Western Norway University of Applied Sciences
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Safety of Autonomous Navigation

A Study on Safety Challenges for Maritime Autonomous Surface Ships, Safe Speed, and Work as Done by Navigators

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A dissertation for the degree of *Philosophiae Doctor* (PhD)

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As the author of this thesis, I also possess a master's unlimited ocean licence and have worked as a deck officer on board internationally trading liquefied gas tankers for several years. I was based at the Department of Maritime Studies in the Faculty of Business Administration and Social Sciences at HVL for the duration of this doctoral study.

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Feeling gratitude and not
expressing it is like wrapping
a present and not giving it.

William Arthur Ward

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Summary

Throughout human history, technological innovation has been an important driver for enhancing human living standards. In the maritime industry, one such technological innovation is the maritime autonomous surface ship (MASS). Its development is seen as an opportunity to increase safety while simultaneously improving environmental performance and enabling more cost-effective shipping.

Research into making MASSs has been happening for some time. Several MASS concepts are being tested around the world. These MASSs must comply with the International Regulations for Preventing Collisions at Sea 1972 (COLREGs), which provide rules that apply to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels.

Fact Box: *COLREGs Rule 6 (Safe Speed)*

Every vessel shall at all times proceed at a safe speed so that she can take proper and effective action to avoid a collision and be stopped within a distance appropriate to the prevailing circumstances and conditions.

In determining a safe speed the following factors shall be among those taken into account:

a) By all vessels:
   i. the state of visibility;
   ii. the traffic density including concentrations of fishing vessels or any other vessels;
   iii. the manoeuvrability of the vessel with special reference to stopping distance and turning ability in the prevailing conditions;
   iv. at night the presence of background light such as from shore lights or from backscatter of her own lights;
   v. the state of wind, sea and current, and the proximity of navigational hazards;
   vi. the draught in relation to the available depth of water.

b) Additionally, by vessels with operational radar:
   i. the characteristics, efficiency and limitations of the radar equipment;
   ii. any constraints imposed by the radar range scale in use;
   iii. the effect on radar detection of the sea state, weather and other sources of interference;
   iv. the possibility that small vessels, ice and other floating objects may not be detected by radar at an adequate range;
   v. the number, location and movements of vessels detected by radar;
   vi. the more exact assessment of the visibility that may be possible when radar is used to determine the range of vessels or other objects in the vicinity.

While it has been proven to be no easy matter to construct an algorithm that ensures MASSs comply with the COLREGs, most of the research related to MASSs has focused on overcoming the technological challenges involved.

Research on COLREGs-compliant MASSs is scarce and has often produced algorithms that either clearly contradict the COLREGs or simply ignore rules crucial to seamanship practice, such as the safe speed rule. To support safe implementation of MASSs in the future, this thesis presents two objectives: first, to list identified safety challenges for MASSs and, second, to focus on the safety challenge of how MASSs can autonomously determine safe speed in any situation in accordance with the COLREGs.

A proposed approach to ensuring MASS compliance with the COLREGs was to use automatic identification system (AIS) data to allow artificial intelligence (AI) to learn the most effective, efficient, and COLREGs-compliant ways of manoeuvring. The research conducted in this thesis has investigated if historic AIS data could be used as a reference for safe vessel behaviours. It was determined that vessel speed data from historic AIS data cannot represent safe vessel speeds as per contemporary safe speed understandings. Feeding AI historic AIS data would therefore not be a suitable solution for teaching MASSs safe vessel speeds in different situations.

Consequently, interviews were conducted with experienced navigators to learn how they determine safe vessel speeds. The interview findings demonstrate that the work as done by navigators differs significantly from work as imagined by researchers and legal scholars. Safe vessel speeds are determined differently at sea from how they are perceived in the literature.

These findings have several implications. Programming MASSs to behave according to the work-as-imagined parameters could provoke problems in coordination and cooperation with conventional vessels, thus posing a risk to safety at sea. To operate safely, MASSs must therefore consider the work done in practice by human navigators. It is thus recommended that MASSs follow a goal-

based approach when attempting to follow the safe speed rule of the COLREGs. The designers of MASSs must resolve their own method of determining the safe speed for these vessels in different situations. The goal should not be limited to compliance with the rules. They must also ensure that the MASS is in control of the situation and that its actions are transparent and understandable to other vessels in the area.

Sammendrag

Gjennom menneskets historie har teknologisk innovasjon vært en viktig driver for å fremme menneskelige levekår. Innen maritim næring er en slik teknologisk innovasjon den maritime autonome overflatebåten (MASS), som anses som en mulighet til å øke sikkerheten samtidig som den forbedrer miljøytelsen og gjør frakt mer kostnadseffektiv.

Forskning på MASS har pågått en stund nå, og det er flere MASS-konsepter som testes rundt om i verden. Disse MASS-er vil måtte overholde de internasjonale reglene til forebygging av sammenstøt på sjøen (Sjøveisreglene / COLREGs), som gir en rekke regler som gjelder for alle fartøyer på åpent hav og i alle farvann navigerbare av sjøgående fartøyer.

Faktaboks: *Sjøveisregel 6 (Sikker fart)*

Ethvert fartøy skal alltid gå med sikker fart slik at det kan manøvrere riktig og effektivt for å unngå sammenstøt og kan stoppes på en distanse som passer til de rådende omstendigheter og forhold.

Ved fastsettelse av sikker fart skal det blant annet tas hensyn til følgende faktorer:

a) Av alle fartøy:
   i. Siktforholdene.
   ii. Trafikktettheten innbefattet konsentrasjoner av fiskefartøy eller hvilke som helst andre fartøy.
   iii. Fartøyets manøvreringsevne spesielt med hensyn til stoppedistanse og svingeevne under de rådende forhold.
   iv. Om natten mulig bakgrunnsbelysning slik som lys på land eller atmosfærisk refleks fra fartøyets egne lanterner.
   v. Vind-, sjø- og strømforhold samt nærliggende farer for seilasen.
   vi. Dypgående i forhold til den tilgjengelige farvannsdybde.

b) Dessuten av fartøy som bruker radar:
   i. Radarutstyrets karakteristikk, effektivitet og begrensning.
   ii. De begrensninger som det benyttede radaravstandsområde medfører.
   iii. Virkning av sjø, værforhold og andre forstyrrelseskilder på radarobservasjoner.
   iv. Muligheten av at små fartøy, is og andre flytende gjenstander ikke kan oppdages ved radar på tilstrekkelig avstand.
   v. Antall, posisjon og bevegelse av fartøy som observeres ved hjelp av radar.
   vi. Den mer nøyaktige bestemmelse av sikten som kan være mulig når radar brukes for å bestemme avstanden til fartøy eller andre gjenstander i nærheten.

Selv om det har vist seg å ikke være en enkel sak å konstruere en algoritme som tillater MASS å overholde COLREGs, har de fleste av MASS-relatert forskning satt søkelys på å overvinne de teknologiske utfordringene som er involvert.

Forskning på COLREGs-kompatible MASS-er er sjelden og har ofte resultert i algoritmer som enten er i klar motstrid med COLREGs, eller rett og slett ignorerer regler som er avgjørende for sjømannskap, som for eksempel sikker-farts-regelen. For å støtte en trygg implementering av MASS-er i fremtiden, presenterer denne avhandlingen to mål: først, å liste opp identifiserte sikkerhetsutfordringer for MASS-er, og andre, å fokusere på sikkerhetsutfordringen med hvordan MASS-er kan autonomt bestemme sikker fart i enhver situasjon i samsvar med COLREGs.

En foreslått tilnærming for å sikre at MASS-er overholder COLREGs, var å bruke automatisk identifikasjonssystem (AIS) data for å tillate kunstig intelligens (AI) å lære de mest effektive og COLREGs-kompatible måtene å manøvrere på. Forskningen utført i denne avhandlingen har undersøkt om historiske AIS-data kunne brukes som referanse for trygge båtadferd. Det ble konkludert med at fartøyhastighetsdata fra historiske AIS-data ikke kan representere sikker fart i henhold til moderne forståelse av sikker fart. Å gi AI historiske AIS-data ville derfor ikke være en egnet løsning for å lære MASS-er sikker fart i ulike situasjoner.

Som et resultat ble det gjennomført intervjuer med erfarne navigatører for å lære hvordan de bestemmer sikker fart. Intervjufunnene viser at arbeidet utført av navigatørene (work as done) skiller seg betydelig fra arbeidet som forestilt (work as imagined) av forskere og juridiske eksperter. Sikker fart bestemmes annerledes til sjøs enn hvordan de oppfattes i litteraturen.

Disse funnene har flere implikasjoner. Å programmere MASS-er til å oppføre seg i samsvar med work-as-imagined parameterne kan føre til problemer med koordinering og samarbeid med konvensjonelle fartøy, og dermed utgjøre en risiko for sikkerheten til sjøs. For at MASS-er skal kunne operere trygt, må de

derfor tar hensyn til det arbeidet som faktisk utføres av menneskelige navigatører. Det anbefales derfor at MASS-er følger en målorientert tilnærming når de prøver å følge sikker-farts-regelen i COLREGs. Designerne av MASS-er må finne sin egen metode for å bestemme sikker fart for disse fartøyene i ulike situasjoner. Målet bør ikke begrenses til overholdelse av reglene. De må også sørge før at MASS-en har kontroll over situasjonen og at dens handlinger er transparente og forståelige for andre fartøy i området.

List of Publications

Paper I: Dreyer, L. O., & Oltedal, H. A. (2019). Safety Challenges for Maritime Autonomous Surface Ships: A Systematic Review. In M. H. Lützhöft (Ed.), *Proceedings of Ergoship 2019*. Western Norway University of Applied Sciences. http://hdl.handle.net/11250/2638416

Paper II: Dreyer, L. O. (2021). Safe Speed for Maritime Autonomous Surface Ships -- The Use of Automatic Identification System Data. In *Proceedings of the 31st European Safety and Reliability Conference (ESREL 2021)*. https://doi.org/10.3850/978-981-18-2016-8_200-cd

Paper III: Dreyer, L. O. (2023). Relation analysis of ship speed & environmental conditions: Can historic AIS data form a baseline for autonomous determination of safe speed? *The Journal of Navigation*, 1-35. https://doi.org/10.1017/S0373463323000127.

Paper IV: Dreyer L. O. (2023). Safe Vessel Operations – The Tacit Knowledge of Navigators. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, 17(3)*, 579-586. http://doi.org/10.12716/1001.17.03.09

These articles are attached to Appendices 1–4 of this thesis.

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List of Abbreviations

AI .... Artificial intelligence
AIS .... Automatic Identification System
COLREGs .... International Regulations for Preventing Collisions at Sea
IACS .... International Association of Classification Societies
IMO .... International Maritime Organization
MASS .... Maritime Autonomous Surface Ship
NMA .... Norwegian Maritime Authority

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Chapter 1.

Introduction

Autonomous shipping can offer better efficiency, reliability, safety and sustainability for shipping.

Päivi Haikkola

Throughout human history, technological innovation has been an important driver for enhancing human living standards. Evidence reveals that technological innovation generally has a positive impact on sustainability and is correlated with raising economic growth and lowering environmental pollution (Ahmad et al., 2023). In the maritime industry, one such technological innovation is the maritime autonomous surface ship (MASS).

Since many in the shipping industry believe that human error is a major contributing factor in 60 to 85% of all shipping accidents (Butt et al., 2013; Felski & Zwolak, 2020; Ziarati & Ziarati, 2007), the development of MASSs is seen as an opportunity to increase safety while simultaneously improving environmental performance and enabling more cost-effective shipping (Vartdal et al., 2018). Scientific research into making autonomous ships a reality has increased since the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project launched in 2012 (Porathe, in press). The focus of this research has been primarily on overcoming the technical issues related to MASS operations (Man et al., 2018a; Porathe, in press; Valdez Banda et al., 2018). Advanced sensor technologies paired with rapidly increasing data processing performance has led to advances in the perception of the surrounding environment, path planning, and vessel control in real time, leading some to believe that full vehicular autonomy is feasible on a technological level (Poikonen et al., 2016).

In reality, the promised value of new technology is rarely delivered, neither immediately nor completely. New, innovative technologies usually follow Gartner's hype cycle, where attitudes about the new technology progress from overenthusiasm through a period of disillusionment towards an eventual understanding of the technology's actual relevance and role in a market. This progress is presented in Figure 1 (Linden & Fenn, 2003).

Figure 1: Gartner's hype cycle. It portrays the common progression of an emerging technology from technology trigger to plateau of productivity (Linden & Fenn, 2003).

The speed at which technological innovations move through the hype cycle is not uniform. While some fast-track innovations may traverse through the phases in two to four years, long-fuse technologies may take one or two decades to pass through the hype cycle (Linden & Fenn, 2003). Indicators of a long-fuse technology include presence of a science-fiction-style fascination, as in Rolls Royce's video on the future shore control centre (Rolls-Royce, 2016); regulation issues, as highlighted by the International Maritime Organization (IMO) MASS regulatory scoping exercise (IMO, 2021); and the creation of new business models, where the advantage of size held by the largest shipping operators is circumvented by gaining logistic manoeuvrability (Mannov et al., 2019). Therefore, it can be argued that MASS will likely take significant time to reach the plateau of productivity of Gartner's hype cycle.

There is, however, no guarantee that new technologies will make it to the last stage of Gartner's hype cycle: the plateau of productivity. It is entirely possible for new technological innovations to become extinct along the way. To help MASS reach the plateau of productivity, several subjects must be addressed. These include technological, legal, economic, and safety issues.

This thesis contributes to addressing some of the safety issues that are connected to MASS. In this regard, the IMO has presented the *principle of equivalence*, where the goal is to ensure that MASSs provide at least the same degree of safety as conventional vessels (IMO, 2019).

1.1. Introduction to Maritime Autonomous Surface Ships

Making MASSs a reality is an endeavour currently being pursued by various actors. These include operators, vessel designers, class societies, and the IMO. The IMO has provisionally defined a MASS as "a ship, which to a varying degree, can operate independently of human interaction" (IMO, 2021). Ships included under this term therefore range from ships with automated processes and decision support for seafarers who are still on board to operate and control the shipboard systems and functions to fully autonomous ships that make decisions and determine actions by themselves (IMO 2021). It is therefore important to note that autonomous does not necessarily mean unmanned.

Interestingly, there is disagreement if the term autonomous should be used at all. For example, SAE International[1] – a globally active professional association and standards developing organisation for various industries – deems the term autonomous to be misleading for being functionally imprecise. Consequently, SAE International has added "autonomous" to its list of deprecated terms and chooses to utilise "driving automation" instead (SAE International 2014). This criticism has been recognised by the IMO, who have identified the matter of refining and agreeing on important terminology as a "high-priority issue" in the outcome of their regulatory scoping exercise for the use of MASS (IMO 2021). In this thesis, the provisional definition of MASS by the IMO is used.

1.2. Objectives and Research Questions

This thesis originated with the aim of studying the topic of safety management and autonomous ships. The topic is, however, so vast that it had to be narrowed down. The objective of this study thus became to identify which safety challenges exist for MASSs, followed by a focus on one of the identified safety challenges: how MASSs can autonomously determine the safe speed in any given situation.

