	0.5	NM
Range	0.7	NM
XTE	0.5	NM
Actual Deviation	1.4	NM

Table 41 Scot Isles Automatic scenario data

Automatic Approach Scot Isles		
Measures	Data	Unit
Time of appearance	04:00:00	Time
Time of detection	04:00:00	Time
Actual time of risk	04:24:01	Time
time of recognition	04:24:01	Time
required action time	04:27:50	Time
actual action time	04:27:50	Time
required CPA	0.5	NM
Range	0.5	NM
XTE	0.5	NM
Actual Deviation	0.8	NM

Figure 155 Scot Isles KPIs' results. This figure shows the KPIs result; the unit for KPIs 1, 2 and 3 are time by minutes. The negative results indicate a delay in the action and a positive result indicate an early action. KPIs 4 and 5 are measured by the ratio and 1 is the benchmark.

8.4.9 The videos observation for performance monitoring

After the data analysis and explanations of the experiments in the previous section, another valuable source of in-depth information about the OOW performance, the video records of the experiments, were studied extensively. This observation provides a generic, yet, an important overview of the factors that affect the situational awareness of the OOW in the navigational bridge.

Moreover, this captures the differences between the *Classical and Automatic approach*es in these experiments. Also, the overall trend of the performance will be highlighted through these video observations. For the similarity nature of the observation results and findings, a generic finding on the important factors that have been observed in these scenarios will be discussed, and when it is necessary the exact scenario's name will be mentioned.

Observations of the Classical approach:

- It was observed that all the OOWs were performing to a high standard as they knew that they are being monitored and filmed in the ship's bridge simulator. Additionally, they were aware that their performance is being monitored and further analysis is going to take place based on their navigational skills, by the author. This was obvious in their performance where they were continually monitoring the performance and development of the navigational situations. Furthermore, the fact that it was an experiment about collision situations and collision avoidance techniques, this makes them wait for a collision situation to develop in the scenarios. Thus, all the OOW were suspicious about almost all the targets around them and extra precautions were taken to prevent collision situations. For this reason, they were acquiring every target appears in the radar screen to assess the risk of collision and in almost all the *Classical scenarios* the OOW tend to take early avoidance action.

- Excessive radar monitoring. It has been observed that a long time is being spent to monitor targets on the radar for many reasons, such as; target detection, targets' information acquisition, risk assessment, and the results of the avoidance action. Accordingly, during this radar monitoring habit, the OOW is collecting the required data for each target to assess the risk of collision. For data collection the target needs to be acquired on the radar screen, then the OOW needs to wait for proximity one to two minutes so the radar can provide accurate data. During this waiting time, the OOW usually moves around the bridge to monitor the performance of the ship, in different navigational equipment, and any other developed situation. This waiting time with the other tasks of monitoring plus if there is more than one target, are all a source of stress for the OOW and increasing the chance of forgetting a task or important information. Thus, the attention of the OOW tends to be distracted by all these monitoring duties on the navigational bridge, which has a direct impact on the level of situational awareness.

- It has been observed that the OOWs are over relying on the navigational equipment (radar and ECDIS) for navigational progress monitoring, where these are the only sources of information to the OOW. Thus, the OOWs tend to only use these systems with minimum visual lookout. Accordingly, this could lead to misunderstanding and misinterpretation of the navigational and traffic situation around the ship. With such a lack of proper monitoring of the whole playing factors around the ship, a chance of wrong decisions is becoming more likely.

- The frequent small actions to avoid a collision. It has been observed that OOWs are more willing to take small actions (usually 5° course alteration) for collision avoidance. After this small action is taken, they keep monitoring the situation to reassess the result of that action, and then if the situation requires, they take additional actions to improve the situation. This act promotes a nervousness behaviour that keeps the OOW always anxious about the avoidance manoeuvre with continuous analysis to ensure the safe avoidance of any target. Additionally, this avoidance behaviour is against the advice of COLREG rule 8 (action to avoid a collision), which recommend large and easily recognised changes in course and/or speed by radar or visually, and to avoid small changes. Moreover, by constant monitoring and analysis, the chance of missing other targets is increasing. On the other hand, to avoid the uncertainty of small actions, large unnecessary actions are taken by some OOW that takes the ship far away from the planned track, and a long time to return back on track.

- It has been observed that in only one scenario the OOW has utilised some of the safety tools on the radar system (ARPA). The OOW has used the parallel index tool, which helps the OOW in maintaining his ship on the original planned track and helps the OOW to realise if his ship is coming closer to the shore or shallow areas. This tool does not have an alarm to alert the OOW, it just helps in monitoring the performance and progress of the ship movement on the radar screen. The other tool that has been used is the guard zone, this is an arc or circle (OOW choice) surrounded the ship in the radar screen. If any target has passed through this guard zone, the radar alerts the OOW and an alarm goes off. This is not a commonly used tool at sea as it is unreliable for target detection for two reasons. First, if the target did not pass through the guard zone boundaries then it cannot be detected, like small targets or in bad weather where targets get lost and suddenly appear again close to the ship, then the guard zone does not detect it. Second, for the noise alarms that go off because of non-dangerous targets breaching the boundaries of the guard zone. Thus, this alarm may go off for radar echoes that are reflecting due to weather state such as clouds, high sea waves, rain and wrong radar settings (gain, sea and rain), which are considered as a target by the radar and it will alert the OOW. Additionally, the landmark and buoys that enter the boundaries of the guard zone will be detected as targets and activate the alarm. Also, any ship passes the guard zone that is not in collision course will trigger the alarm as well. However, all these noise alarms irritate and distract the OOWs, where they usually tend to acknowledge these alarms without investigating its reasons.

- It was observed that on many occasions the OOW uses the VHF as a mean for collision avoidance agreement and negotiations. This is in contradiction with the COLREG and it has many disadvantages. First, the valuable time is that being wasted in these communications, where it would be much better if actions are taken earlier rather than VHF calls. Second, the confusion about the collision and manoeuvres, these calls cause more danger than following the COLREG requirements. However, the correct action that should be taken in case of collision is to assess the situation and take the action based on the COLREG regulation. These regulations give each ship that involves in collision situation a clear instruction to follow to get out of the risk of collision.

Observations of the Automatic approach:

- It was clear that the OOWs have a hesitant behaviour, due to the advice from the Automatic Collision Avoidance System. It may be considered as a normal behaviour when this system was utilised for the first time. In this experiment, the system deliberately (by the author) provided the decision of collision avoidance at the last moment to test its ability in a critical collision situation. However, this hesitation did not affect the response of the OOWs to obey the system and perform the avoidance decision that provided from the system, which led to the avoidance of the collision situation safely. Thus, with more practises and familiarisation with the utilisation of the Automatic system in collision situations, this hesitation will be eliminated and the users (OOWs) will interact with the system with more regularly and confidently.

- It was observed that in the scenarios, which have more than one target to avoid using the Automatic system (like in *ACX Hibiscus* and *CMA CGM Florida*), where the Automatic system has been activated two or three times in the scenario, the OOWs' hesitation has decreased in the second critical collision situation. The hesitation was high in the first time of the Automatic system activation, as the OOW was not sure about the performance and capabilities of the system. However, after the first activation of the Automatic system, which provided a safe collision avoidance manoeuvre, the OOW started building trust in the system. The OOWs became more familiar with the utilisation of the system, where it removed all the hassles of the collision avoidance decision making. When the second collision situation was developing, the OOWs were more relaxed and confident in utilising the Automatic Collision Avoidance System.

- It was observed in the utilisation of the Automatic System, the OOW is less stressed and more comfortable in the navigational duties. Thus, the OOW has more time to visually observe and interpret navigational situations better. Moreover, the OOW was not concerned about the need for collecting the target information and the collision avoidance decision making, as a result of the availability of the Automatic Collision Avoidance System. This is because of the system capabilities to provide the best avoidance action, and the OOW just needs to implement this action to avoid the collision situation.

- The concept of the Automatic Collision Avoidance System is to evaluate the collision situation based on pre-selected parameters (mentioned before) by the OOW, in order to provide comprehensive avoidance decisions. Thereby, the OOW does not need to assess the collision criteria over time and take multiple avoidance actions, in emergency situation.

- Regarding the radar (ARPA) monitoring in the *Automatic scenarios*, in the first five experiments, the radar was turned off, so the OOW has to visually lookout and detects targets. The ECDIS system was available for passage monitoring and local area charts, and the avoidance manoeuvres were given by the developed Automatic Collision Avoidance system. On the final three experiments (*Ever Smart*, *Lykes Voyager* and *Scot Isles*), the radar was operated normally with the ECDIS and the Automatic system. This technique has been adopted in these experiments to observe OOWs' behaviour when they have the radar on for monitoring the targets, but they do not have to collect and analyse data for collision avoidance decisions. The Automatic Collision Avoidance System is utilised to provide the manoeuvring decisions to the OOW in case of collision situation. It has been observed that when the radar is off the OOWs are only utilising the ECDIS system to monitor the progress of the ship with the visual lookout. Thus, all the avoidance manoeuvres are given by the Automatic Collision Avoidance system, where OOWs follow the system's decisions to avoid the collision. This has reduced the level of situational awareness of the OOWs as they were unable to accurately detect the targets around their ships. The OOWs were waiting and monitoring the Automatic Collision Avoidance system to provide the best actions to avoid collisions. When the radar was turned on, the OOWs have started moderately monitoring it to enhance their situational awareness and recognise any targets around them. This radar monitoring has not affected the performance of the OOWs as they knew that they do not need to calculate the avoidance decisions, which will be provided from the Automatic system. The most important factor that has been observed from this technique is that when the Automatic system is available, with the other navigational aids, the OOW tends to be more focused on the navigational duties rather than collecting the data and analyse it for decision making. The advantages of installing the Automatic Collision Avoidance system on-board ships will help the OOWs to concentrate on the ship's progress and the consequences of the action, not on the data collection and analysis, which will improve the situational awareness of the OOW. This will reduce the workload and improve the performance in the navigational bridge.

8.5 Fuzzy-TOPSIS technique for ranking the decisions of the Automatic Collision Avoidance System

This section discusses the need for having a method that can rank the calculated collision avoidance decisions and select the best action to prevent the accident. Where the developed Automatic Collision Avoidance System provides number of avoidance decisions, such as; course alterations with different directions, increase or decrease speed and course/speed change to avoid the collision, it becomes important to use a ranking method to select the best action for each specific scenario. A fuzzy TPOSIS technique has been developed to rank these calculated decisions based on the selected criteria. Below is further discussion about the necessity to develop such a model with the justifications of selecting the fuzzy TOPSIS technique.

After completing all the validation experiments, analysis and the results, a quality management review about the performance of the Automatic Collision Avoidance System has been performed. This review aims to improve the utilisation and operation of the Automatic System in all collision events, most importantly in complex navigational situations. As a result of the system operation review, it has been observed that the utilisation of all the calculated collision avoidance decisions is restricted to course alteration only, similar to the common practices at sea by OOWs. However, in a complicated situation, other options can be more effective than course alteration only, like speed change or stopping the ship. Moreover, it has been mentioned in chapter 6; the Automatic Collision Avoidance System is capable of providing a total of eight avoidance decisions, as follows; two-speed changes, four-course changes and two combined course and speed changes. Thus, in a normal navigational situation, where there are no navigational restrictions, such as; narrow channel, shallow waters, crowded waters, etc. the best action to avoid collision situations is by course alteration, which is recommended by the COLREG. However, in complex situations, it could be impossible to change course and divert from the planned track. In this case, the alternative collision avoidance decisions should be considered, which are already calculated by the Automatic Collision Avoidance System. This has brought the necessity to have an objective approach that is efficient in selecting the optimum avoidance decision, based on the predetermined criteria. This can be achieved by implementing a ranking technique that is able to rank the available avoidance decisions from the top best action to the second possible action and so on.