This focus was chosen because – as a certified master mariner with several years of experience as a navigational officer – I had noted that MASS research has largely ignored the issue of how a safe speed in a situation can be autonomously determined. While researchers on automated driving have remarked that rules which are subject to interpretation (such as California's Basic Speed Law, which requires vehicles to not drive faster than what is safe for current conditions) pose a challenge to automated cars (Wood et al., 2019), it seems that MASS researchers have not yet come to the same realisation. Being both a certified car driver and a navigational watch officer, my experience has demonstrated that

[1] SAE International is a global association of more than 128,000 engineers and related technical experts in the aerospace, automotive, and commercial-vehicle industries (SAE International, 2023). *SAE International – Advancing Mobility Knowledge and Solutions*. Retrieved 20/03/2023 from https://www.sae.org/.

determining the safe speed of a vessel in a waterway is a much more complex issue than determining the safe speed of a car on a road. I thus concluded that rules that are subject to interpretation, such as the safe speed rule of the International Regulations for Preventing Collisions at Sea 1972 (COLREGs), also pose a challenge for MASSs. Moreover, this view has recently been recognised by other researchers (Wróbel et al., 2022).

It was noted early on that MASS operation – even just on a trial basis – would be much more difficult to achieve when changes to existing rules are required (Ringbom, 2019). This view was later substantiated by the outcome of the IMO's regulatory scoping exercise, which states that "COLREG in its current form is still the reference point and should retain as much of its current content as possible" (IMO, 2021, p. 86). As a result, a method that allows MASSs to comply with the current wording of the COLREGs must be determined. To achieve this, it has been argued that the starting point must be "to capture the tacit knowledge of human seafarers who currently operate vessels" (Meadow et al., 2019, p. 7). This thesis was therefore designed around the following research questions:

Research Question 1: What safety challenges for MASSs have been identified in previous research? What research gaps still need to be addressed to ensure safe MASS operations in the future?

Research Question 2: Can historic data of conventional vessels be used as a reference for safe vessel behaviour? Could MASSs autonomously determine the safe speed in a given situation by utilising the historic automatic identification system (AIS[2]) speed data of conventional vessels?

Research Question 3: How do factors such as visibility, wind, waves, and location affect the speeds of conventional vessels?

Research Question 4: How do human navigators interpret Rule 6 of the COLREGs covering the requirement to proceed at a safe speed?

1.3. Aims of the Articles

With aim to achieve the objectives and answer the research questions of this thesis, I wrote four separate articles (all of which are appended to this thesis). Each article has its own central aims, which are described in this section.

Article 1 focuses on reviewed literature to list identified safety challenges for MASSs. The aims of the article are as follows:

- ✓ To explore and analyse relevant scientific literature on MASSs,
- ✓ To list the safety challenges for MASSs that have been identified in previous research,
- ✓ To identify research gaps that must be addressed to ensure safe MASS operations in the future, and
- ✓ To determine a direction for further studies.

Article 2 provides AIS and visibility data collected in an offshore location between 2014 and 2020. The data was analysed with the following aims:

- ✓ To assess the relationship between visibility and vessel speeds,

[2] AIS is a communications system that provides automatic reporting between ships and the shore by exchanging information such as identity, position, time, course, and speed (IALA, 2016). This information is saved in online databases for each individual ship, and the data can be accessed to discern historical patterns.

- ✓ To investigate whether the observed speeds would be considered safe, and
- ✓ To determine whether vessel speed data gathered from AIS constitutes a useful reference for safe vessel speeds in different visibility conditions.

Article 3 is a follow-up study to Article 2. It follows a similar structure and utilises the same AIS and visibility data used in Article 2. However, this data is supplemented with wind and wave data for the offshore location and AIS, wind, and visibility data for the inshore location. The data was analysed with the following aims:

- ✓ To assess the relationship between visibility, wind, waves, and location, and vessel speeds;
- ✓ To investigate whether the observed speeds would be considered safe; and
- ✓ To determine whether vessel speed data gathered from AIS constitutes a useful reference for safe vessel speeds in different visibility conditions.

Article 4 is the final article of this thesis. It provides qualitative interview data to gain a better understanding of the results from Articles 2 and 3. The aims of this article are as follows:

- ✓ To explore how human navigators interpret the requirements of Rule 6 of the COLREGS covering the necessity to proceed at a safe speed,
- ✓ To describe how different influential factors affect navigators in their determination of safe speed, and
- ✓ To provide designers of MASSs with relevant information about how human navigators determine safe vessel speeds in practice.

1.4. Thesis Structure

This thesis is organised into seven chapters. **Chapter 2** provides an overview of the state of the art of the MASS. In **Chapter 3**, the philosophical foundation of this thesis is discussed. **Chapter 4** introduces the theoretical frame of reference for this thesis. **Chapter 5** presents the research methodology and discusses issues related to research quality and ethics. **Chapter 6** presents the research results of each of the articles included in this thesis. **Chapter 7** concludes the thesis. It addresses the fulfilment of the objectives, provides answers to the research questions, highlights the contributions of this research, discusses research limitations, and presents recommendations for future research.

Chapter 2.

MASS: The State of the Art

I believe in innovation and
that the way you get innovation
is you fund research and you
learn the basic facts.

Bill Gates

The international maritime industry is a complex and dynamic sector that encompasses a wide range of activities related to the transportation of goods and people by sea. In 2021 the world's merchant shipping fleet was comprised of more than 100,000 vessels and carried nearly 11 billion tonnes of goods (UNCTAD, 2023). This means that the shipping industry is responsible for transporting around 90% of global trade goods (World Economic Forum, 2021) and hence plays a crucial role in supporting economic growth and development.

Competition in the shipping industry has become intense (Lee & Song, 2015). Together with an increased regulatory focus on sustainability and environmental responsibility, this has led to the industry embracing innovation, with companies continually seeking to develop new technologies and processes to improve efficiency and reduce costs. One of these new technologies might be MASSs, which promise – among other factors – improved working conditions, lower damage-related costs, reduced crew costs, slow steaming, lower structural costs, better environmental performance, and new ship designs (Rødseth, 2018).

This chapter can be considered an overview of the state of the art in MASS development. It provides information about relevant issues regarding research, development, and regulation.

2.1. Research and Development

The following sections provide a brief overview of some of the ongoing or planned initiatives for MASS concepts as well as an overview of some of the established research networks and their research output. A visual overview of where the different research and development activities are occurring is provided on the world map in Figure 2.

2.1.1. Concepts

There are many projects that are connected to autonomous operations at sea. Several projects are working on smaller craft. These include small passenger boats (Brekke et al., 2022) and uncrewed surface vehicles (Maritime Robotics, 2023), designed to sail short distance crossings, as well as subsea and surface vessels, most of which are for oceanographic or military use (Relling, 2020). The non-exhaustive list of projects described below has excluded these smaller craft and instead provides an overview of autonomous concepts directly related to larger commercial vessels.

Japanese shipping company NYK has set a target to employ manned autonomous ships. The company conducted relevant trials on a large pure car and truck carrier in 2019. Their goal is to make use of advanced technologies and remote support from shore to support ship operations and enhance safety (NYK, 2019).

The Chinese-owned *Zhi Fei* is a 120-metre-long electric container ship that has been awarded the title of the world's first autonomous vessel in commercial service. After starting trials in June 2021, it launched its regular service route in April 2022. *Zhi Fei* can be operated in manned, remote control, and unmanned modes (HFW, 2022) but is said to be operating mostly by remote control (Negenborn et al., 2023).

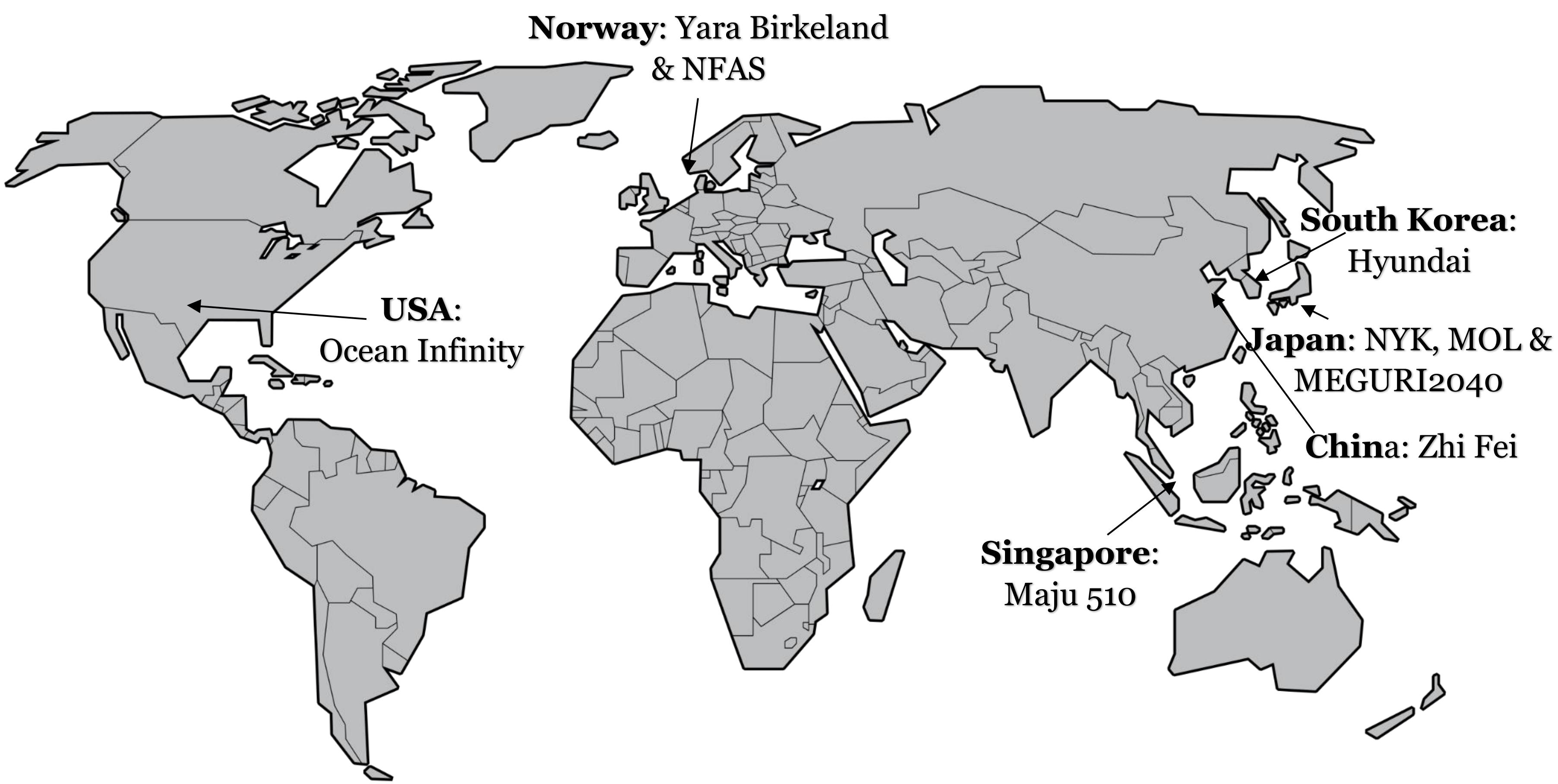

Figure 2: Different research and development activities in the world. Map from Tom B (2011) is modified.

In Norway, the 80-metre-long *Yara Birkeland* is a fully electric container ship looking to commence autonomous operations by 2024. The vessel – which was handed over to Yara in 2020 – commenced commercial operation in 2022 with a first set of highly automated systems with onboard crew (Kongsberg, 2022). Yara had previously planned for the ship to already be capable of fully autonomous operations in 2020 (Kongsberg, 2017).

Further concepts include Hyundai's LNG carrier, *Prism Courage*, which used autonomous navigation systems – under close observation from the crew on board – for half its voyage while crossing the Pacific Ocean in June 2022 (HFW, 2022). Already in January 2022, Japanese Mitsui O.S.K. Lines (MOL) completed trials of both an unmanned coastal containership and an unmanned coastal car ferry in Japanese waters (HFW, 2022). Additionally, a tug in Singapore, the *Maju 510*, has been modified so that it can be remotely operated by joystick control and has been certified to perform autonomous and remote control navigation in a controlled environment with seafarers on board (MarineLink, 2022). Finally, technology company Ocean Infinity has ordered six 85-metre-long multi-purpose offshore vessels from shipbuilding company VARD. While these vessels, which are expected to be delivered in 2025, will have the option of being crewed, they will be designed to be operated from shore (VARD, 2022).

2.1.2. Research Networks

Several research networks working on MASSs have been established. These include the International Network for Autonomous Ships, an informal network of national and regional interest organisations working on unmanned, autonomous, and smart ships. This network is closely affiliated with the Norwegian Forum for Autonomous Ships, an interest group of Norwegian persons or organisations that seeks to strengthen cooperation among users, researchers, and authorities on the topic of autonomous ships (NFAS, n.d.). Prominent members include classification society DNV and shipbuilding company VARD (NFAS, n.d.).

The MEGURI 2040 fully autonomous ship programme of the Nippon Foundation is a consortium of 30 Japanese companies collaborating to develop fully autonomous navigation for container ships. Well-known companies involved in the programme include marine electronics company Furuno and shipping company NYK (The Nippon Foundation, n.d.). The One Sea Association is another global alliance interested in the promotion, creation, and implementation of conditions needed for automated and autonomous maritime transport systems. Notable members include electrical equipment company ABB and manufacturing company Wärtsilä (One Sea, n.d.).

2.1.3. Research Output

Research regarding MASSs covers several different areas, including their technological capabilities, legal matters, the human element, economics, and organisation. One arena which presents current research and academic activities focused on the development of MASS technology and relevant knowledge from around the world is the International Conference on Maritime Autonomous Surface Ships.

Research has yielded positive results (Hogg & Ghosh, 2016; Munim & Haralambides, 2022), which have been revealed by the advances achieved regarding the different MASS concepts mentioned in Section 2.1.1. However, research into making autonomous ships a reality is generally focused on overcoming the technological challenges involved (Banda et al., 2018; Man et al., 2018b; Porathe, in press). The corresponding concern that this strong technology focus will fail to consider issues related to the human element in MASS operations has led to the initiation of the HUMANE project, which stands for Human Maritime Autonomy Enable. This project – which started in 2018 and ended in 2021 – performed a broad, human-centred evaluation of the future implications of MASSs and the related changes required (Lützhöft, 2020). Nevertheless, research gaps related to the human element persist. Negenborn et al. (2023) state that some of the research gaps that still exist in 2023 include how humans and artificial intelligence (AI) interact and how people understand and anticipate the manoeuvres of other ships to avoid collisions in busy waters.

One of the first researchers to highlight the importance of predictability and transparency in MASSs for humans was Porathe (2019a), and this perspective has been echoed by others since (Madsen et al., 2022; Miyoshi et al., 2022). This is especially important for collision avoidance, which is seen as a game of coordination where navigators on different vessels have to choose mutually compatible strategies independently (Cannell, 1981). Collision avoidance at sea is regulated by the COLREGs, a set of rules that is often ambiguous depending on the situation and which is essentially written in a non-machine-readable form (Hannaford et al., 2022; Wróbel et al., 2022). Ensuring MASS compliance with the COLREGs has therefore proven to be no easy matter, and extensive research has been conducted on the subject. A definitive method for ensuring MASS compliance with the COLREGs has still not been determined. Instead, Wróbel et al. (2022) highlight a worrying trend of studies which claim that the algorithms and methods developed therein were at least partially COLREGs-compliant when they actually clearly contradict the rules. Wróbel et al. (2022) continue by questioning how machines can be expected to understand and correctly interpret the ambiguous COLREGs if even academics and practitioners publishing in high-quality research channels have problems understanding the rules themselves.

The issue is further complicated by the fact that vessels currently do not always act in accordance with the COLREGs. While this may sometimes be due to problems in the understanding and application of the COLREGs (Mohović et al., 2015), it has also been observed that navigators frequently make use of Rule 2b of the COLREGs – the so-called seamanship rule[3] – to take evasive action that may not comply with some other rule presented in the COLREGs (Rutledal et al., 2020). Unfortunately, COLREG rules as important to the ordinary practice of

[3] See fact box on next page.

seamen as Rules 6[4], 18[5], and 19[6] are mostly being ignored in contemporary research on COLREGs-compliant MASSs (Wróbel et al., 2022).

Fact Box:

COLREGs Rule 2 (Responsibility)

a) Nothing in these Rules shall exonerate any vessel, or the owner, master or crew thereof, from the consequences of any neglect to comply with these Rules or of the neglect of any precautions which may be required by the ordinary practice of seamen, or by the special circumstances of the case.

b) In construing and complying with these Rules due regard shall be had to all dangers of navigation and collision and to any special circumstances, including the limitations of the vessels involved, which may make a departure from these Rules necessary to avoid immediate danger.

COLREGs Rule 6 (Safe Speed)

Every vessel shall at all times proceed at a safe speed so that she can take proper and effective action to avoid a collision and be stopped within a distance appropriate to the prevailing circumstances and conditions.

In determining a safe speed the following factors shall be among those taken into account:

a) By all vessels:
   i. the state of visibility;
   ii. the traffic density including concentrations of fishing vessels or any other vessels;
   iii. the manoeuvrability of the vessel with special reference to stopping distance and turning ability in the prevailing conditions;
   iv. at night the presence of background light such as from shore lights or from backscatter of her own lights;
   v. the state of wind, sea and current, and the proximity of navigational hazards;
   vi. the draught in relation to the available depth of water.

b) Additionally, by vessels with operational radar:
   i. the characteristics, efficiency and limitations of the radar equipment;
   ii. any constraints imposed by the radar range scale in use;
   iii. the effect on radar detection of the sea state, weather and other sources of interference;
   iv. the possibility that small vessels, ice and other floating objects may not be detected by radar at an adequate range;
   v. the number, location and movements of vessels detected by radar;

c) the more exact assessment of the visibility that may be possible when radar is used to determine the range of vessels or other objects in the vicinity.

[4] Safe speed
[5] Responsibilities between vessels
[6] Conduct of vessels in restricted visibility

COLREGs Rule 18 (Responsibilities between vessels)

Except where Rule 9, Rule 10, and Rule 13 otherwise require:

a) A power-driven vessel underway shall keep out of the way of:
   i. A vessel not under command;
   ii. A vessel restricted in her ability to manoeuvre;
   iii. A vessel engaged in fishing;
   iv. A sailing vessel.

b) A sailing vessel underway shall keep out of the way of:
   i. A vessel not under command;
   ii. A vessel restricted in her ability to manoeuvre;
   iii. A vessel engaged in fishing;

c) A vessel engaged in fishing when underway shall, so far as possible, keep out of the way of:
   i. A vessel not under command;
   ii. A vessel restricted in her ability to manoeuvre;

d)
   i. Any vessel other than a vessel not under command or a vessel restricted in her ability to manoeuvre shall, if the circumstances of the case admit, avoid impeding the safe passage of a vessel constrained by her draught, exhibiting the signals in Rule 28.
   ii. A vessel constrained by her draught shall navigate with particular caution having full regard to her special condition.

e) A seaplane on the water shall, in general, keep well clear of all vessels and avoid impeding their navigation. In circumstances, however, where risk of collision exists, she shall comply with the Rules of this part.

f)
   i. A WIG craft, when taking off, landing and in flight near the surface, shall keep well clear of all other vessels and avoid impeding their navigation;
   ii. A WIG craft operating on the water surface shall comply with the Rules of this Part as a power-driven vessel.

COLREGs Rule 19 (Conduct of vessels in restricted visibility)

a) This Rule applies to vessels not in sight of one another when navigating in or near an area of restricted visibility.

b) Every vessel shall proceed at a safe speed adapted to the prevailing circumstances and conditions of restricted visibility. A power-driven vessel shall have her engines ready for immediate manoeuvre.

c) Every vessel shall have due regard to the prevailing circumstances and conditions of restricted visibility when complying with the Rules of Section I of this Part.

d) A vessel which detects by radar alone the presence of another vessel shall determine if a close-quarters situation is developing and/or risk of collision exists. If so, she shall take avoiding action in ample time, provided that when such action consists of an alteration of course, so far as possible the following shall be avoided:
   i. an alteration of course to port for a vessel forwards of the beam, other than for a vessel being overtaken;
   ii. an alteration of course towards a vessel abeam or abaft the beam.

> e) Except where it has been determined that a risk of collision does not exist, every vessel which hears apparently forwards of her beam the fog signal of another vessel, or which cannot avoid a close-quarters situation with another vessel forwards of her beam, shall reduce her speed to the minimum at which she can be kept on her course. She shall if necessary take all her way off and in any event navigate with extreme caution until danger of collision is over.

There have been two prominent proposals for MASS compliance with the COLREGs in the light of qualitative rules: the first is to locate solutions that are designed to circumvent the COLREGs altogether. These include the creation of algorithms which are designed to ensure that MASSs adjust their course and speed "before rules defined by COLREGs [apply]" (Nakamura & Okada, 2019, p. 2; Nakamura et al., 2019, p. 2). Such an approach does not seem suitable for two reasons: First, rules such as the safe speed rule clearly state that they apply at all times and not only when a risk of collision is determined. Second, these algorithms are only designed to avoid collisions with vessels that have been *detected* – mostly by AIS (Ma et al., 2020). However, without considering the possibility that some objects may not be detected at an adequate range, such an approach would be in clear breach of Rule 6 (b) iv of the COLREGs.

Another more promising suggested approach to this problem is using AIS data to make AI learn the most effective, efficient, and COLREGs-compliant ways of manoeuvring (Porathe, 2019a). Subsequently, AIS data was utilised to build models of normalcy for traffic patterns (Yan et al., 2020), which were then employed to both generate what are described as "safe paths" for MASSs (Xu et al., 2019) and to class vessels as "high risk" if they do not follow the predicted pattern (Yan et al., 2020). This approach hinges on historic AIS data exhibiting safe vessel behaviours. Wróbel et al. (2022) have put it more bluntly: If the AI of a MASS is fed with garbage data, it will produce garbage results. This can be taken as a reference to the classic saying "garbage in, garbage out", which highlights the importance of the quality of input data in machine learning models (Pyle, 1999).

2.2. Regulations

As mentioned at the beginning of this chapter, there were more than 100,000 merchant vessels in operation in 2021. This number has been increasing steadily in recent years. It is therefore safe to presume that even if the MASS enjoys widespread adoption in the coming years, it will remain in the minority for at least the foreseeable future. National and international regulation will therefore be tasked with ensuring safe coexistence between MASSs and conventional vessels where MASSs and crewed vessels share the same waters (Negenborn et al., 2023). While this thesis does not provide an exhaustive list of all regulations and regulatory initiatives, a selection deemed relevant for this thesis is described in the sections to follow.

2.2.1. International Maritime Organization

The IMO is a specialised agency of the United Nations. Its mission is to promote safe, secure, environmentally sound, efficient, and sustainable shipping through cooperation (IMO, 2022b). As the global standard-setting authority for the safety, security, and environmental performance of international shipping, the IMO aims to achieve its mission by creating a regulatory framework for the shipping industry that is fair, effective, and universally both adopted and implemented (IMO, n.d.). As of 2013, the IMO has promoted the adoption of some 50 international conventions and protocols and has adopted more than 1,000 codes and recommendations (IMO, 2013b). One particular IMO convention is of special importance in this thesis. The Convention on the International Regulations for Preventing Collisions at Sea 1972 provided a set of rules that apply to all vessels upon the high seas and in all waters connected therewith which are navigable by seagoing vessels (IMO, 1972b). These rules will therefore apply to any MASS wishing to operate in the future. Rule 6, requiring every vessel to proceed at a safe speed at all times, and the question of how a MASS could determine which speed could be considered safe in a given situation are of major importance in this thesis.

Historically, the IMO has attempted to improve shipping safety largely by implementing new regulations following major accidents. This is reflected by the adoption of the following: the Safety of Life at Sea Convention – which regulates the technical issues of maritime safety – following the sinking of the *Titanic* (Oltedal, 2018), the International Convention for the Prevention of Pollution from Ships following the *Torrey Canyon* disaster, the International Convention on the Standards of Training, Certification, and Watchkeeping for Seafarers following the *Amoco Cadiz* disaster, and the International Safety Management Code following the capsize of the *Herald of Free Enterprise* (Parsons & Allen, 2018).

Concerning MASSs, however, it is positive to see that the IMO has taken a more proactive approach. Since one of the IMO's strategic directions is the integration of new and advancing technologies into the regulatory framework (IMO, 2022b), several regulatory initiatives that can be seen as supporting the integration of MASSs have been implemented. These include *MSC.1/Circ.1455* from June 2013, which provides guidelines for the approval of novel technologies. These guidelines emphasise the importance of the principle of "safety equivalence" (IMO, 2013a), which has commonly been interpreted as a requirement for MASS to be "at least as safe as" conventional vessels (Porathe et al., 2018).

In 2017, the IMO officially included the issue of MASSs on its agenda and initiated a regulatory scoping exercise to determine how it may be introduced in IMO instruments. Interim guidelines for MASS trials were distributed in 2019 in the form of *MSC.1/Circ.1604*. These guidelines again highlight that MASS trials should be conducted in a manner that provides at least the same degree of safety as current relevant instruments provide (IMO, 2019).

The regulatory scoping exercise was finalised in 2021. With regards to the COLREGs, the scoping exercise identified terminology, lights, shapes, and sound signals, the role of the master, the responsibility of the remote operator, and distress signals as potential gaps/themes that require addressing (IMO, 2021).

Rule 6 – the requirement to proceed at a safe speed – was not identified as a theme that requires addressing. In addition to providing an assessment of how the existing regulatory framework might be affected to address MASS operations, it also provides guidance on identifying, selecting, and deciding on future work on MASSs (IMO, 2021). This future work on MASSs includes the currently ongoing crafting of a goal-based instrument in the form of a non-mandatory MASS Code to be adopted in the second half of 2024 and the subsequent development of a mandatory MASS Code envisaged to enter into force in 2028 (IMO, 2022a).

2.2.2. Norwegian Maritime Authority

The Norwegian Maritime Authority (NMA) is the administrative and supervisory authority for vessels flying the Norwegian flag and foreign ships in Norwegian waters. It acts as an advisor, driving force, supervisory authority, and register (Norwegian Maritime Authority, 2016a). As a so-called flag state, the NMA has an important role in enforcing IMO rules (Hoffmann et al., 2020).

The NMA deems it imperative for them to be a central participant in the development of autonomous ships and sees themselves as an important partner for innovators. As such, they want to cooperate with the industry and lead in the development of rules and regulations that take new technologies into consideration (Norwegian Maritime Authority, 2016b). Examples of their support include the designation of autonomous ship test areas (Norwegian Maritime Authority, 2016b), the initiation of a formal collaborative research and development project examining autonomous maritime operations (Norwegian Maritime Authority, 2020b), and the publication of an official circular providing guidance in connection with the construction or installation of automated functionality aimed at performing unmanned or partially unmanned operations. Similar to the IMO's principle of safety equivalence, the NMA highlight in their circular that autonomous and fully or partially remotely operated ships must hold the same level of safety as conventional ships (Norwegian Maritime Authority, 2020a).

2.2.3. Classification Societies

Aspiring to aid the maritime industry and regulatory bodies in ensuring maritime safety, classification societies verify compliance with international and/or national regulations on behalf of flag administrations. Furthermore, classification societies have developed their own rules. Today, the vast majority of commercial ships are built to the standards established by classification societies (IACS, 2022). Several different classification societies exist, and more than 90% of the world's cargo-carrying tonnage is covered by one of the 11 classification societies that are members of the International Association of Classification Societies (IACS) (IACS, 2023). The advancement of the MASS is seen by the IACS as an important subject area, and the association aspires to actively cooperate with regulators and the maritime industry to develop requirements and procedures (IACS, 2019).

Several IACS member classification societies have published advisories, guidelines, and codes on autonomous ships. These include the DNV class guidelines for autonomous and remotely operated ships (DNV, 2021), the Bureau Veritas guidelines for autonomous shipping (Bureau Veritas, 2019), the Lloyd's Register code for unmanned marine systems (Lloyd's Register, 2017), the ClassNK guidelines for automated/autonomous operation of ships (ClassNK, 2020), the Korean Register guidance for autonomous ships (Korean Register, 2021), and the ABS Advisory on Autonomous Functionality (ABS, 2020). While these publications cover how systems supporting the autonomous operation of vessels should be designed, they lack specifics about how they should be applied, with uncertainty voiced especially during times of poor visibility or storms or in sea ice (Negenborn et al., 2023).

2.3. Implication on the Research Conducted in this Thesis

This chapter has highlighted that, while MASSs will need to follow the COLREGs, a definitive method for ensuring MASS compliance with the COLREGs has yet to be determined. While several articles claiming COLREGs-compliant MASS algorithms have been published, many of these algorithms have been proven to clearly contradict the rules. Furthermore, Rule 6 of the COLREGs – the requirement to proceed at a safe speed at all times – is seldom considered in MASS research that concerns COLREGs compliancy (Wróbel et al., 2022). The state of the art further demonstrates that it is unlikely that the wording of Rule 6 of the COLREGs will be changed to better accommodate MASSs. The results of the regulatory scoping exercise conducted by the IMO demonstrate that the IMO does not deem it necessary to amend Rule 6 of the COLREGs to enable MASS compliance.

Finally, as late as this year (2023), leading research has called for a better understanding of how people understand and anticipate the manoeuvres of other ships to avoid collisions in busy waters (Negenborn et al., 2023). With contemporary research largely ignoring possible input by human navigators, this chapter has provided reasons for the necessity of the research conducted in this thesis:

- To investigate the feasibility of different methods for the autonomous determination of safe speed and
- To engage with human navigators to understand how they interpret the COLREGs to ensure MASSs will behave in a way that is intuitive to conventional vessels.

Chapter 3.

Philosophical Foundation

Science was born as a result
and consequence of philosophy;
it cannot survive without a
philosophical base.

Ayn Rand

A fundamental philosophical question encountered in this thesis is as follows: what is a safe speed? This chapter outlines philosophical issues that arise in the discussion of what a safe speed may be.

3.1. The Goal of the Thesis

To locate the goal of this thesis, the following questions must be answered: what is its purpose, and what is its aim? As for the purpose, studying the idea of safe speed at sea not only satisfies my intellectual curiosity but also serves to promote commercial interests and improve society.