For such a decision-making problem, where the aim is to find the best feasible option, the Multiple Criteria Decision Making (MCDM) approach can be utilised to develop a matrix for the alternatives and criteria then rate these alternatives. In this research, the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS), a well-known MCDM method, is implemented in this section to provide an objective approach to rank the calculated collision avoidance decisions (Krohling and Campanharo, 2011). The TOPSIS method has been developed by Ching-lai Hwang and Yoon in 1981, and this method has been presented with additional modification by Chen-Tung Chen and others in (Chen, 2000, Krohling and Campanharo, 2011, Wang, 2014). Where these authors have utilised the fuzzy sets approach for alternatives rating and criteria weighting, which are judged linguistically then transformed into a triangular fuzzy number. The purpose of the fuzzy rating and weighting approach is to get around the inaccuracy and difficulties of assigning a crisp value for each alternative and criteria. Thus, to permit a tolerance level in the collision avoidance decisions, where it is infeasible to evaluate them using a crisp value, the Fuzzy TOPSIS multiple criteria decision making MCDM approach is utilised for decision ranking. The basic principle of the TOPSIS method is to measure the alternatives' distance for the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). Based on these distances, the alternatives are ranked, where the closest to the PIS and the farther from the NIS is the highest ranked alternative. Moreover, in the classical TOPSIS method, the values of the evaluation criteria and the alternatives judgement rates are crisp values. Thus, the scales of the linguistic term and its equivalent triangular fuzzy numbers have been utilised to enable more reliable evaluation of the weights and alternatives rates (Chen, 2000, Krohling and Campanharo, 2011, Wang, 2014).

The fuzzy TOPSIS model has been developed to overcome the issue of action delay and CPA breach, which was observed in scenario 6, the *Automatic Approach* of Ever Smart ship. Table 42 provides the navigation parameters for this scenario and the avoidance action that has been taken in the experiment. In this scenario, the ship was sailing in the channel and had no room to change the course to avoid the drifting vessel on the channel's entrance. However, instead of changing the speed to avoid colliding with that target, the action has been delayed being clear of the channel and then started to change the course to avoid the collision. This has resulted in a breach of the CPA, where the two vessels passed with 0.15 NM apart from each other, which is a very close distance. Accordingly, this ranking technique has been developed to optimise the automatic selection of the best collision avoidance decision in all navigational situations. In this section, the results are being calculated and presented for this specific scenario, the Ever Smart scenario. The results for the rest of the scenarios are available in Appendix B.

Table 42 Own and target ships parameters, Ever Smart scenario, ***Automatic Approach***

Parameters	Own ship parameters	Target ship parameters	The avoidance decision was taken in the experiment
Course	315°	101°	Changing course to 342°
Speed	11 knots	1 knot	
Bearing	307°		
Range	1 NM		

8.5.1 The fuzzy TOPSIS steps

The steps that have been performed to conduct the fuzzy TOPSIS method for ranking the collision avoidance decisions that have been calculated by the Automatic Collision Avoidance System were given below;

Step one: criteria weights and assessment of alternatives

In the first step, the linguistic scales of the weights of the assessing criteria and the rates of the avoidance decisions (alternatives) will be provided and explained. These linguistic scales are divided into two tables; Table 43 has five levels to weigh the importance of each criterion that is used to evaluate the alternatives (Chen, 2000). Table 44 also has five levels to judge the efficiency of the available alternatives (Chen, 2000). These scale tables provide the linguistic terms and its equivalent triangular fuzzy numbers, which are used to weigh the assessing criteria and rate the alternatives (Chen, 2000). Figures 156 shows the triangular fuzzy numbers for the linguistic weights of the evaluation criteria. Figure 157 shows the triangular fuzzy numbers for the linguistic judgment of the collision avoidance decisions. In this study, the triangular membership function has been selected for its effectiveness and simplicity to measure the distance between the triangular fuzzy numbers (Chen, 2000).

Table 43 Linguistic weights and its triangular fuzzy numbers for the evaluation criteria, adopted from (Chen, 2000)

Linguistic weighs	Triangular fuzzy numbers
Very low	(0,.1,.3)
Low	(.1,.3,.5)
Neutral	(.3,.5,.7)
High	(.5,.7,.9)
Very High	(.7,.9,1)

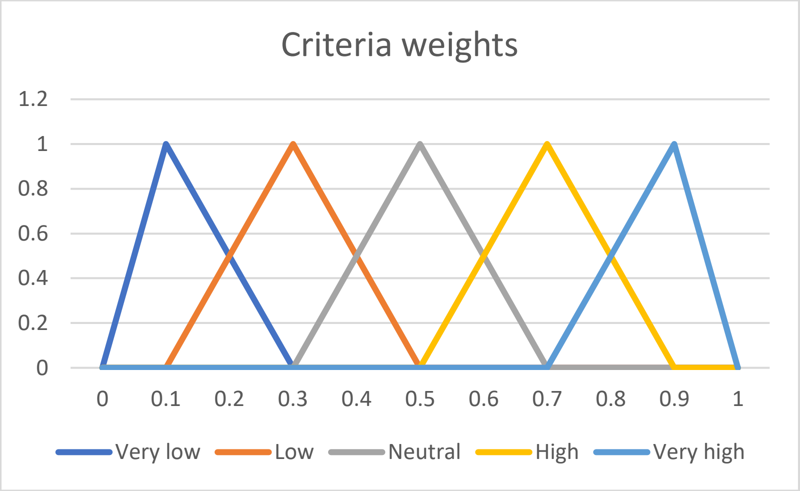


Figure 156 The graphs for the triangular fuzzy numbers for the weighting criteria

Table 44 Linguistic judgment for the alternatives and its triangular fuzzy numbers, adopted from (Chen, 2000)

Linguistic rates	Triangular fuzzy numbers
Very poor	(0,1,3)
Poor	(1,3,5)
Fair	(3,5,7)
Good	(5,7,9)
Very good	(7,9,10)

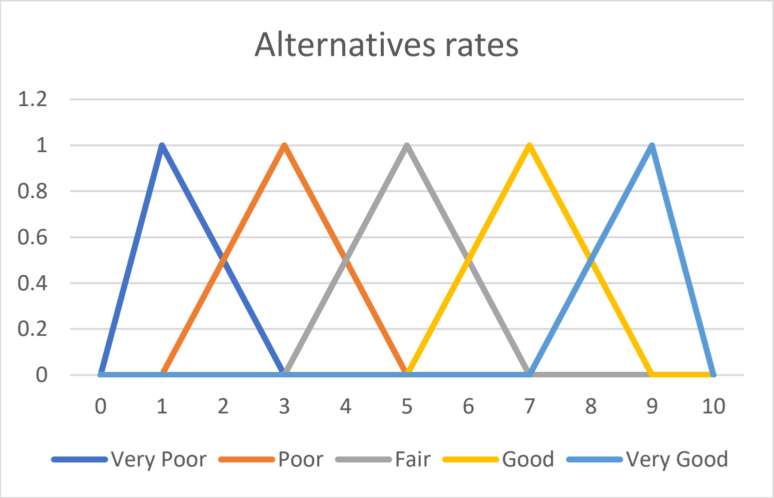


Figure 157 The graphs of the triangular fuzzy numbers for the judgment rates

The alternatives assessment criteria

In this study, the assessment criteria to evaluate the alternatives in table 45 has been made based on the collision avoidance procedures that are followed at sea and the COLREG requirement. The weights are the factors that determine the importance of each criterion that are used to judge the alternatives. In this model, there are four criteria that have been used to evaluate collision avoidance decisions. These criteria are explained below, and after mentioning the evaluation criteria, the method of the judgment of the collision avoidance decision will be explained, with all the required parameters.

- Course change to avoid the collision. For course change, there are four options that can be selected.

- Speed change to avoid the collision. For speed change, there are two options that can be selected.

- Combined course and speed changes to avoid the collision. For the combined change, there are two sets that can be selected.

After presenting the criteria for evaluating the alternatives, the judgement method of the efficiency of each avoidance option and the parameters that are used to make these judgments is explained.

- The efficiency of each course alteration is judged based on the magnitude of the required change of course and the direction of the turn, as well as the compliance with the COLREG recommendations.
    - Very good, a turn between zero to 45° to starboard side.
      $(0 < \text{Very Good} \leq 45°)$
    - Good, a turn between 45° to 90° to the starboard side.
      $(45° < \text{Good} \leq 90°)$
    - Fair, a turn between zero to 90° to the port side. The port alteration is not recommended by the COLREG, but it is still can be used if it is the only available option to avoid the collision.
      $(-90° \leq \text{Fair} < 0)$
    - Very poor, a turn that is bigger than 90°to either side, starboard or port.
      $(90° < \text{Very Poor} < 270°)$
- The judgment of the speed change to avoid the collision is based on the direction of movement of the ship.
    - Good, for foreword direction, so the reduction of speed or stopping the ship will be rated as good.
    - Poor, for reversing the movement of the ship to astern. This is rated as poor to avoid any complication with targets located behind the ship.
- For the combined course and speed changes, each action is rated separately, and the lower-rated is selected to ensure the safety of the ship.

For the judgment of the collision avoidance decisions, the following parameters are used to evaluate the efficiency of the decisions;

- Own ship course and speed.

- The safe distance to manoeuvre.
- The distance to move by own ship.
- The width of the channel.

Table 45 provides the linguistic rates of the alternatives and the utilised criteria for evaluating these alternatives.

Table 45 The assessing criteria and alternatives’ linguistic rates

The assessing criteria and alternatives’ linguistic rates							
Avoidance decisions (Alternatives)			Course deference	Course change	Speed change	Combined Sp/Co	Distance to manoeuvre
Co1	341.68°		26.68°	Very Good			Very Poor
Co2	152.31°		-162.68°	Very Poor			Very Poor
Co3	276.60°		-38.39°	Fair			Good
Co4	97.39°		142.39°	Very Poor			Very Poor
Sp1	0 knot				Good		Very Good
Sp2	-2knots				Poor		Poor
Sp/Co1	0 knot	270.11°	-44.89°	Fair	Good	Fair	Poor
Sp/Co2	1 knot	16.23°	61.23°	Good	Good	Good	Poor

Step two: transformation to triangular fuzzy numbers

In this step, the linguistic judgments of the collision avoidance decisions have been transformed into triangular fuzzy numbers. Table 46 shows the triangular fuzzy numbers for the alternatives and the weights of the criteria.

Table 46 The collision avoidance decisions matrix with the triangular fuzzy numbers for the rates and criteria weights

Collision avoidance decisions matrix												
Alternatives	Course change			Speed change			Combined Sp/Co			Distance to manoeuvre		
Co1	7	9	10	0	0	0	0	0	0	0	1	3
Co2	0	1	3	0	0	0	0	0	0	0	1	3
Co3	3	5	7	0	0	0	0	0	0	5	7	9
Co4	0	1	3	0	0	0	0	0	0	0	1	3
Sp1	0	0	0	5	7	9	0	0	0	7	9	10
Sp2	0	0	0	1	3	5	0	0	0	1	3	5
Sp/Co1	0	0	0	0	0	0	3	5	7	1	3	5
Sp/Co2	0	0	0	0	0	0	5	7	9	1	3	5
Weights	Neutral			Neutral			Neutral			Very High		
	0.3	0.5	0.7	0.3	0.5	0.7	0.3	0.5	0.7	0.7	0.9	1

Step Three: the normalisation

In the step, the collision avoidance decision matrix will be normalised by using the linear scale transformation formula to transform the values in the decision matrix to a comparable scale. This process will provide the normalised fuzzy decision matric, which is donated by ***R***, (Chen, 2000). Table 47 presents the normalised collision avoidance decision matrix.

$$\boldsymbol{R} = \left(\frac{a}{c\ max}, \frac{b}{c\ max}, \frac{c}{c\ max}\right) \qquad \text{(Eq. 32)}$$

Where *c max* is the biggest value in the c column.

This normalisation step is implemented to transform the above matrix in Table 46 to the range of the triangular fuzzy numbers between [0, 1].

Table 47 The normalised collision avoidance matrix

Normalised collision avoidance decision matrix												
Alternatives	Course change			Speed change			Combined Sp/Co			Distance to manoeuvre		
Co1	0.7	0.9	1	0	0	0	0	0	0	0	0.1	0.3
Co2	0	0.1	0.3	0	0	0	0	0	0	0	0.1	0.3
Co3	0.3	0.5	0.7	0	0	0	0	0	0	0.5	0.7	0.9
Co4	0	0.1	0.3	0	0	0	0	0	0	0	0.1	0.3
Sp1	0	0	0	0.6	0.8	1.0	0	0	0	0.7	0.9	1
Sp2	0	0	0	0.1	0.3	0.6	0	0	0	0.1	0.3	0.5
Sp/Co1	0	0	0	0	0	0	0.3	0.6	0.8	0.1	0.3	0.5
Sp/Co2	0	0	0	0	0	0	0.6	0.8	1.0	0.1	0.3	0.5
Weights	Neutral			Neutral			Neutral			Very High		
	0.3	0.5	0.7	0.3	0.5	0.7	0.3	0.5	0.7	0.7	0.9	1

Step four: the weighted values

In this step, the weights of each evaluating criteria are added to determine the importance of each criterion. For the criteria weights, all the values of course change, speed change and the combined course and speed changes have been weighted as neutral, where they are all having the same level of importance and they are all possible solutions for collision avoidance. The distance to manoeuvre has been weighted as a very high because it is the main factor that should be considered before selecting the avoidance decision. Also, because if there is no distance to manoeuvre it would be impossible to change the course of the ship. For the weighted value, each number in Table 47 is multiplied by the weight of the criteria and the results are shown in Table 48, (Chen, 2000).