As mentioned in Chapter 2, MASSs will have to follow the COLREGs. However, due to the qualitative nature of the rules, it is unclear how they may be translated into a machine-readable format (Vartdal et al., 2018). By exploring how safe speed is determined by navigators, this thesis may assist in promoting the commercial interest of employing automated vessels on the high seas. Changes to society can happen by reducing accidents – as human error is often considered a major contributing factor for most shipping accidents (Butt et al., 2013), providing ferry connections in places where it would not be feasible to have manned ferries, and reducing emissions by moving cargo from road to sea. Furthermore, a deeper understanding of how current seafarers determine a safe speed may aid policymakers if some stakeholders call for a change to the current regulations.

It is accepted that cultural values have influenced the perception that it is desirable to reduce accidents, provide better transport, and reduce emissions. These values have played a research-directing role in deciding the purpose of this thesis.

The aim of this thesis is explained by describing how it attempts to achieve its purpose. In social science, this is generally done by collecting and categorising data, providing explanations, making predictions, and offering rationale. In this thesis this was achieved by collecting AIS data that was compared with predictions of how the measured speeds should change in different scenarios. Explanations and reasoning regarding why observed vessel speeds behaved the way they did have been provided through interviews with experienced navigators.

3.2. The Scientificity of the Thesis

The two main approaches to the scientificity of the social sciences can be described as naturalism and anti-naturalism. While *naturalism* affirms that the methodology of the natural sciences can be applied to social sciences, *anti-naturalism* claims that it cannot (Keat, 1971). The school of thought termed *positivism* has been important in influencing the scientific method. Positivism holds that genuine knowledge of the external world must be grounded in experience and observation and has influenced naturalism on three core tenets (Gorton, 2010):

1. Science is a fundamentally empirical enterprise,
2. The primary aim of science is to produce causal explanations grounded in lawlike regularities, and

3. The role of science is to describe and explain the world, not to make value judgements.

These three core tenets apply to the approach taken in this thesis. The view that science is a fundamentally empirical enterprise is reflected in the thesis, as data collection was done by collecting real-world AIS data. To find causal explanations as to how safe speed is determined, in this thesis, I approached the subject by utilising both quantitative and qualitative methods. This corresponds with the second tenet. The third tenet of value neutrality is reflected in the thesis, as it does not indicate judgment regarding whether the speed determined by the navigators is in fact safe. This thesis merely contributes to gaining an understanding of what speed is determined to be safe by current navigators. These findings can be tested, and therefore they can be empirically falsified. This aligns with the view of Karl Popper that science is distinguished from non-science by empirical falsifiability. As such, the influence of naturalism – and positivism in particular – on the thesis is apparent.

However, it seems that interpretivism – a form of anti-naturalism – also applies to this thesis. This is interesting, as interpretivism is grounded in profoundly different assumptions when compared to naturalism (Gorton, 2010). The idea of social phenomena being meaningful cannot be disregarded for this thesis. The speed of the vessel is not simply the result of physical processes but is instead the result of the speed that the navigator has set. What governs the speed of the vessel is the belief of the navigator regarding what speed is safe in the current situation. Having highlighted the important aspect of interpretivism that applies to this thesis, it must be emphasised that the rejection of producing causal explanations for social phenomena, as is done through interpretivism (Gorton, 2010), is at odds with the research conducted in this thesis.

It can be concluded that the main part of this thesis follows a naturalistic approach to finding the initial results. These results are valuable in understanding how different external factors influence the speed chosen by navigators. For a deeper understanding of why navigators have interpreted the different external factors the way they have, an antinaturalistic approach is necessary. This was applied through in-depth interviews with experienced navigators.

3.3. Basic Philosophical Issues of the Thesis

The following sections provide a brief discussion regarding the basic ontological and epistemological issues of the thesis.

3.3.1. Ontological Issues

Ontology is the study of what there is and of what "what there is" is like (Cartwright & Montuschi, 2015). It focuses on what things exist, what categories they belong to, and if there is such a thing as objective reality (Philosophy Terms, n.d.). Regarding the research conducted in this thesis, the obvious question is as follows: what is a safe speed? Concerning marine accidents, it may be easier to define what is not a safe speed. When a collision or allision occurs, an unsafe speed is often listed as a contributing factor. In the COLREGs a "safe speed" is specified as such a speed that a vessel can "take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions" (IMO, 1972a).

Words such as "safe" and "appropriate" include essential normative aspects. A definition of these words is sensitive to not only facts but also values (Cartwright & Montuschi, 2015). It can also be argued that safe and appropriate are dependent on the social group that defines these words. The speeds that are considered safe in a study with a population of Norwegian seafarers may be seen as unsafe by a population of seafarers from a different country. As such, this research aims to decouple the word "safe" from the data collection in the sense that it is not aimed at judging whether the determined speeds were indeed safe. When future research demonstrates stark differences among the determined safe speeds among different groups of seafarers, a closer look into the values that lie behind the words “safe” and “appropriate” may provide a deeper understanding of those differences.

While the phenomenon of a “safe” speed is ontologically subjective, a vessel’s speed that is disconnected from the normative aspect of safe can be ontologically objective.

3.3.1. Epistemological Issues

Epistemology is the study of what knowledge is and how individuals come to have it (Cartwright & Montuschi, 2015). It is concerned with the necessary and sufficient conditions of knowledge and its sources, structure, and limits (Steup, 2005).

As discussed in Section 3.2, naturalism has a strong influence on this thesis. An epistemological doctrine that is strongly linked to naturalism is empiricism, which requires that genuine knowledge of the external world be grounded in experience and observation (Gorton, 2010). This is exactly the epistemological approach of this study: utilising real-world AIS data to determine some of the main and combined effects of different external factors influencing a vessel’s speed, thus grounding the knowledge of how different factors affect vessel speeds in observational data.

A clear issue here however is that an empirical approach is one that is value-free, while the normative idea of a “safe” speed is inherently value laden. It follows that a result such as “the safe speed for situation X is Y knots” would be epistemically subjective, whereas a result such as “the speed considered safe by navigator Z in situation X was Y knots” could be considered epistemically objective.

3.4. Philosophical Issues Regarding Measurement

Measurement involves three different kinds of activities: characterisation, representation, and procedures (Cartwright & Montuschi, 2015). These activities mesh, are consistent, and are mutually supportive. They are closely investigated in the following sections.

3.4.1. Characterisation

Before something can be measured, one must make sure that it is clearly and explicitly established what the quantity or category is and what features it has. Categories must be useful for the purpose of a study and therefore depend on the aim of the social science research. It is not possible to formulate a correct definition of a social science research category, as these do not simply exist in nature but are instead socially constructed (Cartwright & Montuschi, 2015). In this regard, it is interesting to question whether something like safe speed exists in nature.

Initially, it may seem plausible that a speed that is safe in terms of collision prevention can be calculated for vessels traversing the oceans. This is a speed that is safe regardless of the existence of a human society. If two vessels on the open ocean with crossing tracks are on a collision course, it is possible to calculate how much one ship could accelerate or decelerate to avoid collision. However, such calculations would remove other factors from the calculation.

If a ship accelerates to pass ahead of the other vessel, would this speed still be considered safe if the steering system broke shortly before passing, causing the vessel to head straight into the other one? Maybe reducing the speed would be more advisable. This, however, could lead to the vessel losing its steering ability and being at the mercy of the wind and tides. The problem becomes apparent when considering a large container vessel entering the port of Hamburg. No matter what speed the vessel enters the port with, if major mechanical failures occur, it will not be possible to prevent it from colliding or alliding. Even if it sailed with only 0.1 knots and subsequently suffered a blackout, it could then be pushed against the shore by the wind and/or current. The question therefore clearly lies in what is safe. However, what is considered “safe” is a socially constructed concept.

One concept that concerns characterisation in measurement is the Ballung concept, which characterises by resemblance among individuals rather than by a definite property (Cartwright & Montuschi, 2015). It seems that the idea of safe speed fits with this concept. The aim of this study is to precisely locate where (and if) the chosen speed of different navigators clusters.

3.4.2. Representation

The category of safe speed must be represented in some way. The representation must fit the characterisation discussed in Section 3.4.1 (Cartwright & Montuschi, 2015). For many social science research projects, this seems to be a demanding endeavour: It must be decided whether a concept is represented in a "yes or no" manner; in a "degree of" manner; on a numeral, ordinal, interval, or ratio scale; as a probability distribution; or with a table of indicators (Cartwright & Montuschi, 2015). However, it seems obvious that the best way to measure speed is on a ratio scale with a natural zero point. A measurement taken in the study at hand may therefore be represented as a speed of 6 or 10 knots, which was the chosen speed by vessel X in scenario Y. This representation of the data would constitute to be what Taylor refers to as "brute data". He defines this kind of data as "data whose validity cannot be questioned by offering another interpretation or reading, data whose credibility cannot be founded or undetermined by further reasoning" (Taylor, 1985). The speeds collected via the AIS data are exactly that. While it may be questioned whether these speeds are indeed safe, it cannot be questioned that each of these is the speed that the vessel proceeded with under the observed circumstances.

3.4.3. Procedures

Procedures describe what must be done to measure social science concepts (Cartwright & Montuschi, 2015). While social science research can encounter several difficulties in deciding the procedures by which the measurements shall occur, these difficulties do not apply to the research conducted in this thesis. If the aim is to measure the speed at which a vessel proceeds in different scenarios, it is straightforward to extract this data from the AIS data. Other usual social science problems, such as setting priorities with regard to data accuracy versus the cost of collecting the data and having to use data collected from others that may not coincide with the aims of the social science researcher (Cartwright & Montuschi, 2015), do not apply to this thesis.

3.5. Philosophical Issues Regarding Causation

While the notion of causation has faced longstanding philosophical issues (Steel, 2013), causation remains important in the social sciences (Cartwright & Montuschi, 2015). Nevertheless, how can knowledge about cause and effect be acquired? Correctly inferring a cause-and-effect relationship is generally agreed to be difficult in the social sciences (Steel, 2013) – in part because correlation does not mean causation and because causes do not always produce the same effects (Williamson & Illari, 2013).

There are five main different approaches to causality: the probabilistic view, the counterfactual view, the interventionist view, the process view, and the mechanistic view. The first three perspectives fall under the difference-making view, while the last two fall under the production view (Williamson & Illari, 2013). As it is considered unclear how the process view on causality is to be employed in a social science setting (Williamson & Illari, 2013), this will not be discussed further here. The other four views are discussed in greater detail in the upcoming sections.

3.5.1. Probabilistic Theory

The basic philosophical idea of the probabilistic causation theory is that, when a cause is present, the probability of the effect occurring should be higher than if it were absent (Baxter & Sommerville, 2011). The problem with this theory is that it could wrongly identify something that correlates with the effect as its cause. Another problem is encountered when a cause does not raise the probability of an effect. This would be the case if a cause caused the navigator to reduce the ship's speed to a minimum, but the navigator cannot do this, as the ship's speed is already reduced to a minimum due to other causes. These drawbacks have a noticeable effect on the research conducted in this thesis, where speeds collected from AIS data in different conditions essentially provide probabilities for changes in speed.

3.5.2. Counterfactual Theory

If the cause is absent, the effect is also absent. This is the basic idea of counterfactual theory. This theory collapses when there is more than one cause for an effect. If both reduced visibility and increased traffic density cause a reduction in the ship's speed by the navigator, both causes are rejected if the counterfactual theory is employed. Consider that you suspect reduced visibility to cause a reduction in speed. Under counterfactual theory, causation is proved when you see the effect disappear when the cause is removed. In this case, if you saw vessels return to their standard speed when there is no reduced visibility. If, however, the vessels were to be operating in an area of increased traffic density – removing the reduced visibility may not cause an increase in observed vessel speeds. A person employing counterfactual theory would therefore observe that the effect of reduced vessel speeds is present even when the suspected cause of reduced visibility is absent and would therefore conclude that reduced visibility does not cause reduced vessel speeds.

3.5.3. Interventional Theory

The intervention view of causation is closely linked to the experimental manipulations used to find causes (Williamson & Illari, 2013). The idea is that, if one manipulates the causes, one can affect their effects (Williamson & Illari, 2013). Causal relationships are sensitive to even slight changes in context (Williamson & Illari, 2013). Since the context is not controlled when collecting AIS data, interventional theory does not fit the research conducted in this thesis. It may, however, be useful for future research where one might want to create a simulator study where influencing factors can be accounted for.

3.5.4. Mechanistic Theory

The mechanistic theory falls under the production view (Williamson & Illari, 2013). The basic idea is that something is the cause of something else if it produces it. A popular philosophical account is that, in a causal mechanical process, energy is transferred at each step, but this does not seem to be of much help in the social sciences (Cartwright & Montuschi, 2015). Furthermore, this theory is problematic for causes that do not have mechanisms. This theory would therefore be fitting when attempting to explain that a change in propeller revolutions per minute caused an increase in speed, but it seems to be less suitable in explaining how a change in environment caused the navigator to deem a different speed to be safe.

3.6. Reflection on the Philosophical Foundation

In this section I have reflected around the philosophical foundation of the research carried out in this thesis and have acknowledged how some of my personal values have influenced the aim of the research. While arguing for the scientificity of the research, it became apparent that the employed methodology generally follows naturalism, the normative nature of the word safe speed has opened the door for interpretivism – a form of anti-naturalism – to be included as well. While the issue of measurement was not particularly challenging for this thesis's research, correctly inferring a cause-and-effect relationship proved to be as difficult in this thesis as it is in the social sciences in general.

Chapter 4.

Theoretical Frame of Reference

Experience without theory
is blind, but theory without
experience is mere
intellectual play.

Immanuel Kant

The research in this thesis has drawn from a number of different theoretical frames in the realm of safety science. This chapter discusses the major characteristics of different relevant theories that form the theoretical frame of reference for this thesis.

4.1. Sociotechnical Systems

A widely used way of solving problems is to divide them into smaller parts and then solve these smaller problems independently. However, it has been argued that this reductionist approach has directly led to modern-day troubles with technology (Grech et al., 2019; Vicente, 2006). This view was first popularised through research conducted by the Tavistock Institute in the late 1940s and early 1950s, where action researchers found that having separate approaches to the social and technical systems of an organisation was no longer feasible (Trist, 1981). Instead, the social requirements of people doing the work should be integrated with the technical requirements needed to keep the work systems viable (Fox, 1995).

Sociotechnical systems theory considers modern work processes to be complex, where many interdependent elements (i.e. cognitive, social, and technological factors) must work together in a broader team, organisational, and social context to achieve success. As a result, changing one part of a work system without first considering how such a change might affect – or require change in – other parts of the work system will generally not be effective (Davis et al., 2014). Instead, sociotechnical systems theory advocates for the consideration of both technical and social factors when seeking to introduce new technology (Cherns, 1976; Davis et al., 2014) and claims that when social and technical systems are balanced and harmonised, productivity, worker satisfaction, and safety can be optimised in parallel (Waterson et al., 2015). In this regard, it is interesting to indicate that the maritime domain is deemed to be persistent with the sociotechnical systems perspective (Koester, 2007).

Sociotechnical systems can be modelled after the sociotechnical system model (also called the Septigon model), which advocates for a more holistic, systematic approach for handling the relationships among the various elements that form a system. The Septigon model, which refers to society and culture; physical environment; practice; technology; and individual, group, and organisational environmental networks, is displayed in Figure 3 on the next page (Koester, 2007).