$\boldsymbol{V} = R * W$ (Eq. 33)

Table 48 weighted collision avoidance decisions matrix

Weighted and normalisation collision avoidance decision matrix												
Alternatives	Course change			Speed change			Combined Sp/Co			Distance to manoeuvre		
Co1	0.21	0.45	0.7	0	0	0	0	0	0	0	0.09	0.3
Co2	0	0.05	0.21	0	0	0	0	0	0	0	0.09	0.3
Co3	0.09	0.25	0.49	0	0	0	0	0	0	0.35	0.63	0.9
Co4	0	0.05	0.21	0	0	0	0	0	0	0	0.09	0.3
Sp1	0	0	0	0.17	0.39	0.70	0	0	0	0.49	0.81	1
Sp2	0	0	0	0.03	0.17	0.39	0	0	0	0.07	0.27	0.5
Sp/Co1	0	0	0	0	0	0	0.10	0.28	0.54	0.07	0.27	0.5
Sp/Co2	0	0	0	0	0	0	0.17	0.39	0.70	0.07	0.27	0.5
A*	0.21	0.45	0.7	0.17	0.39	0.7	0.17	0.39	0.7	0.49	0.81	1
A-	0	0.05	0.21	0.03	0.17	0.39	0.1	0.28	0.54	0	0.09	0.3

Step five: define the FPIS and FNIS

After calculating the weighted and normalised values of the collision avoidance decision matrix, which are positive triangular fuzzy numbers within the interval [0, 1]. Then, the Fuzzy Positive Ideal Solution (FPIS, A*) and the Fuzzy Negative Ideal Solution (FNID, A-) can be determined; these are presented in Table 48. The A* is the biggest number in every column, and the A- is the smallest number in every column (Chen, 2000).

Step six: measuring the distance from the FPIS and the FNIS

To calculate the distance for every alternative from the A* and the A- can be calculated by the Euclidean formula;

$$d\ (m, n) = \sqrt{\frac{1}{3}\ [(m1 - n1)^2 + (m2 - n2)^2 + (m3 - n3)^2]}\text{(Eq. 34)}$$

Where m = (m1, m2, m3), and n = (n1, n2, n3). In this case, these represent the triangular fuzzy number for every collision avoidance decision, and the n represents the triangular fuzzy number for the A* and the A-. The results of this formula are available in Table 49 for the FPIS and in Table 50 for the FNIS.

Table 49 Measured distance from the FPIS

Distance from FPIS					∑ di*
Alternatives	Coerce change	Speed change	Combined Sp/Co	Distance to manoeuvre	
Co1	0	0.472934	0.472934104	0.64510981	1.590978018
Co2	0.384794	0.472934	0.472934104	0.64510981	1.975772335
Co3	0.1812	0.472934	0.472934104	0.143759058	1.270826971
Co4	0.384794	0.472934	0.472934104	0.64510981	1.975772335
Sp1	0.495513	0.002029	0.472934104	3.20494E-17	0.970475908
Sp2	0.495513	0.234766	0.472934104	0.489217062	1.69243069
Sp/Co1	0.495513	0.472934	0.117886044	0.489217062	1.575550411
Sp/Co2	0.495513	0.472934	0.002028602	0.489217062	1.45969297

Table 50 Measured distance from the FNIS

Distance from FNIS					∑ di-
Alternatives	Course change	Speed change	Combined Sp/Co	Distance to manoeuvre	
Co1	0.3847943	0.246238367	0.355903	8.01234E-18	0.986935
Co2	0	0.246238367	0.355903	8.01234E-18	0.602141
Co3	0.2053452	0.246238367	0.355903	0.507969815	1.315456
Co4	0	0.246238367	0.355903	8.01234E-18	0.602141
Sp1	0.1246328	0.232873444	0.355903	0.64510981	1.358519
Sp2	0.1246328	0.002796235	0.355903	0.160519988	0.643852
Sp/Co1	0.1246328	0.246238367	0.002869	0.160519988	0.53426
Sp/Co2	0.1246328	0.246238367	0.118182	0.160519988	0.649574

Step seven: calculate the closeness coefficient

In this step, the calculation of the closeness coefficient for each alternative will be provided. Based on the results of the closeness coefficient, the ranks of the alternative will be decided, the closest the number to one is the higher-ranked the alternative. The closeness coefficient formula is;

$$CCi = \frac{di-}{(\mathrm{di}- + \mathrm{di}*)} \text{ (Eq. 35)}$$

Table 51 presents the results of the CCi and the rank of each alternative.

Table 51 The ranks of the collision avoidance decisions, Ever Smart Scenario

Alternatives	Avoidance decisions		CCi	Ranks
Co1	342°		0.38	**3** This decision was taken in the experiment
Co2	152°		0.23	7
Co3	277°		0.51	**2**
Co4	97°		0.23	7
Sp1	0 knot (stop the ship)		0.58	**1**
Sp2	-2 knots (astern)		0.28	5
Sp/Co1	0 knot	270°	0.25	6
Sp/Co2	1 knot	16°	0.31	**4**

The results of the fuzzy TOPSIS model, have ranked collision avoidance decisions, which have been calculated by the developed Automatic Collision Avoidance System, Table 51. From this ranking method, it has been clear that the course alteration is not the best action for collision avoidance in every situation. Also, it emphasises the importance of evaluating all the possible decisions and take the best action to avoid the collision depending on the circumstances at every specific collision situation. Like in Ever Smart, scenario 6, the ship was sailing in a narrow channel, and in such situation, the speed change is the only available option to prevent the collision, which has been ranked as the first action to be taken by the fuzzy TOPSIS model. However, in the simulator experiment, the first decision of course alteration, to change course to 342°, was taken, which was ranked as number three by the fuzzy TOPSIS model. After that, the port alteration decision has been ranked as the second-best action. Although the port alteration is not recommended by the COLREG, in this situation, where the ship has limited options, this has been compromised to ensure the safety of the ship. The port alteration was feasible in this case because the ship was almost leaving the channel, where she was sailing on the starboard side on the traffic direction and this gives her a limited distance on her starboard side and a more space on the port side (the Channel width is 380 m, 0.17 NM). Also, the drifting vessel was sailing to the east and the port alteration would allow the ships to move farther away from each other. As a result of implementing MCDM model within the framework of the developed Automatic Collision Avoidance System, Overall system will enhance the automation capability of decision making in all navigational situations, including complex situations.

8.6 KPI results in a comparison between the *Classical and Automatic approaches*

Hereafter, all the scenarios' KPI results will be demonstrated. The presentation of the results will be based on a comparison between the *Classical and Automatic approaches*. For each KPI, the results of all the scenarios in the *Classical approach* will be compared with all the results of all the scenarios in the *Automatic approach*. These KPI results will be represented in one graph to demonstrate the trend of performance for the selected KPI within all the scenarios, Classical and Automatic. Additionally, these results in graphical forms will be supported by the explanatory discussions to elucidate the performance preferences in each approach with its cons and pros. Therefore, this will provide thorough analytical results for the collision avoidance procedures and practices in both *Classical and Automatic approaches*.

Moreover, a results' rating scale is developed to evaluate the performance efficiency for every KPI's results in Figure 158. The rating technique for the results is based on the author's experience, which will be justified for every KPI separately. The justifications will depend on the aspects of that KPI, where the effect of the factors on the results is considered carefully.

Very Efficient	Efficient	Semi Efficient	Inefficient	Very Inefficient

Figure 158 The KPIs results' rating scale

KPI 1: Target Detection

The main aim of this safety KPI is to measure the efficiency of detecting targets in the vicinity. This can be either by radar or visually. In classical navigational procedures, this process has no specific distance that has been standardised for determining at what distance a target should be detected. This is left to OOW to ensure safe navigation of the ship. On the other hand, in the developed automatic system, this distance is specified to detect all targets inside the detection zone. The detection range has been selected to be 10 NM in these experiments. Thus, in the *Automatic approach*, the moment that a target reaches the distance of 10 NM from own ship, the system detects it.

These KPI results have been rated based on two factors:

- The amount of time delay in target detection. How long it takes the OOW to see the target.
- The time of target detection with regard to the actual time of risk. How much time is remaining to the actual time of risk after the target is detected?

By looking at this KPI's graph in Figure 159, it shows the fluctuation in the results of the *Classical scenarios*. This variation in the result is due to a delay in target detection. This delay reached to over 20 minutes, like in experiment 4, wherein this scenario the target ship was an overtaking vessel and the OOW was not aware of that ship approaching from the stern of his ship. Especially when the OOW maximises the radar view to see the longer distance in front of the ship, this reduces the view of the stern of the ship. Also, in experiment 8, the delay in target detection was about 10 minutes. This was a crossing situation in TTS crossing area, the OOW was busy manoeuvring to avoid other ships, and he detects the target ship later than it should be. In experiment 5, the weather condition and visibility were all good, and there were no other targets in the vicinity, this led to immediate detection of the target ship. However, the OOW took and early action that diverted the ship for a long distance from the original track, and unnecessarily large passing distance from the target.

Moving on to results of the Automatic Collision Avoidance scenarios, the target detection process was in the ideal performance for all the scenarios, where the system was able to detect all targets within the detection zone (10 NM). However, no alert is issued at this stage, as the target is still far away for any avoidance manoeuvre, but the system has detected the target for further assessment for the risk of collision.

This KPI provides us with the overall trend in target detection, which tends to be late detection in almost all the *Classical scenarios*. However, great caution is needed for this process, as this will lead to further complications in the decision-making process as discussed in the following results. In the case of developed Automatic Collision Avoidance System, this issue is solved by continues electronic and automatic monitoring of the detection zone.

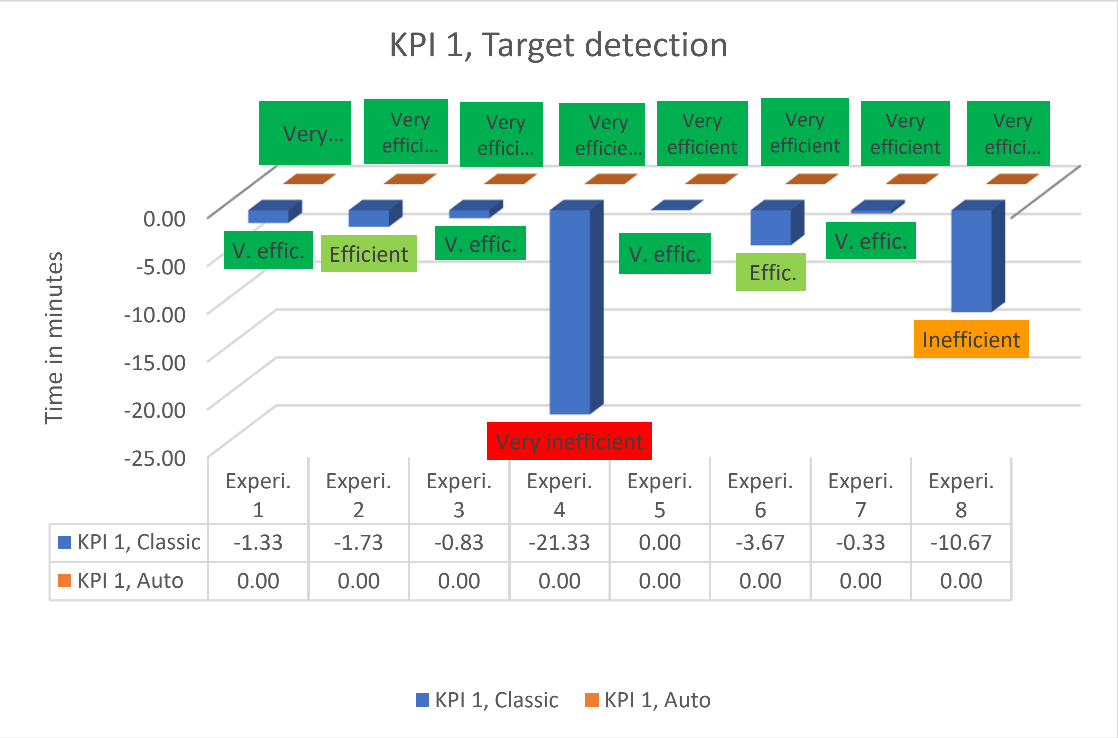


Figure 159 KPI 1 results, Target detection

KPI 2: Risk Recognition

The risk recognition KPI is a safety indicator factor. This is indicating that the OOW is aware of the risk situation and is preparing to take the necessary action to avoid the collision. Again, there is no standardisation for distance or time for this process to take place; it is left to the OOW and his good seamanship practices to ensure the safety of the ship. In the *Automatic approach*, this KPI is measured by the TCPA, and it has been standardised to 10 minutes before the collision time. At this moment, the situation should be fully understood, and the preparation for the action to avoid collision should be ready.