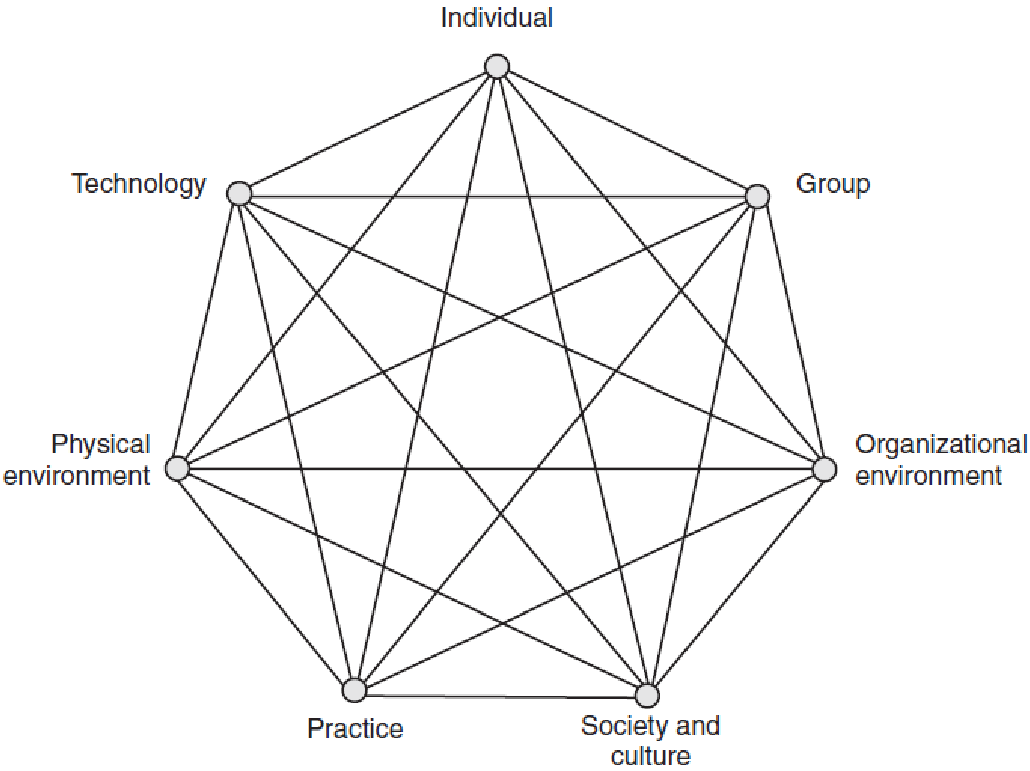

Figure 3: The sociotechnical system model (Koester, 2007).

The Septigon model indicates how various factors interact to influence system performance and can be used as a tool that ensures a systematic approach when managing the safe operations of a system as a whole (Grech et al., 2019).

4.2. Relevant Safety Management Theories

Various theories, models, and methods for managing safety in sociotechnical systems have been developed. An overview is provided in Figure 4 on the next page.

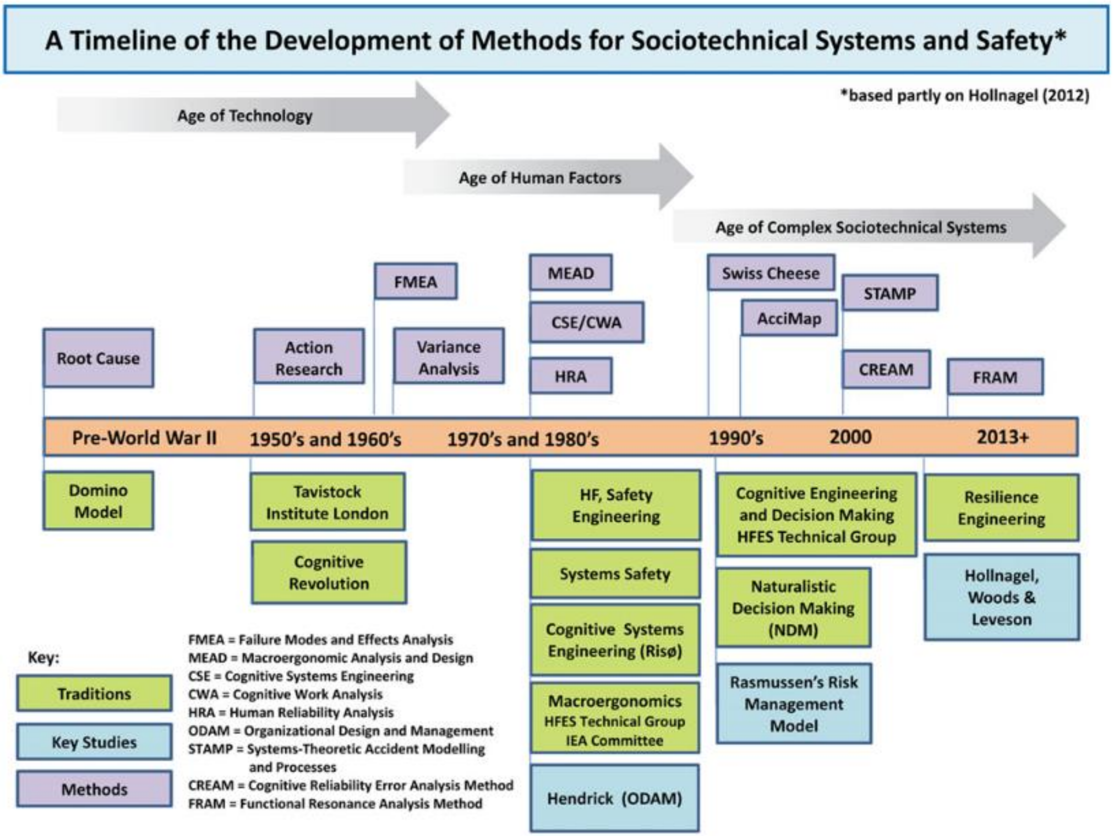

Figure 4: A timeline of the development of methods for sociotechnical systems and safety (Waterson et al., 2015). This is based partly on Hollnagel (2012).

Some of the theories depicted in Figure 4 above, which are considered of increased importance for this thesis, are described in more detail in the following sections.

4.2.1. Rasmussen's Risk Management Model

An influential contributor to safety science was Jens Rasmussen. In 1997 he published a paper called "Risk management in a dynamic society: a modelling problem", which is seen to have provoked a paradigm change in engineering for safety (Leveson, 2017). At the time, Rasmussen noted that many levels of politicians, managers, safety officers, and work planners are involved in the control of safety. He further noted that the sociotechnical system involved in the control of safety (depicted in Figure 5) often seeks to constrain the behaviour of workers to increase their safety performance (Rasmussen, 1997).

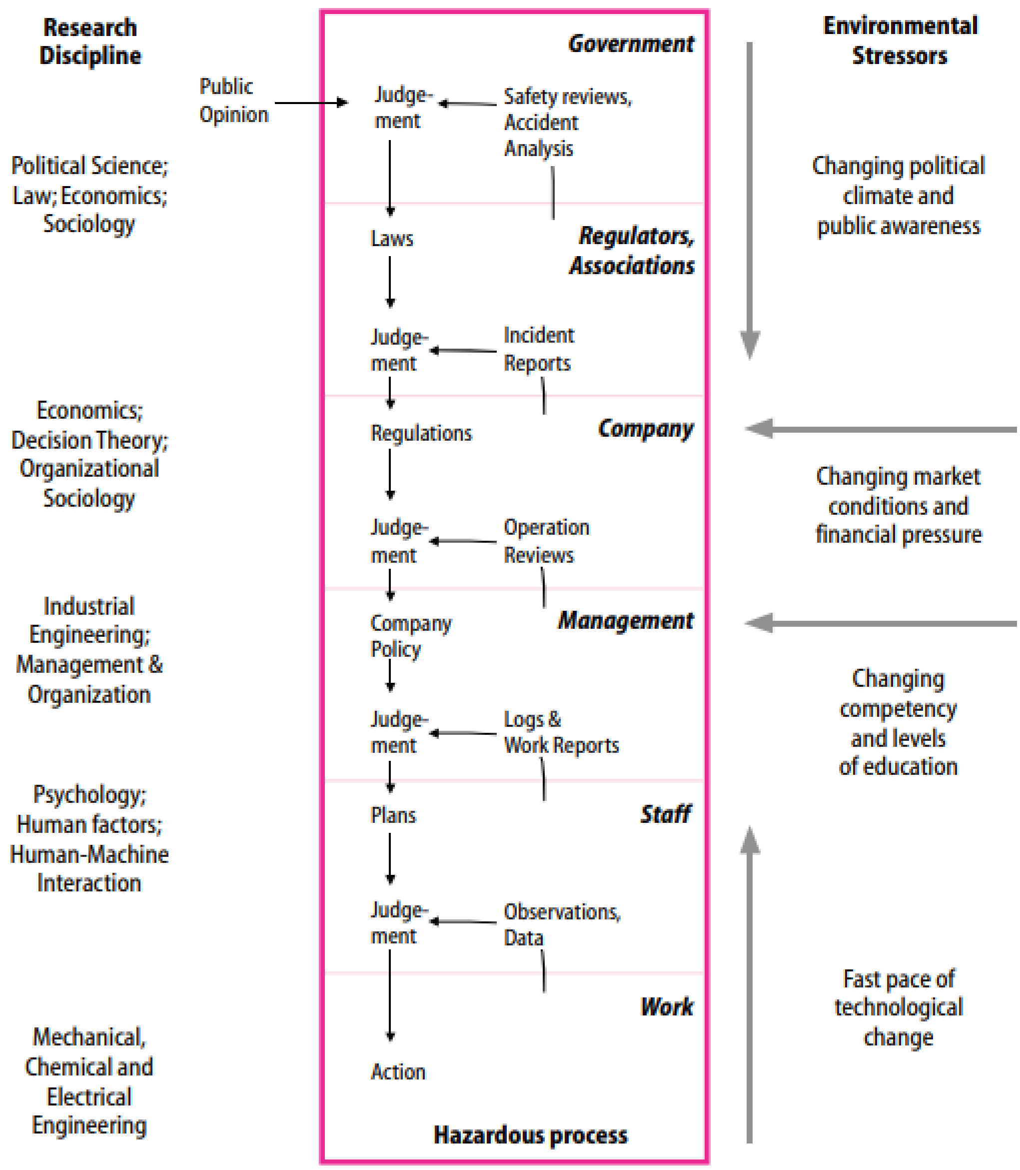

Figure 5: The sociotechnical system involved in risk management (Rasmussen & Svedung, 2000).

Rasmussen argues that, while this classic, prescriptive, command-and-control approach where rules of conduct are derived in a top-down manner may work under stable conditions, it is inadequate in the present-day dynamic world.

Because it is impossible to foresee all local contingencies in the work context, rules, laws, and instructions are practically never followed to the letter. Instead, it is the workers who need to regularly adapt within local administrative, functional, and safety-related constraints (Rasmussen, 1997). These constraints form boundaries, which – when taken together – create an envelope within which a sociotechnical system can feasibly operate. Rasmussen's dynamic safety model visualises this, as seen in Figure 6 below.

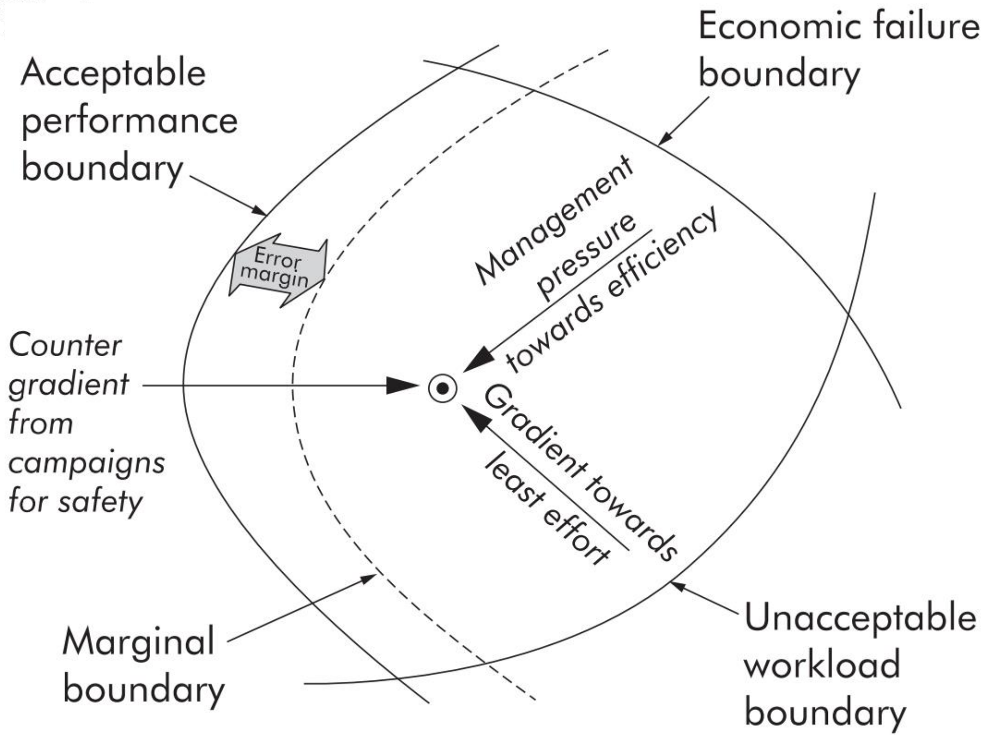

Figure 6: Rasmussen's dynamic safety model (Cook & Rasmussen, 2005). Modified from Rasmussen (1997).

According to the model, normal changes in local work conditions prompt significant variability in the work conducted in sociotechnical systems. Over time, actors will identify ways to reduce effort (the effort gradient), and management will introduce pressure towards efficiency (the cost gradient). These gradients normally result in a systematic migration towards the boundary of acceptable performance, where a quite normal variation in someone's behaviour can result in an accident. The takeaway is that effective efforts to increase safety should avoid focusing on human errors and violations and instead more closely view the mechanisms generating behaviour in the actual, dynamic work context (Rasmussen, 1997).

4.2.2. Work as Imagined and Work as Done

In Section 4.2.1, the sociotechnical system involved in risk management is depicted in Figure 5. This figure reveals the different layers – from government to management – that directly or indirectly affect the conditions under which work is conducted. On one side, the players who do not directly participate in the actual work being done are termed the *blunt end*. On the flip side is the *sharp end*, where the work is conducted and where the consequences of actions present themselves directly and immediately. This relationship is depicted in Figure 7 below.

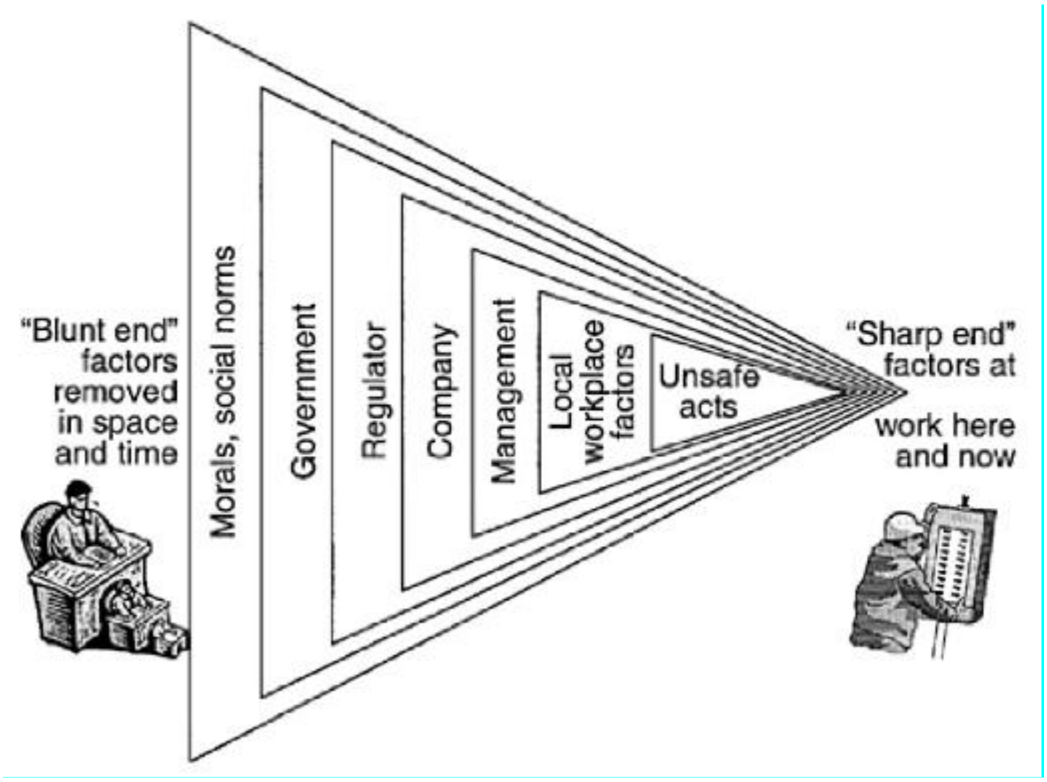

Figure 7: The sharp end - blunt end relations (Hollnagel, 2004).

The fact that the blunt end is removed in time and space from the activities conducted at the sharp end results in the two of them being neither calibrated nor synchronised (Hollnagel, 2014).

Working practises are usually determined by people at the blunt end and codified into routines, procedures, rules, and regulations (de Vries, 2017). They are often based on the view that there is only one correct way to achieve an outcome and that minimal variation is therefore expected (Ball & Frerk, 2015). In reality, it has been proven impossible for those at the blunt end to anticipate all the different possible conditions that can exist (Hollnagel, 2014). Moreover, the varying conditions encountered by those at the sharp end require continual adjustment and variation in activity to ensure that tasks are achieved safely and efficiently (Ball & Frerk, 2015). This aligns with Rasmussen's previously mentioned observation that – in reality – rules, laws, and instructions are practically never followed to the letter (Rasmussen, 1997).

This disconnect has prompted the emergence of two important concepts: work as imagined and work as done, which were popularised by Erik Hollnagel. In this regard, work as done refers to the practical and pragmatic way that tasks are achieved at the sharp end (Ball & Frerk, 2015). This lies in contrast with work as imagined, which is how people at the blunt end imagine how work should be done, given their general assumptions about what working is like or should be like (Hollnagel, 2014). This distinction is important because investigations have historically identified human errors based on work as imagined, with a linear narrative that falls short of hindsight bias. Trying to improve safety by focusing on work as imagined is a key part of a Safety-I culture, which is understood as the traditional approach to safety. Under Safety-I, it is assumed that things go wrong because of identifiable failures or malfunctions of specific components, such as technology, procedures, or human workers. The focus of this approach is to ensure that as few things as possible go wrong, and a popular strategy for reaching this goal has been to constrain variability (Hollnagel et al., 2015).

However, this approach has revealed that practical, achievable improvements remain elusive (Ball & Frerk, 2015).

As systems have continued to become more complex, it has been demonstrated that continuous adjustments are necessary to maintain acceptable performance (Hollnagel et al., 2015). Variability is therefore not something that should be constrained in these systems. Under Safety-II, a newer approach to increasing safety, the focus is on how everyday work – as performed by practitioners – generates safety (de Vries, 2017). Acknowledging that work as done differs from work as imagined, is imperative to genuinely start moving in the direction of safe and resilient operations (Ball & Frerk, 2015).

4.3. Implication on the Research Conducted in this Thesis

Maritime transport can be seen as a sociotechnical system, and any introduction of new technology must consider both technical and social factors (Cherns, 1976; Davis et al., 2014). Social factors will therefore play a large role in the implementation of MASSs. This includes understanding that the speeds of conventional vessels are not only influenced by safety considerations. Utilising historic data on conventional vessel speeds as a baseline for safe vessel speeds may therefore not be expedient. Furthermore, the theoretical frame of reference described in this chapter highlights the importance of understanding how work is actually done by practitioners. Designing a COLREGs-compliant MASS algorithm that does not consider how human navigators interpret the COLREGs in practice is therefore unlikely to yield positive results. Therefore, an implication of this thesis is that social factors are highlighted throughout the research.

Chapter 5.

Methodology

All methodologies, even
the most obvious ones,
have their limits.

Paul Feyerabend

This chapter describes the research methods applied to answer the research questions outlined in Section 1.2. As mentioned previously, this thesis incorporates both quantitative and qualitative approaches. In this regard, the quantitative approach is used to generate numerical data to uncover patterns and relationships that can be projected to a larger population (Bernard & Bernard, 2013), while the qualitative approach is concerned with understanding human behaviours and social phenomena from the perspectives of informants (Yin, 2015).

Incorporating a mixed-methods research approach recognises that all methods have strengths and weaknesses. Combining different methods ensures compensating strengths that generate more credible results (Hunter & Brewer, 2015). Furthermore, due to the novelty of MASS research and because the problem of safety management for autonomous ships – and especially the problem of how autonomous ships ought to determine safe speed – was not clearly defined when the research conducted in this thesis began, an exploratory approach has been utilised.

Exploratory research tends to tackle new problems on which little or no previous research has been done (Brown, 2006). It therefore does not aim to provide the final and conclusive answers to the research questions but merely explores the research topic with varying levels of depth (Dudovskiy, 2022). Indeed, an important part of conducting exploratory research is the willingness to change the research direction in light of new data or insights (Saunders et al., 2015).

The exploratory research began with the problem that future MASSs had to be at least as safe as conventional, manned vessels.[7] To gain an overview of what is needed to achieve this goal, a systematic literature review was conducted in Article 1. One of the results of this article is that smart methods and criteria allowing for the autonomous determination of safe speeds must be developed (Dreyer & Oltedal, 2019). Articles 2 and 3 then explore the suitability of using AIS data to teach MASS AI what speeds constitute safe speeds in different scenarios.[8] The results differ from what would be expected from a work-as-imagined view, resulting in Article 4 being based on expert interviews to provide an understanding of how safe speed is determined by navigators.

The methodological choice for each article that forms part of this thesis is summarised in Table 1. These choices are discussed in more detail in the following sections.

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[7] Refer to section 2.2.1. above.

[8] Reference is made to Porathe, T. (2019b). *Safety of Autonomous Shipping: COLREGS and Interaction between Manned and Unmanned Ships* 29th European Safety and Reliability Conference, http://rpsonline.com.sg/proceedings/9789811127243/pdf/0655.pdf

Table 1: Methodological choice for each research article.

Article	Approach	Method	Data
Article 1	Qualitative	Systematic literature review	Published research
Article 2	Quantitative	Linear regression analysis Graphical data representation	AIS and visibility data for 14,420 unique vessel transits
Article 3	Quantitative	Regression analysis Graphical data representation	AIS and environmental data for 47,490 unique vessel transits
Article 4	Qualitative	Interviews Systematic text condensation	Eight participants

5.1. Methodology of the First Article

The first article that forms part of this thesis was developed to answer Research Question 1.[9] To map which safety challenges have been identified in previous research, a literature review was conducted. This is because a literature review is considered an excellent way to synthesise research findings and uncover areas in which more research is needed (Snyder, 2019).

Several different types of literature reviews exist, meaning that a specific type of literature review had to be chosen as the methodology for the first article. While the systematic literature review was originally developed within medical science (Snyder, 2019), the transparent, rigorous, and reproducible nature of the

[9] What safety challenges for MASSs have been identified in previous research? What research gaps still need to be addressed to ensure safe MASS operations in the future?

systematic review methodology means that it has clear advantages over other types of literature reviews (Boland et al., 2017). With Denyer and Tranfield (2009) describing a systematic literature review as a methodology that "locates existing studies, selects and evaluates contributions, analyses and synthesizes data, and reports the evidence in such a way that allows reasonably clean conclusions to be reached" (p. 671), it was decided that the systematic literature review would be best suited to answer Research Question 1.

An important guideline for systematic literature reviews is the PRISMA statement (Moher et al., 2009), which stands for preferred reporting items for systematic reviews and meta-analyses. The review conducted in Article 1 was therefore designed to conform with the requirements contained therein. This includes the incorporation of a review protocol, which specifies the objectives, methods, and outcomes of the primary interest of the systematic review. The literature review process followed four stages, previously used by Snelson (2016), as detailed in Figure 8 on the next page.

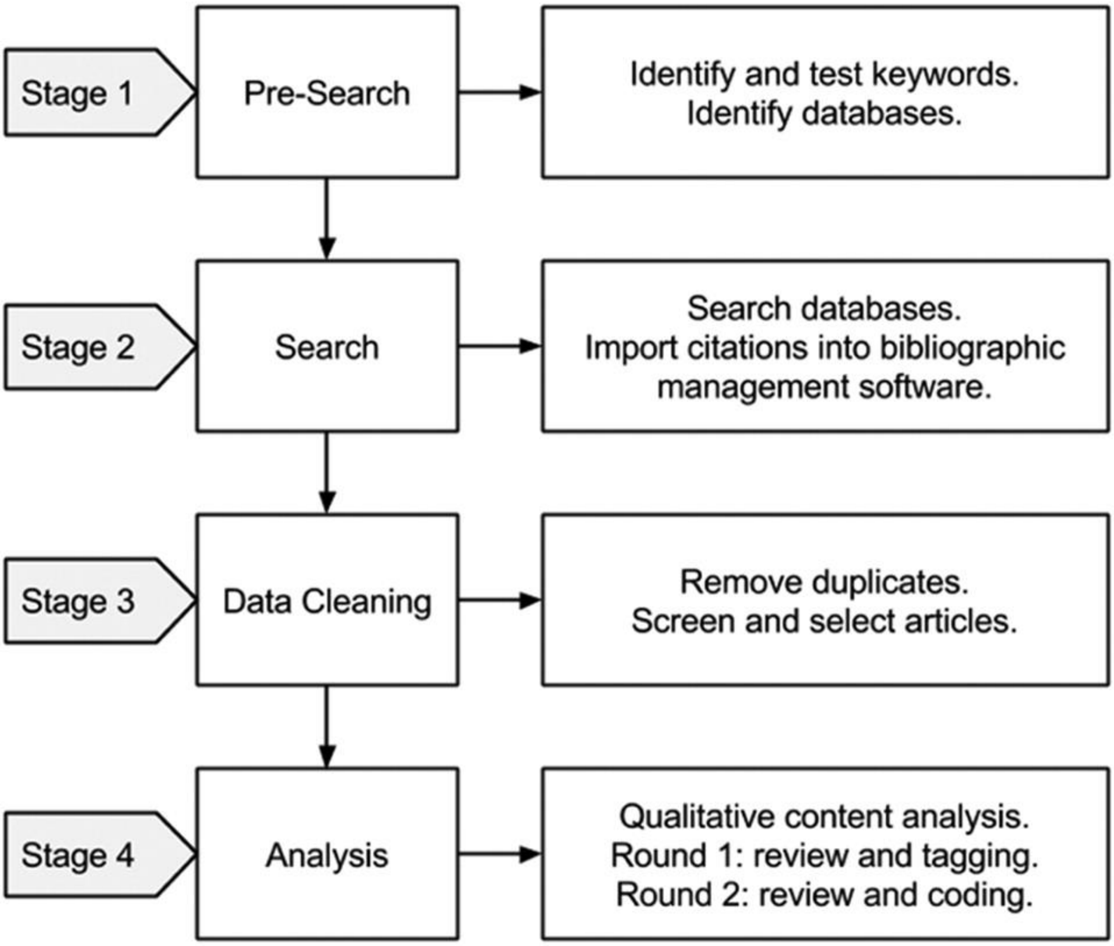

Figure 8: Stages in the literature review process (Snelson, 2016).

The identified research articles were checked against seven predetermined criteria for their eligibility. Each article included in the analysis conforms with the following criteria:

1. Published in or after 2008,
2. Published in English,
3. Published in a peer-reviewed journal,
4. Full text copy of the article is available,
5. Focuses on MASSs and the challenges related to their safety management,
6. Search terms were used in the setting/for the meaning they were intended, and

7. Is a non-duplicate study.

Following the screening of articles, a quality appraisal and a risk of bias assessment were conducted for each study included in the analysis. The methodological quality was critically appraised using a set of screening questions utilised by Gillman and Pillay (2018), which were in turn adapted from the Critical Appraisal Skills Programme (Critical Appraisal Skills Programme, 2018). The risk of bias assessment was conducted by manually assessing the risk of bias in three categories (Thomé et al., 2016).

I conducted the synthesis of results as a narrative synthesis. This was done according to guidance from Popay et al. (2006). It resulted in the use of words and phrases to summarise and explain the findings of the synthesis. The results are presented in Section 6.1.

The safety challenges for MASSs identified in the review were used as a point of departure for the remaining articles that form part of this thesis.

5.2. Methodology of the Second and Third Articles

The second and third articles forming part of this thesis were aimed to address Research Questions 2[10] and 3.[11] To answer Research Question 2, historic AIS speed data of conventional vessels would need to be both safe and legal. As discussed in Chapter 3 of this thesis, the concept of a "safe" speed is ontologically subjective. The legal standard was therefore applied to answer Research Question 2.

[10] Can historic data of conventional vessels be used as a reference for safe vessel behaviour? Could MASSs autonomously determine the safe speed in a given situation by utilising the historic AIS speed data of conventional vessels?

[11] How do factors such as visibility, wind, waves, and location affect the speeds of conventional vessels? Note that Article 2 only considers the relationship between visibility and vessel speeds.

5.2.1. Narrative Literature Review

To gain a clearer understanding of the legal standard for safe speed, a narrative literature review was conducted. Due to their advantage of being concise while finding the common ground in cited studies, this was done in the form of an integrative mini-review (Pautasso, 2019).

The structure of the integrative mini-review largely followed the conceptual diagram from Pautasso (2019) displayed in Figure 9 below.