The KPI results have been rated based on:

- The time of risk recognition. How much early or late the risk was recognised. The early risk recognition could lead to, either; early and significant actions that take the ship far away from the original planned track and promotes conflicts with other targets. Or, with the earlier recognition, the OOW would mostly delay the avoidance action and then he/she could forget to take it at the right time. Moreover, the late risk recognition is greatly dangerous than the earlier detection, as the risk of collision will be higher and less likely to be avoidable. Thus, the delay in risk recognition is ranked to be more inefficient compared to the early recognition, when the results are rated.

Figure 160 the C*lassical scenarios* show the oscillation in the KPI result for the time of risk recognition. In scenarios such as experiment 3, the risk has been recognised almost half an hour earlier than it should be. This resulted in very early action and deviation from the original track for a long time, whereas, in the *Automatic scenarios*, the risk recognition KPI results show consistency in the recognition time.

These results show the fact that almost all the OOWs are usually suspicious about the targets in their detection range. However, this promotes a high level of uncertainty in the navigational process, where they do not have a clear and accurate interpretation of the targets around them. This issue is also proven to be better dealt with in the Automatic system, where the system provides an alert to the threatening targets to prepare the OOW for any avoidance action.

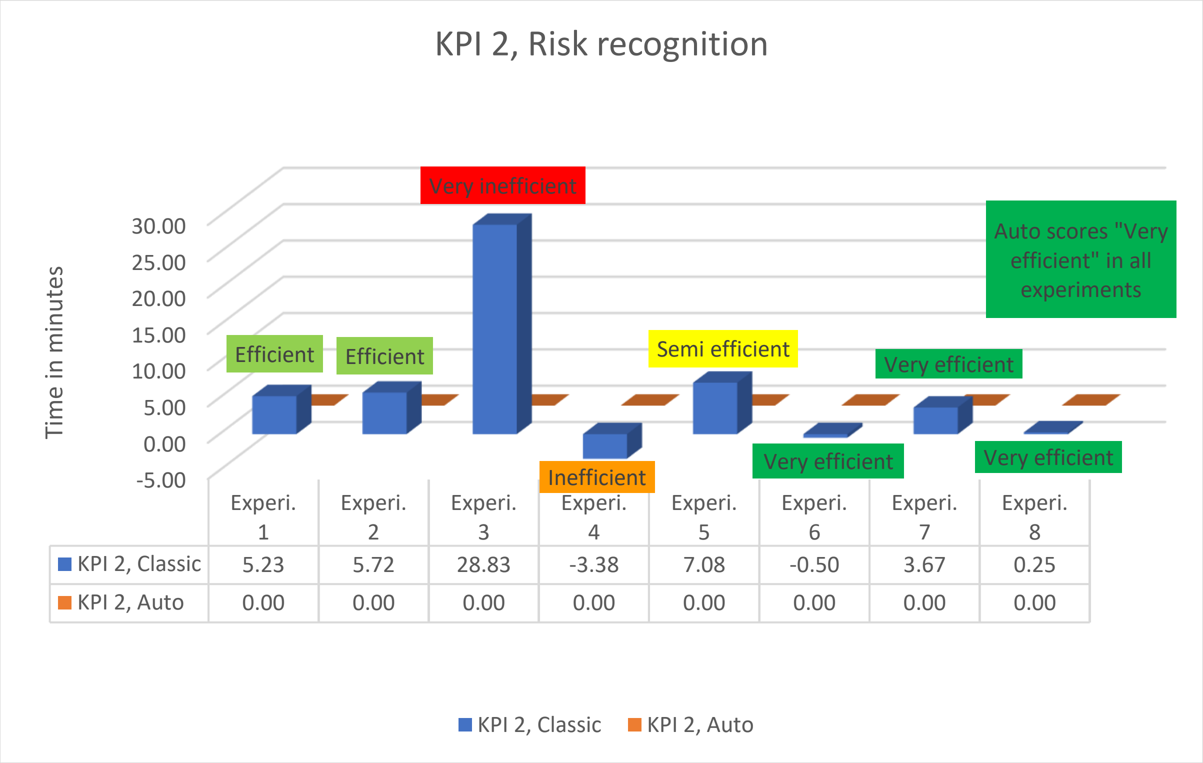


Figure 160 KPI 2 results, Risk recognition

KPI 3, Action time (response)

This safety KPI measures the efficiency of the time to take the avoidance action. This is the indicator of the required time of starting the manoeuvre. Where there is no standardisation for such factor in the classical navigational procedures, in this experiment, this has been selected to be 1 NM before the collision. Whereas this is a very close distance to start manoeuvring, it has been selected intentionally to test the feasibility of the system to act in a critical collision situation.

The KPI results have been rated based on:

- The time of taking action; how much earlier the avoidance action has been taken. As the time of action is set to be the last moment before collision, then earlier action would cause a longer deviation from the original planned track.

Figure 161 illustrates the action time results. This shows that an early action has been taken in all the *Classical scenarios*. Also, in some experiments, the avoidance action is taken very early, about 20 minutes before the collision time.

In experiment 6, there is a semi-efficient time of action in the *Automatic scenario*, as the operator of the system (the author decided to delay the system intervention). A reason for that delay, as there was not enough room for the ship to manoeuvre, compared to the rest of the scenarios. This KPI highlights the fact that the OOWs are always becoming over precautious when they face a situation that requires them to decide their action to avoid it, which is usually early actions. This leads to some unnecessary action or larger than the required actions to remove the uncertainty of the situation. This is recognised in case of course alterations to avoid collisions, where they increase the alteration to ensure the safety distance from the targets. Also, in the case of avoidance for multiple targets to prevent further conflictions, the OOWs prefer to start the course alteration early with large alteration to avoid all the targets in the ship's course, even if this is not necessary.

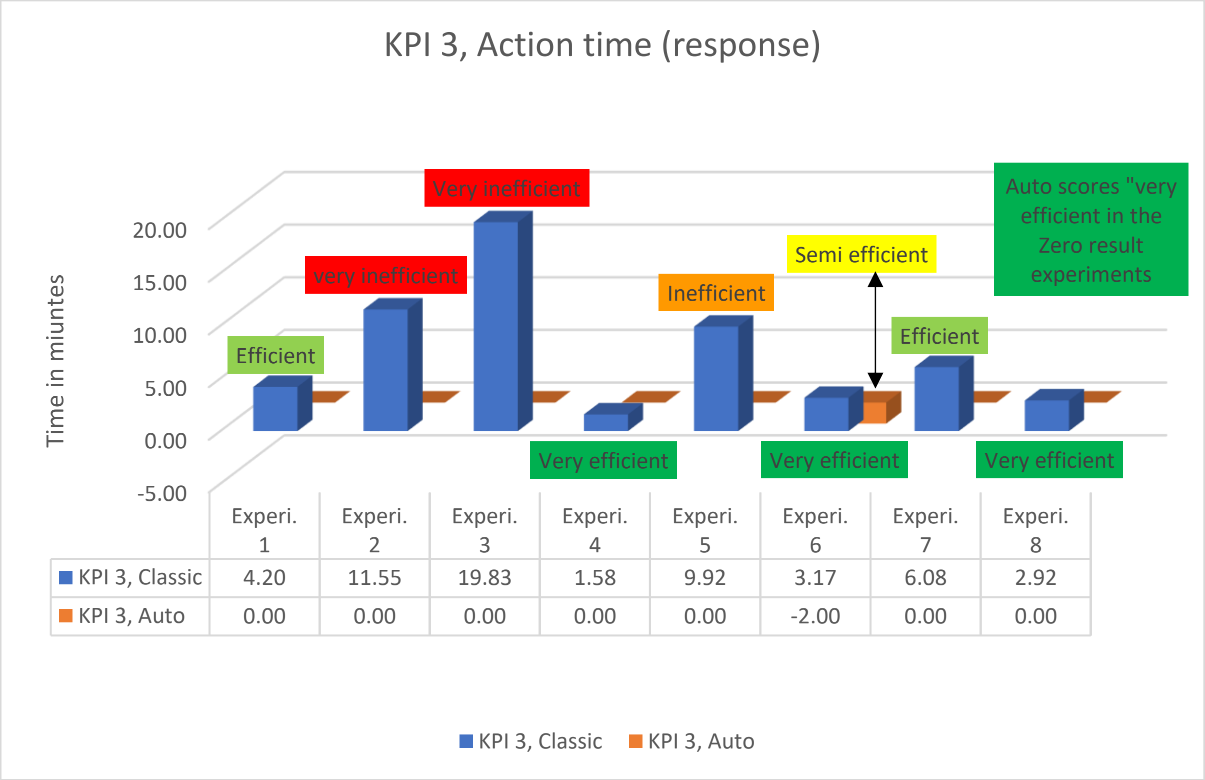


Figure 161 KPI 3 results, Action time (response)

KPI 4: Accuracy of action

The accuracy of action KPI is an indicator of the successful decision and action that has been taken to avoid the collision. This is a safety and efficiency factor in measuring the outcome of the actions taken to avoid the collision. For this KPI, the CPA distance is used to evaluate the performance of the action. In the classical navigational procedure, this is decided by the master of the ship, in the captain standing order, it is between 0.5 and 1 NM. This is depending on the navigational area, in narrow channels and in restricted waters it is 0.5 NM, and in open seas, it is usually 1 NM. Moreover, the same technique for measuring the accuracy of the action is implemented in the *Automatic approach* scenario. The required CPA distance is entered in the Automatic Collision Avoidance System as user preference parameters.

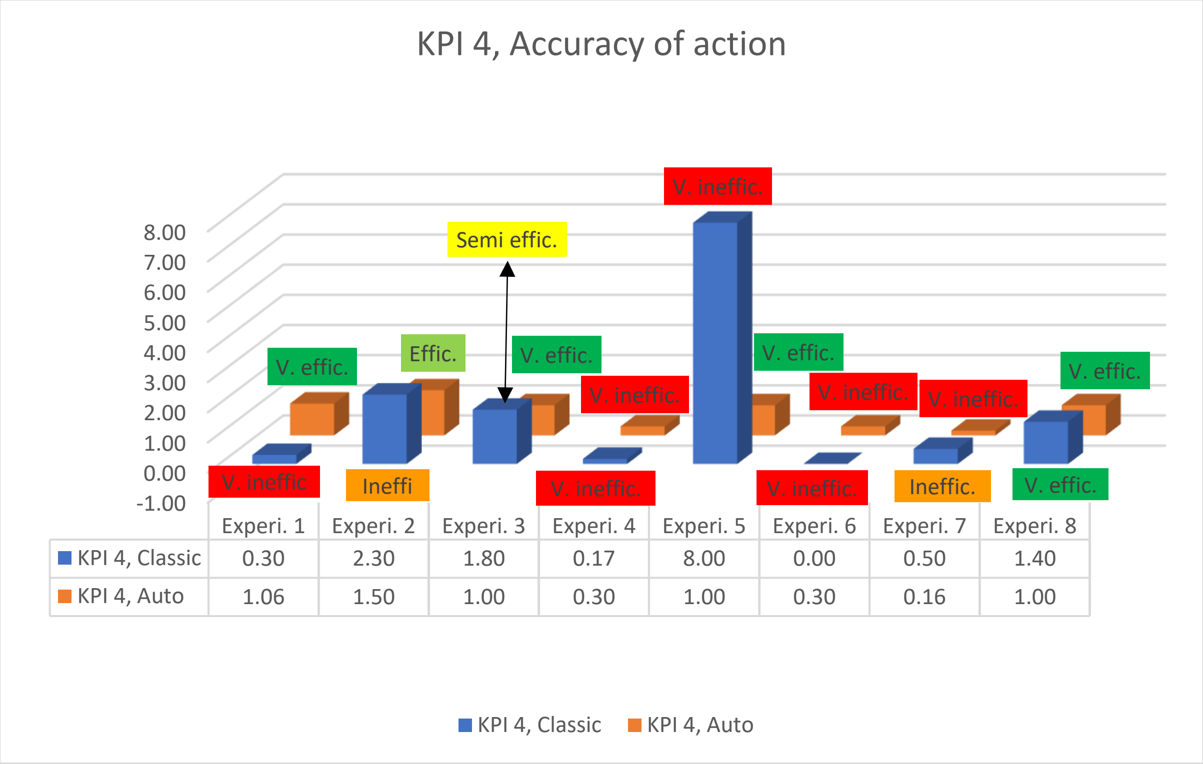
The KPI results have been rated based on:

- Range when passing the target ship. How far or close the distance was when passing the target ship. If it is less than the required CPA it will be a dangerous situation, and more than the CPA it will be inefficient practice.