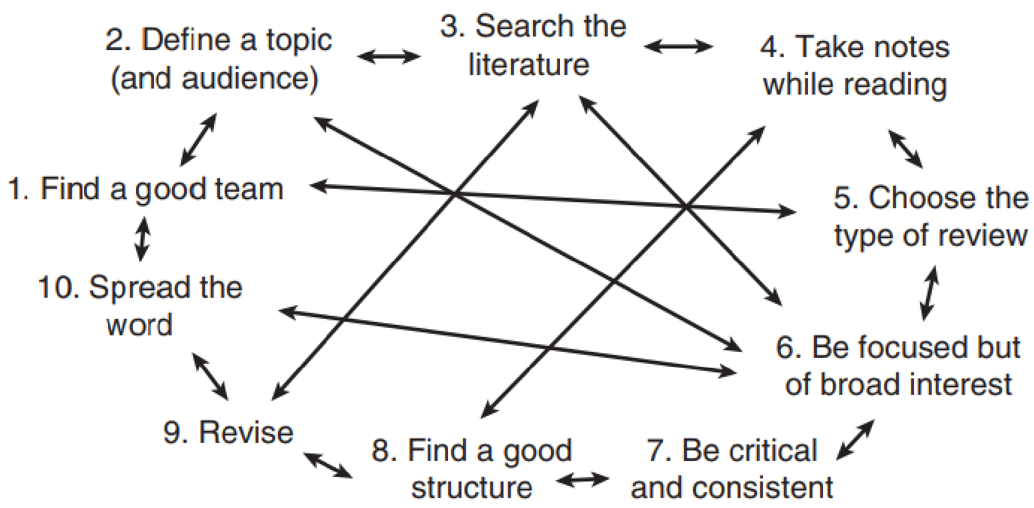

Figure 9: Conceptual diagram of the narrative literature review (Pautasso, 2019).

The outcome is an understanding that vessel speeds must adhere to a particular pattern that can be judged as safe from a legal standpoint. Historic AIS speed data must therefore follow this pattern to be used as a reference for safe vessel speeds.

5.2.2. Descriptive Statistics

Since it is difficult to make sense of a particular dataset without summarising its main characteristics in a meaningful way, measures of central tendency and dispersion were utilised for the collected data (McIntosh et al., 2010). These were, namely, reporting the mean and standard deviation for the different parts of the collected data.

The mean is algebraically denoted as follows:

$$mean\ (\bar{x}) = \frac{\sum x}{n} \qquad (1)$$

where $\sum x$ is used to denote the sum of all observations, and n is the total number of values. Simply put, it is the sum of all the values divided by the number of values.

The standard deviation is a single number that summarises the variability in a dataset by representing the typical distance between each data point and the mean (Frost, 2021). It is algebraically denoted as follows (McIntosh et al., 2010):

$$SD = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}} \qquad (2)$$

5.2.3. Regression Analysis

To ascertain whether the safe speed model uncovered in the narrative literature review fits with the AIS data collected from actual vessels, a regression analysis was accomplished. Regression analysis is the study of relationships between two or more variables and is usually conducted for the following reasons (McIntosh et al., 2010):

1. To determine whether any relationship between two or more variables actually exists,
2. To gain an understanding of the nature of the relationship between two or more variables, and
3. To predict a variable given the values of others.

Depending on the number of predictor variables available, regression analysis can either take the form of a simple linear regression (if there is only a single predictor variable in the model) or a multiple linear regression (when there is more than a single predictor value; Daniel, 2020). The equations for a simple linear regression (Equation 3) and a multiple linear regression (Equation 4) are provided below:

$$Y_i = \beta_0 + \beta_1 X_i \tag{3}$$

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2 X_i + \cdots + \beta_p X_p \tag{4}$$

Where Y is the dependent variable, X_i through X_p are the independent variables, β_0 is the Y intercept, and β_1 through β_p are the slope coefficients.

The regression analyses were conducted using the tools available in Microsoft Excel. When using this software, the output of the analysis is not limited to only providing the Y intercept and slope coefficient(s). It also provides statistics that are essential to understanding the result of the regression analysis and should therefore be reported as well (McIntosh et al., 2010; University of Calgary, n.d.). This includes the confidence interval, the F-statistic, the p-value, and the value of R2. These are briefly described below.

Confidence intervals are the range of plausible values that a variable may take in the real world (McIntosh et al., 2010). They are used to provide more information on how well the sample statistic estimates the underlying population value (NIST/SEMATECH, 2012).

The F-statistic indicates whether the linear regression model provides a better fit to the data than a generic model that does not contain any independent variables (Frost, 2017). Higher values for the F-statistic generally indicate that the independent variables included in the regression equation have improved the fit.

The p-value indicates whether there is a significant relationship between the dependent and independent variables of the regression equation. A low p-value indicates that the overall regression model fits the data better than a model with no predictor variables.

Finally, there is the R2 value, which is also known as the coefficient of determination. It is a number between 0 and 1 that measures how well a statistical model predicts an outcome. In the cases of Articles 2 and 3, it indicates the proportion of variance in the dependent variable that can be explained by the independent variable. If the coefficient of determination is high, observations are close to the model's prediction. In contrast, if the R2 value is low, observations are far from the model's prediction (Turney, 2022).

Since the result of a linear regression analysis is a straight line, it can only be used where a linear relationship between dependent and independent variables exists. It is therefore important to combine a regression analysis with the use of graphs, as these are useful when attempting to detect non-linearity between the dependent and independent variable(s) (Seltman, 2018).

5.2.4. Graphical Representation

A commonly used graphical method for revealing relationships or associations between two variables is the scatter plot. While the scatter plot uncovers some structured association between X and Y, any association does not necessarily imply causality (NIST/SEMATECH, 2012).

In practice, a scatter plot is a plot of the values of Y versus the corresponding values of X. This can be used to provide answers to the following questions (NIST/SEMATECH, 2012):

1. Are variables X and Y related?
2. Are variables X and Y linearly related?
3. Are variables X and Y non-linearly related?
4. Does the variation in Y change depending on X?
5. Are there outliers?

Some examples of scatter plots are provided in Figure 10 below:

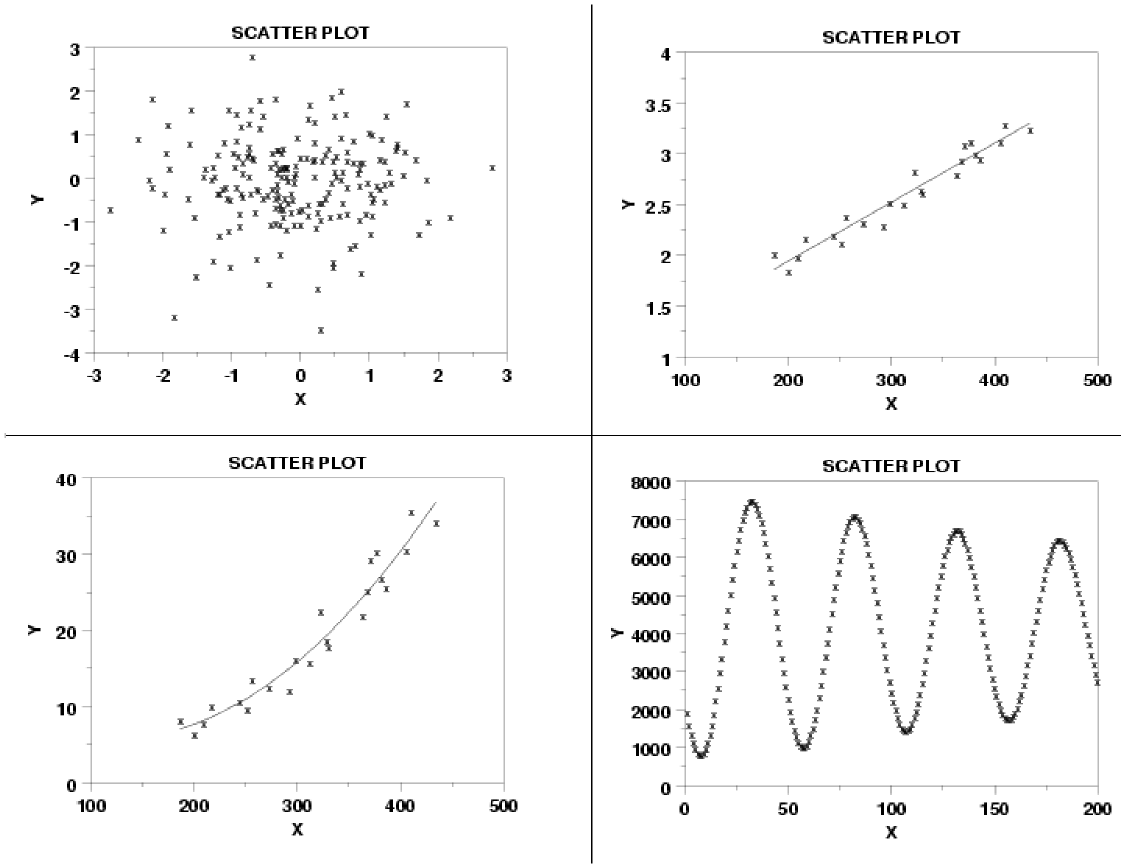

Figure 10: Examples of different scatter plots (NIST/SEMATECH, 2012).

The scatter plots depicted in Figure 10 above are examples for the following:

- Top left: No relationship,
- Top right: Strong, linear, and positive relationship,
- Bottom left: Quadratic relationship, and
- Bottom right: Sinusoidal relationship.

As it turned out, the scatter plots created from the collected data were not as easily interpreted as the examples provided above. As a result, they were supplemented by another graph. To create this graph, the X-axis was divided into several smaller segments, and the average speeds in those segments were calculated. This was then used to create a line graph that represents the average – or mean – vessel speeds in the different X-axis segments. This graph is useful for interpreting the data visualised in the scatter plots.

5.2.5. Statistical Testing for Differences: The T-Test

Research Question 3[12] required studying the effect of location on the speeds of conventional vessels. This was done by comparing the speeds in two different locations: offshore and inshore. As it is one of the most common statistical tests for examining the differences in the means between two populations, the t-test was utilised for this purpose (McIntosh et al., 2010).

The t-test statistical test involves the calculation of the following:

$$t = \frac{Observed\ difference\ in\ means}{Standard\ error\ of\ the\ observed\ difference} \tag{5}$$

T becomes larger – and is more likely to be significant – as the difference in means increases or when the standard error decreases (McIntosh et al., 2010). The practical value of the t-test is its ability to statistically determine if the two population means are significantly different from one another (NIST/SEMATECH, 2012).

5.3. Methodology of the Fourth Article

The fourth and last article that forms part of this thesis is concerned with answering Research Question 4.[13] Since qualitative research can attend to the contextual richness of how people function in their real-world settings (Yin, 2015), this approach was chosen to complement the more quantitative approach followed in Articles 2 and 3.

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[12] How do factors such as visibility, wind, waves, and location affect the speeds of conventional vessels?

[13] How do human navigators interpret Rule 6 of the COLREGs covering the requirement to proceed at a safe speed?

A researcher can gain an inside view of why people behave in the way they do and better understand their thought processes by conducting an interview (Stuckey, 2013). A main advantage of this method is that, instead of forcing participants to choose among fixed responses, it offers them the opportunity to respond in their own words (Mack et al., 2005). This requires the interviewer to listen carefully to what the participants say, engage with them in an individual way, and encourage them to elaborate on their answers (Stuckey, 2013). While the conversational mode employed when conducting interviews somewhat resembles normal conversation, several important differences exist. Key aspects of the conversational mode that must be followed by the interviewer include the requirement to speak in modest amounts, the practice of being nondirective, the necessity of staying neutral, and the interpersonal manner of maintaining rapport (Yin, 2015).

Interview styles and methods vary widely, but the three most common types are structured, semi-structured, and unstructured interviews (George, 2022). Structured interviews follow a specific set of questions in a predetermined order that limits the number of response categories (Denzin & Lincoln, 2008); they have questions that are often closed-ended (George, 2022). While structured interviews can mitigate research bias and provoke higher reliability and validity, the overly formal approach was considered not to be most advantageous for the research question at hand. Unstructured interviews, however, are characterised by not having pre-determined questions (George, 2022). While the flexibility of this method can be seen as an advantage for gaining detailed information on a topic, the risk of asking leading questions and soliciting biased responses meant that this approach was also not chosen for the fourth article. The semi-structured interview can be seen as drawing from both of the previously mentioned types to create a method that is flexible but also follows a predetermined framework to support order (George, 2022). As such, it is the most commonly used type of interview in qualitative research (Stuckey, 2013). This approach requires the drafting of an interview guide, which provides a clear set of instructions that can provide reliable, comparable qualitative data (Stuckey, 2013). Important questions are open-ended, where the researcher encourages participants to use their own words and not the researcher's terminology (Yin, 2015). The different individual responses provided by different participants determine the direction each interview takes. This means that participants do not need to answer the questions prepared in the interview guide in any particular order and that discussion can diverge from the interview guide (Stuckey, 2013).

Having decided on the interview methodology, the design process then shifted focus towards choices regarding sampling. To ensure that participants in the study would yield the most relevant and plentiful data, purposive sampling techniques were employed. Since the focus is on seafarers, homogeneous sampling based on one's professional background was utilised. Furthermore, due to the inherent difficulties in recruiting navigators who are available to be interviewed, the participants represent a convenience sample, recruited with the help of a maritime training facility and the administration of the Norwegian maritime pilots. This has drawbacks in terms of the sample not being a representative sample and possibly being biased, which were considered when evaluating the results of this study (Yin, 2015).

While there is no definitive formula defining the minimum number of interviews to be conducted in a given study (Yin, 2015), the question of how many participants to recruit was important when designing the methodology of the fourth research article. An important consideration here is that, while quantitative research seeks to create a sample that represents a larger population, qualitative studies aim to maximise information without reference to any larger population (Yin, 2015). As a result, the concept of saturation is often mentioned as the most important factor to be considered when deciding on sample sizes in qualitative research (Dworkin, 2012). Saturation is achieved "when gathering fresh data no longer sparks new theoretical insights, nor reveals new properties of your core theoretical categories" (Charmaz, 2014, p. 113, p. 113). Following the eight semi-structured interviews that were conducted, saturation was considered to have been achieved.

The data analysis conducted following the completion of the interviews is described in the fourth article as follows: “The data collected in this study was analysed by means of systematic text condensation (Malterud, 2012). The approach is described as a four-step procedure: (1) reading the transcripts to get an overall impression and identifying preliminary themes; (2) extracting meaning units from the transcripts and sorting them into codes and code groups; (3) condensing the meaning within each code group; (4) summarizing the content into meaningful descriptions (Hagen et al., 2017; Malterud, 2012). The author conducted all steps of the analysis. In this regard it must be noted that the author’s background as a navigational watch officer with knowledge and experience within the field has influenced the process of collecting and interpreting data. As the final descriptions were developed and refined over time, the interview transcripts were read repeatedly to ensure that the constructed descriptions were grounded in the empirical data.”

In line with the recommendations by Stuckey (2013), the semi-structured interviews were conducted only after I had developed a keen understanding of the topic of interest – in this case, the last article of this thesis. Interviews were conducted individually, without disturbance, at a time and place most comfortable for the interviewees.

5.4. Research Quality

It must be possible to judge research regarding its quality. While there are accepted criteria for evaluating the research quality of both quantitative and qualitative research, there are currently no accepted criteria for judging the quality of mixed-methods research (O'Cathain, 2010).

The traditional way of evaluating the quality of research has emerged out of quantitative traditions (Sommer, 2015). Quantitative research is usually judged on criteria such as validity, reliability, replicability, and generalisability (O'Cathain, 2010). Agreeing on quality criteria for qualitative research has historically been more contentious. Some researchers have simply adopted the quantitative criteria, some have developed new criteria,[14] and others have rejected the idea that the quality of qualitative research can be judged based on predetermined criteria entirely (O'Cathain, 2010).