Figure 162 shows the results for both the *Classical and Automatic approaches*. Figure 162 provides an indication of the rapid changes in the accuracy of the action in the *Classical scenarios*, with a dramatic increase in experiment 5. The reason for this dramatic increase is due to the fact that the OOW has taken a very early action to avoid the target ship, which is the result of the over-cautious action of the OOW. This early action resulted in very large passing distance. The reason for this fluctuation in the *Classical scenarios'* results is due to the uncertainty in the outcome of the avoidance action. However, the OOWs usually either take larger course change or earlier actions or both together, a larger and earlier action to avoid the uncertainty of the avoidance situation.

In the *Automatic scenarios*, there are three experiments where the accuracy of action has scored below the required results. From these scenarios; we have learned valuable lessons about the safety precautions when the developed Automatic Collision Avoidance System is utilised. In experiment 4, the autopilot has been used to perform the avoidance action. This had resulted in a low rate of turn when the action was performed, which led to slow execution of the action. Thus, the learned lesson here is to execute the avoidance action in the fastest way (hard turn) to quickly reach the required course change. In experiment 6, the fact that the navigational area was a narrow channel, which resulted in a delay of the avoidance action has reduced the passing distance. However, in restricted waters and narrow channels, the speed change is more effective than course change, due to the availability of the manoeuvring area. In experiment 7, the collision situation was head-on; in this case, the approaching rate (speed) was very high. These factors must be considered to enhance the performance of the developed system.

In this KPI results, it shows the importance of integrating the developed Automatic system with the other navigational bridge equipment to get the best possible results. This would prevent the slow execution of the avoidance manoeuvre in scenario three by prompt turn to avoid the collision. The fully automated system would have suggested speed change (stopping the ship) in scenario six, which could have prevented the delay of the action. Finally, in scenario seven, if the Automatic system was operating fully automatically, that would provide the decision faster to avoid the small CPA.



	Experi. 1	Experi. 2	Experi. 3	Experi. 4	Experi. 5	Experi. 6	Experi. 7	Experi. 8
■ KPI 4, Classic	0.30	2.30	1.80	0.17	8.00	0.00	0.50	1.40
■ KPI 4, Auto	1.06	1.50	1.00	0.30	1.00	0.30	0.16	1.00

Figure 162 KPI 4 results, Accuracy of action

KPI 5: Track Deviation

This KPI is important to measure the efficiency of the actions taken to avoid collisions. This shows the distance that the ship has travelled from the original planned track to avoid the collision. The minimum distance the ship has to travel will be better when she later needs to move back to the planned track. For this KPI a distance of 0.5 to 1 NM, port and starboard sides, is the tolerance distance, which does not affect the ships passage plan. Furthermore, the ship needs to adjust its course to get back on track. This is an efficiency factor, which does not affect the safety of the ship and has no consequences if the ship travelled for long-distance.

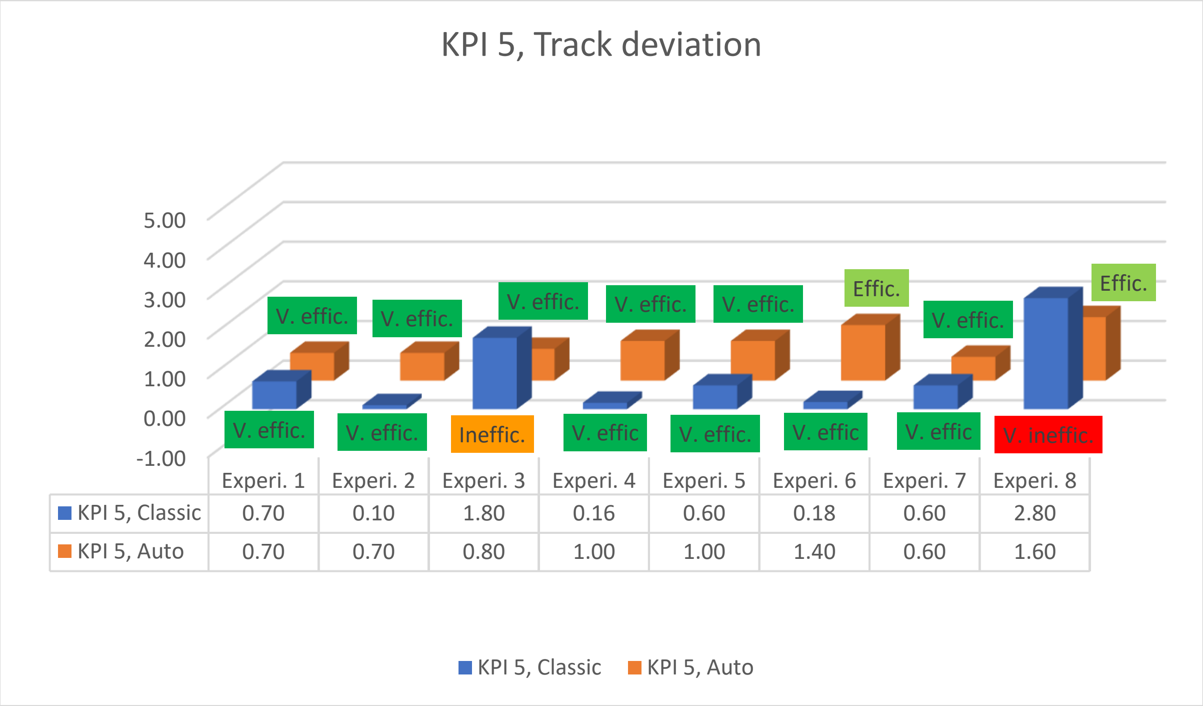
The only effect is the longer distance the ship will need to travel to complete the passage. Moreover, as the extra miles the ship needs to travel, this will cause extra fuel consumptions and more CO2 emission release into the air.

These KPI results have been rated based on:

- The distance that the ship has moved away from the original planned track.

In the *Classical scenarios*, the changes in the results are dramatic as it is presented in Figure 163. This is due to the OOW decision for collision avoidance. In experiment 2, the result was good due to the fact that the ship was already out of track to avoid other targets. Then the OOW decided to take the avoidance action to bring him back to the planned track. In experiment 3, the OOW took an early action that takes him far away from the planned track. Where, in experiment 8, the OOW took a large course alteration to ensure a safe avoidance action.

In the *Automatic scenarios*. Almost all the results show a deviation distance in the tolerance limit. However, in experiments 6 and 8, the ships have crossed that limit for a small distance. In scenario six, the large track deviation was because of the use of the autopilot, which took a long time to complete the required course alteration and then to bring the ship back on track.



	Experi. 1	Experi. 2	Experi. 3	Experi. 4	Experi. 5	Experi. 6	Experi. 7	Experi. 8
■ KPI 5, Classic	0.70	0.10	1.80	0.16	0.60	0.18	0.60	2.80
■ KPI 5, Auto	0.70	0.70	0.80	1.00	1.00	1.40	0.60	1.60

Figure 163 KPI 5 results, Track deviation

Table 52 contains all the KPI results that have been calculated and used to create these graphs. The results in the table are labelled based on the rating scale that was used earlier for the KPIs' results in Figure 164.

Figure 164 The KPIs results' rating scale

Table 52 the results of all the KPIs

List of KPIs	Experi. 1	Experi. 2	Experi. 3	Experi. 4	Experi. 5	Experi. 6	Experi. 7	Experi. 8
KPI 1, Classic	-1.33	-1.73	-0.83	-21.33	0.00	-3.67	-0.33	-10.67
KPI 1, Auto	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
KPI 2, Classic	5.23	5.72	28.83	-3.38	7.08	-0.50	3.67	0.25
KPI 2, Auto	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
KPI 3, Classic	4.20	11.55	19.83	1.58	9.92	3.17	6.08	2.92
KPI 3, Auto	0.00	0.00	0.00	0.00	0.00	-2.00	0.00	0.00
KPI 4, Classic	0.30	2.30	1.80	0.17	8.00	0.00	0.50	1.40
KPI 4, Auto	1.06	1.50	1.00	0.30	1.00	0.30	0.16	1.00
KPI 5, Classic	0.70	0.10	1.80	0.16	0.60	0.18	0.60	2.80
KPI 5, Auto	0.70	0.70	0.80	1.00	1.00	1.40	0.60	1.60

8.7 The Observed Limitation of the Automatic Collision Avoidance System

After the completion of the validation experiments of the Automatic Collision Avoidance System, some limitations in the operation and procedures of the system have been observed. In this section, it worth highlighting these limitations with the potential solutions to overcome them in the future. Also, justifications will be provided why these limitations have existed in the first place.

- The number of targets that the Automatic system can provide an avoidance manoeuvre against to avoid the collision with them. In this research, the number of targets that the Automatic system can avoid is set to two targets at the same time. This is due to the fact of the mathematical complications, which are associated with more than two targets avoidance calculations. In this case, the avoidance manoeuvre should be calculated to avoid the targets without involving in further conflicting situations with other targets. Thus, computer programming codes are required to run the calculation in the loop that checks the results against all other targets involved in the collision situation.

- A firm selection of the operational parameters should be done to ensure a maximum safety level is achieved by utilising the Automatic system for collision avoidance. These parameters are;

  - The time when the system should alert the OOW of the threatening targets that has a potential of risk of collision. At this stage, no avoidance manoeuvre is required yet, but the alert is to prepare the OOW for the collision avoidance manoeuvre.

  - The time, when the system should provide the OOW with the avoidance manoeuvre to avoid the collision situation.

  - The maximum time that the OOW should take to perform the avoidance manoeuvre.

  In order to decide these parameters, further experiments are required to find the optimum operational capabilities. In this experiment, these parameters were selected to be the latest moments, if no actions were taken at this moment the collision will not be avoidable. It has been decided to test the capabilities of the Automatic system at the most critical collision situations to ensure the safety of the ship in any scenario. However, in the normal operational condition, it would be better if there have been extra tolerances for better safety procedures.

- The interaction with the obstacles on the navigational charts. These obstacles include all the hazards that can disrupt the safe navigation of the ship. this includes;

  - Land and shallow waters

  - Navigational marks and buoys

  - Lighthouses

  - Breakwater

  - Port berths

  - Especial marks and areas

  To achieve this goal, the Automatic Collision Avoidance System should be integrated with the ECDIS system. This will enable the Automatic system to detect all kind of obstacles that on the navigational charts and provide comprehensive avoidance decisions that ensure the safety of the ship at all circumstances.

8.8 The limitation in the simulator experiments

In general, the experiment was performed successfully, according to the plan. The simulator utilisation and availability made it convenient to create the required scenarios ideally. However, a number of issues were observed during the experiment, which was related to human behaviour and performance, as well as some technical issues. Thus, great caution was taken to ensure that the scenarios were as similar as possible to the collision reports from MAIB.

The first group of limitations included technical issues, which are related to the creation of the scenarios. In some scenarios, the same location where the accident has had happened was not available in the simulator database. Nevertheless, an alternative location has been selected to create these scenarios. Yet, the same characteristics and parameters of the scenario have been structured and taken into consideration. In most of the cases, an open sea area has been selected to create the scenarios that are not available in the database. In the scenario explanation section, when an alternative location is used, this will be mentioned. These alternative locations have been used in four scenarios, which are; *CMA CGM Florida, Ileksa, Hyundai Dominion and Lykes Voyager*. Where in the other four scenarios, the same location of the real collision (from MAIB's reports) has been used to reconstruct the scenarios.

The second group of limitations included human behaviour and performance issues, where there are three particular issues that need to be highlighted.

- First, the fact that it is impossible to emulate human behaviour in real operational conditions. This includes the factors that affect human performance in decision making, such as; fatigue, stress, sleepiness, tiredness, health status, etc., which were impossible to be simulated. Even though the scenarios have been constructed with great caution to be similar to the real situation that led to a collision in the investigation reports. However, the OOWs (participants) have not been exposed to the same conditions as in real ship, like the time spent on-board the ship, the frequent watch duties and the workload.

- Second, the pressure of being monitored. The OOWs (participants) were aware that they are constantly monitored by the instructor (the author). This put them under the pressure of performing outstandingly to avoid the embarrassment of taking wrong actions and they were trying to perform perfectly as much as they can.

- Third, the length of the scenarios (average of 50 minutes), that allowed them to perform better, especially when it is compared to the four hours' navigational watches on board ships.

With all these being mentioned, in general, the performances of the OOWs (participants) were excellent, where only one collision has happened among the sixteen scenarios that have been performed. This collision situation will be explained later in the results section.

The third group of limitations is the fact that it was impossible to integrate the developed Automatic Collision Avoidance System into the Simulator software (it is a classed software), this has forced the author to operate the system. The operation of the Automatic Collision Avoidance System was performed by the author. Moreover, the required data was collected from the simulator and fed into the Automatic Collision Avoidance System, manually by the author, to calculate the avoidance action. After this, the system's decision was delivered to the OOW in the simulator navigational bridge through the detected screen, which mirrors the instructor's computer, as it was mentioned above. Also, the VHF was used to orally (phonetically) alert the OOW about the dangerous situation. As a result of this human (the author) intervention, a slight time delay was involved, which was required to collect the data, do the calculation, type the decision to the OOW and then alert him about the situation. This time delay is approximately one minute, this what the author roughly needs to do the process of collision avoidance and provide the decision to the OOW. With this limitation in the performance of the experiment, the results were promising, and no critical situation has developed, except in one scenario. This was an *Automatic approach* scenario, with the utilisation of the Automatic Collision Avoidance System. The approaching rate to the target ship (speed) was very high as it was a head-on situation and the ships were moving toward each other quickly. This resulted in a CPA breach, but the ships passed each other safely.

The limitation that disabled the automatic integration of the developed Automatic Collision Avoidance System within the bridge simulator platform has a little effect on the experimental performance due to the time delay in providing the avoidance decision to the OOW. However, if the whole process of the Automatic Collision Avoidance System is performed automatically. Then, the decision is delivered to the OOW on time (without the time delay), this would improve the overall performance of the *Automatic approach*. Fortunately, the newer version of the bridge simulator software has the feature that allows the automatic interaction with the system. This will enable the automation of the whole process, which will improve the automatic response of the developed Collision Avoidance System. This will be tested in the future, as the future work for this research.

8.9 Chapter Summary

In this chapter, the validation of the newly developed Automatic Collision Avoidance System was carried out. There are two main aims; first, validation of the operational performance of the newly developed system. This was addressed by measuring the system abilities by providing feasible and applicable collision avoidance decisions in every critical situation. Second, validation of the model standard, which was achieved by running 8 different scenarios to see how the intervention of the developed system fits the purpose of collision avoidance, the Man-machine interaction and reliability. At the beginning of this chapter, the following points were explained; the procedure of the experiments, the layout of the ship's bridge simulator, and its essential elements. This section is the road map of the experiments and their basic requirements. Therefore, every step of the validation trip to perform the experiments have been discussed in this section. This includes the simulator familiarisation and operation, the experiment methods, the data collection and data analysis.

In the second section, the data analysis method and their required parameters to run the analysis were explained including highlighting the importance of every element and the relation between them. After that the demonstration of the key factors, which were used to assess the outcome of this experiment took place. Finally, the illustration of the measurement factors, which are the Key Performance Indicators (KPIs), were discussed. This KPIs allowed a formulation of standardisation in the results to enable the reader to recognise the difference in the navigational performance when the developed system or the *Classical Approach* is utilised. The mathematical formulas that have been used to measure these KPIs were discussed as well.

In the final section, the experimental approaches; first, the traditional navigational procedure, which is the *classical approach*, second, the developed navigational procedure, which is the *Automatic approach*, were illustrated. Also, the results were explained, taking into account the KPI measurement of each scenario, compared against the selected benchmarks. After applying the two different experimental methods, which are the same OOW performed both approaches and different OOW performed each of the approaches. There were no significant differences observed.

To conclude this chapter, it is worth mentioning the important outcomes that have been achieved from these validation experiments. This can be summed up under two themes.

The first theme is the benefits that might be achieved by implementing the developed Automatic Collision Avoidance System in the navigational procedures. In the results section, the proposed system showed excellent potential to enhance navigational safety at sea. Additionally, the validation of the experiment has proven the capabilities of the developed system to operate and provide valuable and reliable decisions for the avoidance of the collision at sea. Also, it can be considered a great assistant for the OOW.

The second theme is the performance standards of the developed system. In this theme, a number of issues have been elevated to the attention of the author. These are technical issues about the best practices of utilising the system to achieve the outstanding results, barriers for collision prevention. For example, the risk of collision assessment logic, the alerting levels and best time to provide the avoidance decision. These two themes will be discussed further in the following chapter with all the details and evidence behind it.

9 Discussion and recommendation

9.1 Achievement of research aim and objectives

The main aim of this research was to develop an automatic collision avoidance system to support the OOW in taking the most appropriate avoiding actions, objectively. These actions should be taken based on the real surrounding environment and targets. In addition, any subjectivity in the OWW's actions need to be avoided. These subjective decisions are made based on the wrong interpretation of the entire situation around the ship. The intelligent E-navigation framework, aviation technologies and more enhanced procedures were used to conduct this research. This has been achieved by the integration between all navigational aids on-board ship be utilised and displayed in the new system, with a user-friendly display unit. The new system has considered the concept of the human-centred design in the layout, displaying information to provide the OOW with warnings and optimum avoiding actions. Moreover, the results of the experiments in the bridge simulator were promising, which should enhance the overall situational awareness on the bridge, and the maritime safety generally by reducing the number of accidents at sea.

With absolute attention to the main aim of this research, the development of a comprehensive solution that could prevent collisions at sea has been achieved successfully. This solution has been directed through the requirements of completing this research. Moreover, by conducting the research activities, the objectives of the research have been achieved. Detailed discussions about the outcomes of each chapter of this thesis and the contribution to the research objectives are given below.

- Critically review the available literature on maritime safety and the factors that cause the maritime accidents. Also, the aviation's approach to avoiding the mid-air collision has been intensively reviewed to find a compatible solution for ships.

To find the root causes of maritime accidents, especially collisions, an exhaustive critical review was performed in several topics to identify the underlying reasons behind collisions. The review has revealed that human errors are mostly the prime causes of accidents. Accordingly, with further investigations in the navigational bridge procedures, and its conjunction with the human psychology studies, this has exposed interesting facts. The review has shown that the number of responsibilities that needs to be handled by the OOW is exceeding human mental abilities. Therefore, this contributes to mental fatigue, which deteriorate the OOW's performance and increases the chances of making errors leading to the accidents. Some of the diagnosed symptoms of performance deterioration can be listed as; fatigue, stress, sleepiness, task omission, etc.

In addition, by reviewing the navigational equipment, it has been discovered the fact that these systems are only providing information to the OOW in regard to the navigational situation. However, there is no support from any device that helps the OOW in decision making. Accordingly, the OOW needs to collect the required information to process it, and then make the decision based on his own perception of the situation. Hence, educational psychology studies proved that human cannot hold more than five pieces of information at the same time. Then it is an arduous task for the OOW to efficiently respond to multiple missions at ones without missing a piece of important information related to tasks in hand.

In the interest of attaining the best possible solution that helps the OOW to optimally conduct a safe navigational duty, a search in other industries was performed. This has resulted in a detailed study of TCAS system in the aviation industry. The TCAS system is the collision prevention system that is available in aeroplanes to stop the mid-air collision from happening. The system has proven its efficiency to prevent the mid-air collision. The system is capable of detecting the collision situation and provide the best action to avoid the collision. This placed the pilot in the situation of only following the system's decision to get out of the collision situation. However, no need to seek for information, process the situation and find the best decision to avoid collisions, like in ships navigation.

- The development of the framework for the maritime collision avoidance system. This is the system's architecture that illustrates the operational principles, specification and functions of the best utilisation of the system.

After thoroughly completed the critical review, the weaknesses and difficulties in the navigational duty processing were identified. Also, by reviewing the psychology-related topic, this has provided the sole justifications to develop an automatic collision avoidance system which is similar to the TCAS system from the aviation industry. The framework was the backbone of the system that has provided a clear visualisation of the system's concept of operation. To develop a state-of-the-art system's architecture, real maritime collision reports (MAIB accident investigation reports) were exploited to create the system based on real-life events. The utilisation of these reports provided comprehensive information that helped the development stage significantly by revealing insights about collision events. This has assisted in surmounting all the possible conditions that can be encountered in a marine collision situation.

- Developing the collision avoidance model, which is capable of assessing the encounter situation to evaluate the risk of collision, if it exists. When a collision situation is detected, the system provides the best avoidance decision to the OOW to avoid the collision situation.

After the completion of the system's architecture, the development of the mathematical model was performed. This is to create the prototype of the system, which have made it possible to test the operational behaviour of the system. In this stage, the mathematical algebra, the geometry and the trigonometrical calculation were formulated to solve the maritime collision avoidance problems. After developing the prototype, the numerical tests were vital to confirm the correctness of the mathematical model and the worthiness of the model's results. This validation stage was performed on the desk as a computer-based validation stage. In these tests, navigational exercises for the manual radar targets plotting and collision avoidance were utilised, and the result was compared with the prototype's results. Also, real navigational situations were detected from the MarineTraffic website to test the prototype in real cases. The validation results were promising and impressive with high potential for further tests on the prototype to be validated on advance level.

- Experimental validation tests in the full-mission ship's navigational bridge simulator. These experiments were performed in the simulator environment with participants from the nautical college, who were freshly graduated OOWs.

With the automatic collision avoidance system (prototype) developed and tested, it was ready for the validation using the real accident scenarios. For the experiments' scenarios, the same collision investigation reports, from MAIB, that were used to develop the system's framework earlier were utilised to validate the system. These scenarios were created in the simulator and saved in the database to be used for the experimental exercises. In these experiments, the Key Performance Indicators (KPI) were created to capture the performance differences of the OOWs in the classical approach navigational procedures and compare them with the performance of the OOWs in the automatic approach, where the automatic collision system was utilised. These validation experiments were performed in the simulator environment successfully. Moreover, the results have provided a good understanding of the benefits of utilising the automatic collision avoidance system on-board ships. The utilisation of the developed automatic collision avoidance system on the simulator environment was of grand benefits to evaluate the performance of the system itself and discover the best operational practises of the system in real scenarios.

- The development of the Fuzzy TOPSIS model for the selection of the best avoidance decision. Where the Automatic Collision Avoidance System provides a number of avoidance decisions, this model was developed to select the best action for collision avoidance.

After testing the Automatic Collision Avoidance System in the validation experiments, it has been realised that there is a need to select the most appropriate decision for every collision situation. Where the developed system provides many avoidance actions, they are not equally sufficient for every collision situation, depending on the navigational circumstances and the feasibility to perform the actions. However, it was important to develop an automatic approach that is capable of evaluating the available decisions and rank them. For this purpose, the Fuzzy TOPSIS model has been developed to automatically evaluate the avoidance options and rank them based on the selected weighting criteria.

9.2 Novelties and contribution to the field

In this section, the ideas that have helped to attain the novelty of the research to enhance maritime safety will be mentioned and discussed.

Although other scholars addressed the needs for automatic collision avoidance system and suggested frameworks and models for their systems, none of these studies has considered the data-link and decisions sharing techniques with target ships. Thus, the main aim of the proposed Automatic Collision Avoidance System is to enhance navigational safety. This aim has been achieved;

A) By improving the information flow and control in the navigational bridge in human-centred design.

B) The information exchange between ships in the vicinity, including the information of the decision sharing between ships, this research will comprise the data-link and exchange channel techniques as well.

Additionally, the inspiration by other industries to adopt the most successful collision avoidance technique has significantly helped to develop the Automatic Collision Avoidance System in this research. Thereby, the TCAS system in the aviation industry, which is an automatic collision avoidance system for aeroplanes, has been utilised to develop much the same for the maritime industry. These comparable industries have a great match for the operational requirements and the level of safety that need to be achieved. On that account, utilising the already available TCAS system from the aviation industry has greatly contributed in the successful development of the Automatic Collision Avoidance System for the ship, which could be named as the Maritime Collision Avoidance System (MCAS).

- The examination of navigational equipment on the bridge has revealed important facts about the working environment and the collision avoidance process at sea. The first fact is that all the navigational systems are processing systems only, which means they perform calculations and provide parameters to the OOW. Therefore, this information has not got any meaningful sense without further analysis by the OOW to gain valuable meanings. The second one is the decision-making process, which totally depends on the OOW's perception and experience level. However, the OOW is responsible for all the decisions, based on the information he collects from different systems and the knowledge he has, to ensure the safety of the ship. Also, in case of collision avoidance process, the OOW follows the COLREG regulations to avoid the collision without knowing the intention of the target ship.

- With these factors in mind, two novel frameworks have been developed in this research to enhance the navigational process and the safety level on the bridge. The first framework has been developed with a simple modification to the classical procedures of a navigational watch. An automatic function of sharing the avoidance decision with the target ship has been introduced in the classical navigational procedures. When the target ship receives the avoidance decision of the other ship, she must acknowledge her awareness about the situation. This would allow all involved ships to share the same mental model of the situation and the actions. Also, if the target is not responding this will inform the OOW about her situation to take the best action to avoid the collision. Additionally, the sharing of the related navigational information in this model is enhanced for more accurate data in real-time. The second framework has been developed to introduce more intelligence to the system in the navigational bridge. This model is proposing a whole automated process of the navigational duties. This means the new system collects the required data, from all the equipment on the bridge and from the target ship, then do the essential analysis and provide the necessary proposed actions to the OOW. Additionally, the proposed automated framework also has the sharing decision function with target ships. This will enhance the entire navigational process by supporting the OOW in decision making and sharing the same mental model with parties involved in the situation.

- After developing the framework and the system's prototype, the proposed technique has been validated in the full-mission ship's bridge simulator. This validation experiment for such an automatic collision avoidance system is the first of its kind. This simulator environment experiment has allowed the author to examine two interconnected factors that have a substantial influence on navigational safety. First, is testing and confirming the capabilities of the developed model of automatic collision avoidance. This is a justification of the system's abilities to provide a comprehensive avoidance decision, which can prevent a collision at sea. Second, are the opportunities to monitor and measure the OOWs' performance in the navigational duty. This process has allowed the author to compare OOWs' performance in the classical and automatic approaches to collision avoidance procedures. The outcome of the experiment has uncovered the important potential for the new system's influence on navigational safety

- The Key Performance Indicators (KPI) method was deployed for human performance measurement and monitoring in the navigational duty. This technique was successfully utilised in the simulator environment experiment to quantify the performance enhancement of the OOWs when the automatic collision avoidance system was operated.

9.3 Limitations of the developed model

In this section, the obstacles that have been encountered during this research will be discussed;

- The integration of the developed prototype of automatic collision avoidance systems into the simulator platform was an inevitable challenge. However, this issue has been surmounted by utilising a mirroring screen that displays the information from the instructor station. In the instructor station, the author was operating the prototype and insert the decisions in the screen, which was mirroring the information on the bridge. Additionally, the audible alerts were pronounced using the VHF calls to alert the OOW about the detection of the collision situation. The outcome of the followed approach to solving this challenge was satisfyingly acceptable. However, this has introduced a time delay for providing the avoidance decision to the OOW. Yet, the experiment's result was excellent and proved the capability of the developed system.

- The limited availability of the full-mission ship's bridge simulator has made it impossible to carry on further experiments. Accessing to simulator would allow testing more experimental approaches, which would facilitate collecting more data and results with better insights observing the system's benefits and utilisation.

- The advanced level of computer programming skills that required to develop the software of the automatic collision avoidance system. In order to develop a software that automates the process of any task, a scripting language programming experience is required.

9.4 Recommendation for future research

The recommendation for future research and the development of the automatic collision avoidance system can be listed as;

- Develop the current Automatic Collision Avoidance System to detect and avoid more than two targets. This will require advanced computer programming techniques and skills to create software with high computational performance. Additionally, include the Artificial Intelligent tools in the automatic collision avoidance system to improve decision-making abilities. Besides that, utilise electronic learning tools to train the system with the expert opinion approach for the best decision-making techniques.

- As future work, validating the developed automatic collision avoidance system through two bridge simulators, where both own and target ships are equipped with the automatic system to test the efficiency when both ships are utilising the system. This is to see how the target ship communicates and implements the input from the decision support system, if conflict is created.

  - Extend the research scope to develop the automatic navigational system. The outcome of this research is to achieve a fully autonomous vessel. Therefore, the research of autonomous vessels is a hot topic in the IMO, with rapid progress to develop the regulatory framework for the autonomous vessels.

  - The utilisation of other MCDM tools to assess and rank the calculated avoidance decisions by the automatic collision avoidance system. This include Mamdani fuzzy rules to rank the calculated decisions based on expert human operator to select the best avoidance action.

- The utilisation of the developed Key Performance Indicator (KPI) on the navigational bridge on-board ships. This will allow constant monitoring for the OOWs' performance in the navigational duty. Moreover, the continuous monitoring of OOWs' will indicate any deterioration in the performance, which will help in detecting the symptoms of fatigue and tiredness of the OOWs. Additionally, the availability of the performance monitoring data will provide valuable and interesting understandings about the influencing factors on the performance level. Therefore, this will help in finding the best solution for maritime safety enhancement techniques. This approach needs additional research to cover all the related factors, then validate the method through the experimental approach.

9.5 Research outputs

During this research, one conference paper has been presented in the 3rd International Symposium on Naval Architecture and Maritime (INT-NAM 2018) and published in the conference proceedings. Also, this paper has been published in the GMO Journal of Ship and Marine Technology.

ABDUSHKOUR, H., TURAN, O., BOULOUGOURIS, E. & KURT, R. E. 2018. Comparative review of collision avoidance systems in maritime and aviation. GMO Journal of Ship and Marine Technology, 24, 20-32.

10 Concluding Remarks

During the path of this research, intense investigation and studies were performed in multi-subjects that all flow in the direction of a broad theme, the enhancement of maritime safety. Under the theme of maritime safety, there are three branches that cover the entire maritime industry in relation to safety concerns. The safety of lives at sea and the protection of properties and environment. Therefore, the IMO has realised the importance to intensify the global efforts to continually revise and develop the best maritime practises to have excellent safety records. To achieve this, the IMO has developed three international conventions, where each one of them focuses on one of the maritime safety branches, as follows;

- The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). This convention focuses on the qualification of the seafarers and the requirement of the educational level. Also, the requirement of the working hours and environment.

- The International Convention for the Safety of Life at Sea (SOLAS). This convention focuses on developing minimum standards for the construction, equipment and operation of ships to ensure safe operational standards are implemented.

- The International Convention for the Prevention of Pollution from Ships (MARPOL). This convention focuses on the stoppage of ships' pollution, which are happening from maritime operations and accidents.

In correspondence for the thorough research in the maritime accident reports, statistics and studies, it was apparent that the human factors are dominating the direct or indirect reasons for the accidents. In order to solve this problem, the vast majority of the studies were focusing on improving the performance of human by training and education or imposing new regulations to prevent accidents. However, the main concentration of the research of the thesis was given to the development of a supporting system to help the OOW in conquering the difficulties of the navigational watch. Understanding the human role in the navigational watch, in addition to the OOW behaviour and nature in problem-solving for a critical situation, It was essential to accept the limitation of the OOW's abilities, then finding a solution that can provide aids in a critical navigational situation to prevent the collision between ships.

By referring to the psychological studies, it has shown that the human is incapable of dealing with a massive amount of information (numbers, targets, names, parameters and etc.). Thus, in critical encounter situation, the OOW has to be aware of the tremendous amount of data, such as; own ship's parameters, target ship's parameters, other targets in the vicinity, weather condition, avoidance decision, target behaviour monitoring and so on.

Collison accident analyses clearly demonstrate that lack of situational awareness on the bridge is one of the key reasons of such collisions despite the advanced technologies, information flow, procedures and training. Accordingly, the concept behind this research was to get the most of the technological advancement to develop a system that helps the OOW by performing the essential processes to enhance the situational awareness. This is a decision support system that collects the required data from the navigational equipment then process it and provide the best action to the OOW.

The developed automatic collision avoidance system is a decision support system for collision avoidance. This system monitors the area around the ship; when a target is detected, the system makes the necessary processes and provide the avoidance decisions to the OOW. The automatic collision avoidance system is able to enhance navigational safety by providing the following benefits;

- Lookout supportive function by detecting targets around the ship.
- Data collection function by providing the required information to the OOW.
- Collision risk assessment, by evaluating the situation with the target ship and alert the OOW in case of collision.
- Collision avoidance decision, by conducting the mathematical calculation and provide the avoidance decision to the OOW

In the validation experiment, the results showed a promising potential of the automatic collision avoidance system to enhance the situational awareness in the navigational watch. It is a difficult challenge to mimic a collision situation in the simulator environment, where OOWs are trained to perform good seamanship practises, and usually accidents happen in a chain of events. However, the experimental result in the simulator had shown excellent improvement in the performance of the OOW when the automatic collision avoidance system was operated. The final outcomes of the experiment have given an immense motivation to carry on further examination and experiments on the developed automatic collision system to achieve an outstanding and exceptional product.

In conclusion, to achieve a satisfying safety level in the maritime safety, it is essential to start switching the focus from changing the nature of how humans behave to finding the essential technologies and level of automation to support human in the loop. This will dramatically change the operational standards in the maritime industry towards better safety records. However, nowadays, technological advancement is unstoppable and capable of performing or reaching the required level of automation, still, a human who decides the necessity of these technologies and its contribution to their life. At the end of this thesis, the author would like to conclude with the famous proverb "*Necessity is the mother of invention*".

10.1 Key conclusion

This research demonstrated that the automatic collision avoidance system will enhance the OOW's performance significantly and reduce the risk of collision at sea.

- The developed automatic collision avoidance system allowed more time for the OOW to assess the navigational and collision situations rather than collecting and analysing the information for decision making.

- The utilisation of the automatic collision avoidance system enhanced the OOW's situational awareness by better target detection and collision risk assessment.

- The validation experiments have shown that the automatic collision avoidance system was capable of avoiding all the collision situations in all the scenarios.

- The OOW's performance has improved substantially during the availability of the automatic collision avoidance system for better support in the decision-making process.

- After the performance of the Automatic Approach Scenarios of the validation experiments, all the participants have agreed about the benefits of the system to enhance the situational awareness and support the OOWs in decision making in collision situations.

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Appendices

Appendix A – The briefing documents for the experiments' participants

Briefing paper

Validation experiment for performance monitoring when utilising the newly developed automatic collision avoidance system for ships

First, **I would like to thank all of you** for participating in this experiment, which would be impossible to be completed without your efforts and help.

This experiment is part of the PhD research of the "**Human Oriented Design: Automatic Collision Avoidance by Better Man-Machine Interaction and Information Flow"**, which takes place in the University of Strathclyde, Glasgow, the United Kingdom. Where the successful accomplishment of this research is highly dependent on the outcome of this validation experiment results. Accordingly, it is greatly appreciated if you take this experiment seriously and follow the provided instruction. This will ensure the best results and outcome of the experiment. Once again thank you for your participation in this experiment.

The **duration of each exercise is approximately two to three hours,** depending on the scenario and exercise provided.

This experiment will take place in the ship bridge simulator environment. Basically, a number of different scenarios and strategies will be performed to measure the performance of the OOW in each case. The participants will be given the required instruction before they start their assigned exercises. Every participant will have a different scenario and exercise. **However, I would like to kindly ask all participants to please not discuss their scenario and exercise with any other participants.** This is to avoid any bias performance and results.

Best wishes.

Hesham Abdushkour

The exercise sheet

The newly developed automatic collision avoidance approach

In this exercise, the newly developed approach for collision avoidance will be utilised in case of collision situation. Accordingly, you will be performing a normal navigational duty. However, do not react to any collision situation unless you have been instructed to do so by the automatic collision avoidance system. You will receive the instruction verbally from the provided walkie-talkie unit. The instruction will be announced in the following technique;

- The system will alert you about any collision situation.
- The system will provide the lactation of the target ship.
- The system will inform if you are the give-way or stand-on vessel.
- The system will suggest the best action to avoid the collision.
- You should follow the suggested decision immediately.
- After you pass the target ship safely, return to the original planned track.

Have a safe voyage and best wishes.

The exercise sheet

The ***classical approach*** for collision avoidance at sea

In this exercise, please perform a normal navigational duty. Perform the best sea-keeping practices to navigate the ship on the provided passage plan safely. Take extra cautions for traffic in the vicinity. In case of collision, take the best action to avoid it. Consider COLRED for collision avoidance decisions.

Have a safe voyage and best wishes.

Appendix B – the fuzzy TOPSIS collision avoidance decisions rank for all the scenarios of the validation experiments

In this section the results of the fuzzy TOPSIS model for the decision of the Automatic Collision Avoidance System will be elaborated. There are two tables for every scenario, the first table for the own and target ships parameters, which have been collected for the bridge simulator. The second table contents collision avoidance decisions, which were calculated by the Automatic Collision Avoidance System, and the fuzzy TOPSIS results to rank these decisions and highlight the best action to be taken to prevent the collision. This will provide the results for all the scenarios of the validation experiments with a brief explanation;

- Scenario 1: *ACX Hibiscus*
- Scenario 2: *CMA CGM Florida*
- Scenario 3: *Dutch Aquamarine*
- Scenario 4: *Ileksa*
- Scenario 5: *Hyundai Dominion*
- Scenario 6: *Ever Smart* (this scenario has been discussed in Chapter 8, the validation experiments)
- Scenario 7: *Lykes Voyager*
- Scenario 8: *Scot Isles*

Scenario 1: ACX Hibiscus

In this scenario, it was a head-on collision situation in open water with enough space to manoeuvre, where the COLREG states that every vessel should alter course to the starboard side to prevent the collision situation. Thus, the OOW in the own ship, ACX Hibiscus has altered his course to the port side without seeing the target ship. Table 53 shows the ships parameters. The Automatic Collision Avoidance System has calculated the avoidance decisions shown in table 54, and the fuzzy TOPSIS model has ranked these decisions. The first decision was to alter course to the starboard side to 035°, which is the smallest course alteration, and this is the recommended manoeuvre by the COLREG regulation. The second option was to alter course to the port side, which is against the COLREG regulation, but it features a small change in the ship's course. The third option was to stop the ship a move astern. This option can be applied in critical emergency situation as the last option to avoid the collision.

Table 53 Ships parameters

Parameters	Own ship parameters	Target ship parameters	The avoidance decision taken in the experiment
Course	10	211.9	035°
Speed	14.9	16.7	
Bearing	15.5		
Range	3.1		

Table 54 Fuzzy TOPSIS ranking results

Alternatives	Avoidance decisions		CCi	Ranks
Co1	210°		0.41	
Co2	35°		0.55	**1** This was taken in the experiment
Co3	212°		0.41	
Co4	355°		0.48	2 Against COLREG
Sp1	81 knots		0.35	
Sp2	-2 knots (astern)		0.47	3
Sp/Co1	11 knots	28°	0.44	4
Sp/Co2	11 knots	19 °	0.44	4

Scenario 2: CMA CGM Florida

This collision situation was a crossing situation and the own ship (CMA CGM Florida) is the stand-on vessel, which should maintain her course and speed and the give-way vessel is responsible to perform the avoidance manoeuvre. Due to miscommunication between the ships via the VHF calls, both vessels were assuming the other will take action to avoid the collision, but no one took an action and they collided. Table 55 provides the ships parameters. Although, own ship was the stand-on vessel, but the Automatic Collision Avoidance System has calculated the avoidance manoeuvres as in table 56. The fuzzy TOPSIS has ranked these decisions and selected the course alteration to the starboard side to be the best action to prevent the collision according to the COLREG regulations.

Table 55 Ships parameters

Parameters	Own ship parameters	Target ship parameters	The avoidance decision taken in the experiment
Course	57.6	155	101°
Speed	22.9	11.5	
Bearing	23.3		
Range	2.869		

Table 56 Fuzzy TOPSIS ranking results

<table>
<tr><th>Alternatives</th><th colspan="2">Avoidance decisions</th><th>CCi</th><th>Ranks</th></tr>
<tr><td>Co1</td><td colspan="2">169°</td><td>0.41</td><td></td></tr>
<tr><td>Co2</td><td colspan="2">101°</td><td>0.55</td><td>1
This was taken in the experiment</td></tr>
<tr><td>Co3</td><td colspan="2">151°</td><td>0.41</td><td></td></tr>
<tr><td>Co4</td><td colspan="2">54°</td><td>0.48</td><td>2</td></tr>
<tr><td>Sp1</td><td colspan="2">17 knots</td><td>0.47</td><td>3</td></tr>
<tr><td>Sp2</td><td colspan="2">72 knots</td><td>0.47</td><td></td></tr>
<tr><td>Sp/Co1</td><td>13knots</td><td>109°</td><td>0.42</td><td></td></tr>
<tr><td>Sp/Co2</td><td>15knots</td><td>110°</td><td>0.42</td><td></td></tr>
</table>

Scenario 3: Dutch Aquamarine

This was an overtaking collision scenario and the own vessel (Dutch Aquamarine) was approaching from behind and she was the give-was vessel. Both vessels did not detect each other until they collided, Table 57 has the ships parameters. The Automatic Collision Avoidance System has calculated the avoidance manoeuvre, which has been ranked by the fuzzy TOPSIS model, the decisions and its rank are available in Table 58. The course alteration to the starboard side has been selected as the best action to avoid the collision, which matches with the COLREG regulation and the best action to prevent further conflict with other ships. This action will take the ship to the outer lane of the TTS and clear of all other targets. The second option is to the port side, this is a correct action based on the regulations but is less favourable as it will take the ship to the inner side of the TTS, still this will keep the ship inside the TTS. The third option is to reduce the ship's speed to avoid the collision.

Table 57 Ships parameters

Parameters	Own ship parameters	Target ship parameters	The avoidance decision taken in the experiment
Course	229.8	6.2	244°
Speed	14.7	230	
Bearing	230.3		
Range	1.4		

Table 58 Fuzzy TOPSIS ranking results

Alternatives	Avoidance decisions		CCi	Ranks
Co1	244°		0.63	**1** **This was taken in the experiment**
Co2	080°		0.23	
Co3	218°		0.51	2
Co4	021°		0.23	
Sp1	6 knots		0.37	3
Sp2	6 knots		0.37	
Sp/Co1	8 knots	044°	0.22	
Sp/Co2	8 knots	056°	0.22	

Scenario 4: Ileksa

This was an overtaking situation, where the own vessel (Ileksa) was on the front and was the stand-on vessel. The Cepheus J was the give-way vessel, but the OOW did not detect the collision risk until it was too late to avoid the collision, Table 59 provides the ships parameters. The Automatic Collision Avoidance System has calculated the avoidance decisions, and the fuzzy TPOSIS has ranked the decisions and selected the best avoidance action as in Table 60. Still, the own ship is the stand-on vessel bet as the give-way vessel was not taking any avoidance action. Thus, the best action by own vessels was to alter course to the port side, which is the easiest action as the ship was approaching to a waypoint of course alteration. The second option to change course to the starboard side, which will take a longer time to reach. The third action was to increase the speed to avoid the collision.

Table 59 Ships parameters

Parameters	Own ship parameters	Target ship parameters	The avoidance decision taken in the experiment
Course	138.9	130	091°
Speed	9.2	18.8	
Bearing	312.9		
Range	.99		

Table 60 Fuzzy TOPSIS ranking results

Alternatives	Avoidance decisions		CCi	Ranks
Co1	042°		0.41	
Co2	091		0.52	2
Co3	243°		0.41	
Co4	155°		0.55	1 **This was taken in the experiment**
Sp1	13 knots		0.49	3
Sp2	27 knots		0.40	
Sp/Co1	16knots	313°	0.42	
Sp/Co2	16knots	306°	0.42	

Scenario 5: Hyundai Dominion

This is crossing collision situation and the own ship is the stand-on vessel (Hyundai Dominion). The give-way vessel has assumed the situation as an overtaking situation, and she has the right to cross the bow of Hyundai Dominion. This was a wrong assessment of the collision situation made by the give-way vessel; accordingly, she was waiting for Hyundai Dominion to keep clear of her way. Table 61 shows the ships parameters. The Automatic Collision Avoidance System has calculated the avoidance actions and the fuzzy TOPSIS has ranked it, Table 62 provides the avoidance actions and the ranks.

Table 61 Ships parameters

Parameters	Own ship parameters	Target ship parameters	The avoidance decision taken in the experiment
Course	29.8	91	090°
Speed	21.9	16.3	
Bearing	352.5		
Range	1.6		

Table 62 Fuzzy TOPSIS ranking results

Alternatives	Avoidance decisions		CCi	Ranks
Co1	170°		0.30	
Co2	090°		0.54	1 **This was taken in the experiment**
Co3	001°		0.34	
Co4	103°		0.45	2
Sp1	13 knots		0.38	3
Sp2	-89 knots		0.28	
Sp/Co1	16 knots	272°	0.29	
Sp/Co2	19 knots	242°	0.29	

Scenario 7: Lykes Voyager

This was a head-on situation in restricted visibility, the Lykes Voyager is the own ship. The target ship has initiated a VHF call to agree on the avoidance manoeuvre, however, Lykes Voyager did not answer on that call and another ship has replied and they agreed to pass form the starboard side, which is against COLREG regulation. Based on this agreement the target ship started to turn to the port side and this put him in a collision course with the Lykes Voyager, and they collided. Table 63 shows the ships parameters. The Automatic Collision Avoidance System has calculated the avoidance actions and the fuzzy TOPSIS has ranked the decisions, Table 64 shows the results. The best action was to alert course to the starboard side to avoid the collision. The second and third options were to reduce the speed and alter the course to the starboard side, each option with different magnitude of changing the course and speed.

Table 63 Ships parameters

Parameters	Own ship parameters	Target ship parameters	The avoidance decision taken in the experiment
Course	39.1	243	096°
Speed	19	17	
Bearing	30.7		
Range	1		

Table 64 Fuzzy TOPSIS ranking results

Alternatives	Avoidance decisions		CCi	Ranks
Co1	230°		0.41	
Co2	096°		0.54	1 **This was taken in the experiment**
Co3	306°		0.41	
Co4	224°		0.41	
Sp1	-19 knots (astern)		0.34	
Sp2	-12 knots (astern)		0.34	
Sp/Co1	16 knots	51°	0.44	2
Sp/Co2	15 knots	46°	0.41	3

Scenario 8: Scot Isles

This was a crossing situation in Dover TTS, the own ship (Scot Isles) was give-way and crossing the TTS and collided with the target ship. Both ships did not see each other until the moment before the collision. Table 65 shows the ships parameters. The Automatic Collision Avoidance has calculated the avoidance actions and the fuzzy TOPSIS has ranked them as in Table 66. The best action was to change the ship's course to the starboard side to avoid the collision. The second and third option were to reduce the speed change course with different magnitudes of changing.

Table 65 Ships parameters

Parameters	Own ship parameters	Target ship parameters	The avoidance decision taken in the experiment
Course	109.4	42	186°
Speed	11.4	14.3	
Bearing	176.1		
Range	1.5		

Table 66 Fuzzy TOPSIS ranking results

Alternatives	Avoidance decisions		CCi	Ranks
Co1	186°		0.54	1 **This was taken in the experiment**
Co2	040°		0.34	
Co3	045°		0.34	
Co4	092°		0.34	
Sp1	14 knots		0.38	4
Sp2	3knots		0.28	
Sp/Co1	11 knots	050°	0.43	2
Sp/Co2	10 knots	43°	0.43	3