In the absence of a definitive approach for judging research quality in mixed-method studies, the following provides an overview of two considerations that are presented as important by Tashakkori and Teddlie (2008), who have been described as the two leading scholars in the field of mixed-method research quality assessment (O'Cathain, 2010). The mentioned considerations are the quality of the design (design quality) and the quality of the interpretations (interpretative rigour; Tashakkori & Teddlie, 2008).

Design quality refers to the degree to which the most appropriate procedures for answering the research question(s) have been utilised and implemented. Four terms are important in this regard: design suitability, design adequacy/fidelity, design consistency, and analytic adequacy. *Design suitability* refers to how adequately and appropriately the research question(s) were translated into the elements of the design. For this study, I attended a course on mixed-method methodology and utilised the knowledge gained during this course to actively search for and implement the most appropriate research design to answer the different research questions of this thesis.

Design adequacy or *fidelity* is a term that is important with regard to judging whether the components of the research design have been implemented adequately. It refers to the degree to which procedures were strong enough to create the expected effect. Concerning this thesis, the procedures employed in all four articles created the expected effect: the literature review highlighted safety issues related to MASSs, the AIS articles provided insight on the speeds conventional vessels proceed with under different circumstances, and the semi-

[14] These quality criteria include credibility, confirmability, transferability, dependability, transparency, relevance to others, and reflexivity.

structured interviews designed for the fourth article created the desired effect of gaining a deeper understanding of the tacit knowledge of Norwegian navigators.

Design consistency refers to how well the components of the design fit together in a seamless and cohesive manner. In this thesis, the design of the different articles was chosen so the articles would complement and build on one another.

Finally, *analytical adequacy* refers to the degree to which the data analysis techniques are appropriate and adequate for answering the research question(s). In this thesis, different analytic techniques were employed in each article, and these were chosen with the goal of being the most suitable for answering the research question(s). The consideration of design quality in this research is revealed in the descriptions of the different research methodologies employed in the study.

Interpretive rigour refers to the degree to which credible interpretations have been made on the basis of the obtained results. Five criteria – or standards – must be met to achieve such rigour. These are interpretive consistency, theoretical consistency, interpretive agreement, interpretive distinctiveness, and integrative efficacy. *Interpretive consistency* investigates whether the conclusion closely follows the findings and if multiple conclusions based on the same results agree with one another. Interpretive consistency requires the type of inference to be consistent with the type of evidence and that the level of intensity reported is consistent with the magnitude of the effects that were determined. In this thesis, interpretations of the research results were worded carefully to avoid drawing strong conclusions based on limited evidence. Instead, the conclusion section in each article is preceded by a discussion section, where the strengths, weaknesses, and importance of the findings are discussed. Furthermore, especially with Articles 2 and 3, care was taken not to confuse correlation with causation.

Theoretical consistency refers to how consistent each inference is with the current theories in the academic field. In this thesis, different relevant (i.e. contemporary) theories of the field are presented. Where the data indicates a divergence between the results of the second and third articles and contemporary legal understandings, relevant safety management theories are presented to explain the observed divergence.

Interpretive agreement refers to the agreement of the individuals making the conclusions. An important aspect is the extent to which other scholars would reach the same conclusions on the basis of the results of the study. This is a delicate criterion for this thesis, as most of the research was conducted by only one researcher. However, control mechanisms were enacted. Formally, these include the oversight of two independent supervisors and the peer-review process that the articles went through. Informally, they include the discussions I had with other researchers, instructors, and practitioners.

Interpretive distinctiveness refers to whether each conclusion reached in a research project is clearly different and more defensible than other plausible conclusions. In the research conducted in this thesis, this was addressed in the discussion sections of the different articles, where the strengths and weaknesses of the reached conclusions are highlighted.

Finally, *integrative efficacy* is the degree to which the findings and conclusions from each of the applied research methods are integrated. In this regard, integration does not necessarily mean the creation of a single understanding on the basis of the results. Instead, it incorporates concepts such as elaboration, completeness, contrast, and comparison. Consistency between two sets of inferences derived from qualitative and quantitative strands is widely considered an indicator of quality in mixed-methods research.

In this thesis, Articles 2 and 3 uncover the speeds at which vessels proceed in different situations. The quantitative methods employed revealed that vessels do not follow a simplified, legal pattern. This was corroborated by the qualitative findings of Article 4, which highlight the more complicated nature of how vessel speeds are set. This can be interpreted as a sign of the integrative efficacy of the research conducted in this thesis.

5.5. Research Ethics

Research ethics contribute to fostering good scientific practice and are therefore useful in promoting free, reliable, and responsible research (NESH, 2022). To comply with ethical research standards, the Norwegian Centre for Research Data has received and approved notification of this PhD project.

Participants who were interviewed as part of the fourth research article received an information letter and provided consent to participate. Information was shared regarding each participant's option to withdraw from the study at any time without providing any reason (until publication). Responses provided by the interview participants have been treated confidentially, were only used for the purposes for which they were collected, and are presented in such a way that identification of individual participants is not possible.

5.6. Final Reflections on Research Approach

This thesis has evolved and progressed over a number of years. Throughout the journey – from the initial literature review scoping out safety challenges that need addressing to the final interviews designed to provide a clearer understanding of the tacit knowledge on safe speed that navigators have, my own understanding of the issues surrounding MASSs, safe speed, and research at large has steadily developed. However, my background as a navigational watch officer has typically played a part in how I understand the topic and may therefore be a source of bias that could have had an effect on how I approached, conducted, and analysed the research.

Practical issues have had their effects on how this research was approached. These include extreme issues, such as the onset of a pandemic in the middle of the research. Data collection can therefore be seen as somewhat chronologically divided. While this divide may not have been planned initially, it does not need to be a disadvantage from a methodological perspective. Having a moderate amount of time pass between different data collection periods provides a researcher with the necessary time to reflect on the previously collected data, develop knowledge within the field, and keep in touch with the academic world (Fangen, 2010; Sommer, 2015; Wulff, 2002).

Indeed, the time that passed between the different articles ended up being useful for me. My understanding and knowledge of the subject matter gradually increased as I alternated between the different tasks that are so important in research: reading the literature, discussing with other researchers, exploring different study designs, running trials, collecting data, analysing data, writing articles, and presenting the findings, to name a few.

While I would not quite call it triangulation, making use of different research methodologies has provided a nuanced view on the topic of MASSs and safe speed. The initial literature review provides a strong foundation, and the following AIS and interview articles provide further insight that was used to map out the problem at hand. A challenge has been providing a concrete solution to the problem highlighted in this thesis. I am unsure if this would have been possible given a different research approach.

Chapter 6.

Research Results

> The scientific man does not aim at an immediate result. [...] His duty is to lay the foundation for those who are to come, and point the way.
>
> *Nikola Tesla*

This chapter provides a summary of each article that forms part of this thesis. The summary includes the objective, the applied method, the main results, and the conclusions. For more detailed information on each article, please refer to the appended articles.

6.1. Summary and Results of Article 1

Dreyer, L. O., & Oltedal, H. A. (2019). *Safety Challenges for Maritime Autonomous Surface Ships: A Systematic Review*. Paper presented at Ergoship 2019 Conference, Haugesund, Norway. http://hdl.handle.net/11250/2638416

The objective of Article 1 was to systematically review peer-reviewed journal articles to collect all safety challenges for merchant MASSs identified therein.

Furthermore, an objective not stated in the article itself was to use the results to set the direction for the remainder of the research conducted in this thesis.

To reach this objective, a systematic literature review was employed as the method. The systematic literature review was designed using the PRISMA statement as a guideline and used four databases as data sources. While 943 records were identified through database searching, only 14 studies were included in the qualitative synthesis after the completion of the selection process. The qualitative synthesis was conducted in the form of a narrative synthesis, where the outcomes of the different included studies are presented as categories of themes with explanations.

The main result of the review is the identification of three main groups of challenges. These are technological challenges, human factors, and procedural challenges, each having several sub-groups, as presented in Table 2 below.

Table 2: Main groups of identified challenges with sub-groups.

Main Groups	**Sub-Groups**
Technological	1. Hardware 1.1. Sensors 1.2. Communication 1.3. Fire Safety 1.4. Mooring 2. Software 2.1. Decision System 2.2. Software Errors 2.3. Cyber Security

Main Groups	Sub-Groups
Human Factor	1. Training 2. Effect of Technology on Human Operator 3. Human Centred System Design 3.1. Migration of Workplace 3.2. Presentation of Data
Procedural	1. Undesirable Events 1.1. Anticipated 1.2. Unanticipated 2. Standard Operations 2.1. Navigation 2.2. Maintenance 2.3. Cargo Care 2.4. Risk Assessment 2.5. Safety Controls 2.6. Absence of Regulations

Challenges related to technological sub-group 2.1 Decision System have guided the direction of the remainder of the research conducted as part of this thesis. In this regard, the systematic literature review identified two major challenges, namely the ability of MASSs to avoid collisions with other traffic in accordance with the COLREGs and their ability to avoid and react to unfavourable weather conditions.

Results demonstrate that the loss of the foresight of a human navigator would cause serious problems for COLREGs-compliant MASS operations and that smart methods and criteria that could ensure COLREGs compliance by MASS are an issue that requires more research. Indeed, the issue of avoiding collisions regardless of whether other vessels in the vicinity of the MASS follow the COLREGs has been mentioned as a special concern.

When it comes to reacting to unfavourable weather conditions, the results of Article 1 reveal that more work is required in identifying potentially dangerous situations during the voyage. More work is also required to ensure that the MASS reacts by executing suitable mitigating actions, such as changing course and/or speed.

Importantly, the literature review demonstrates that these two challenges cannot be solved independently but require a holistic approach. As autonomous ships will be required to adhere to the requirements of the COLREGs and because Article 1 highlights that no method is available to allow MASSs to autonomously comply with the requirements of the COLREGs, this challenge has shaped the research conducted in the remaining articles of this thesis.

6.2. Summary and Results of Article 2

Dreyer, L. O. (2021). Safe Speed for Maritime Autonomous Surface Ships – The Use of Automatic Identification System Data. Paper presented at European Safety and Reliability Conference, Angers, France. https://rpsonline.com.sg/proceedings/9789811820168/pdf/200.pdf

Based on the challenge of ensuring MASS compliance with the COLREGs – specifically the requirement to proceed at a safe speed – identified in the first article, the second article provides investigation into one possible method of tackling said challenge. Previous research has revealed the possibilities of utilising historic AIS data as a database for teaching AI safe behaviours. The objective of the second article was therefore to investigate if MASS can determine the safe speed without human support by utilising historic AIS speed data from other vessels.

A mixed-methods approach was applied, with the article starting with a narrative literature review to provide a more advantageous understanding of the legal concept of safe speed and how vessel speeds would need to change in different visibility conditions in order to be deemed safe. The AIS and visibility data was then collected and merged,[15] and a simple linear regression was calculated and supplemented by two graphical methods for revealing relationships between two variables.

The results of the narrative literature review revealed that visibility is seen as one of the major factors – if not the major factor – to influence safe speed in a given situation. For the vessel speeds collected via AIS to be considered safe, the following standards would have to be met:

1. There must be a strong relationship between visibility and vessel speeds, and
2. Vessel speeds must be significantly reduced in restricted visibility.

The result of the AIS and visibility data analysis demonstrates that transit speeds through the study area were generally close to being normally distributed (Figure 11).

The regression analysis found a significant regression equation[16] where the predicted average speed $Y = 9.8 + 0.08\ X_1$, where Y is measured in knots, and X_1 is the meteorological optical range[17] (visibility) measured in kilometres. However, this equation only had an R^2 value of 0.033, indicating that only 3.3% of the speed variation in the dataset can be explained by changes in visibility. Furthermore, with a β_1 value of only 0.08, the regression equation predicts a

[15] Providing a dataset of 14,420 unique vessel transits.

[16] $F\ (1, 14418) = 489.647$, $p < 0.0001$

[17] Meteorological optical range is an objective measurement of the transparency of the atmosphere. World Meteorological Organization. (2018). Measurement of Visibility. In *Guide to Instruments and Methods of Observation* (Vol. 1, pp. 315-336). https://library.wmo.int/doc_num.php?explnum_id=10179

reduction in speed of just 0.7 knots when visibility deteriorates from good to very poor.[18]

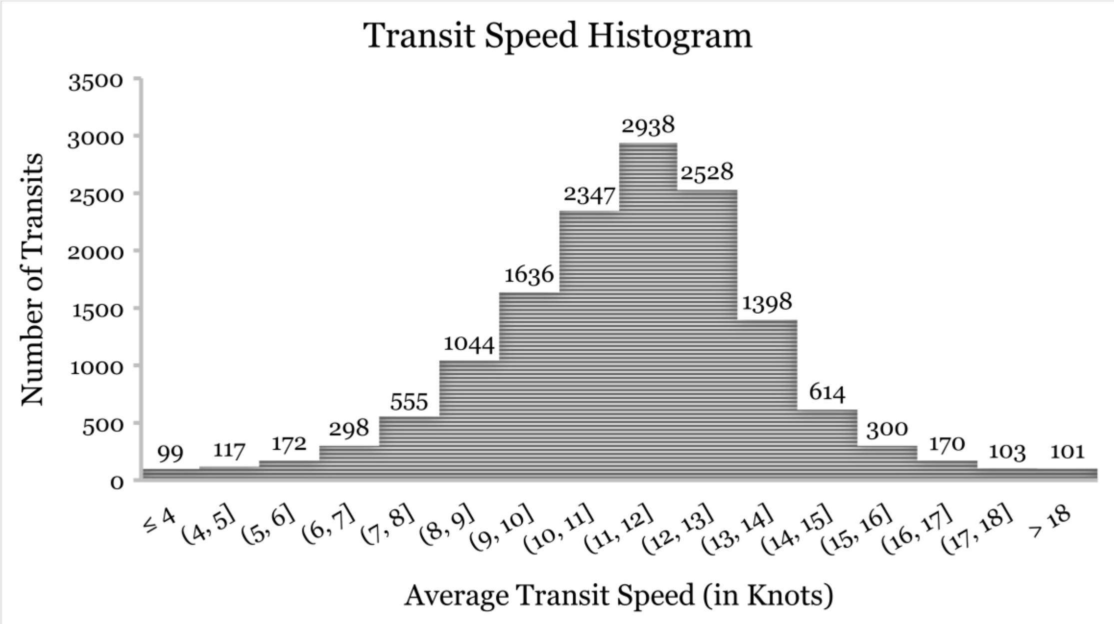

Figure 11: Transit speed histogram. Number on top of each bar represents the total number of transits at different average speeds.

The relationship between visibility and vessel speeds collected via AIS can perhaps be better understood by observing the two graphical methods utilised in Article 2. The first one is the scatter plot (Figure 12), which reveals no clear relationship between visibility and speed. The second graphical model is a graph presenting the average transit speeds in different visibility ranges (Figure 13), which reveals that the average transit speeds of vessels proceeding in very poor visibility conditions were higher than those of any other visibility range.

The conclusions drawn from Article 2 are that no strong relationship was found between visibility and the recorded vessel speeds. Furthermore, instead of

[18] According to the classifications of the national meteorological service of the United Kingdom. Met Office. (2021). *Marine forecasts glossary*. Retrieved 24/02/2021 from https://www.metoffice.gov.uk/weather/guides/coast-and-sea/glossary

revealing a trend of reduced speed in restricted visibility, the AIS data actually demonstrates that the average vessel speeds in the worst visibility conditions were higher than the average vessel speeds in any other visibility range.

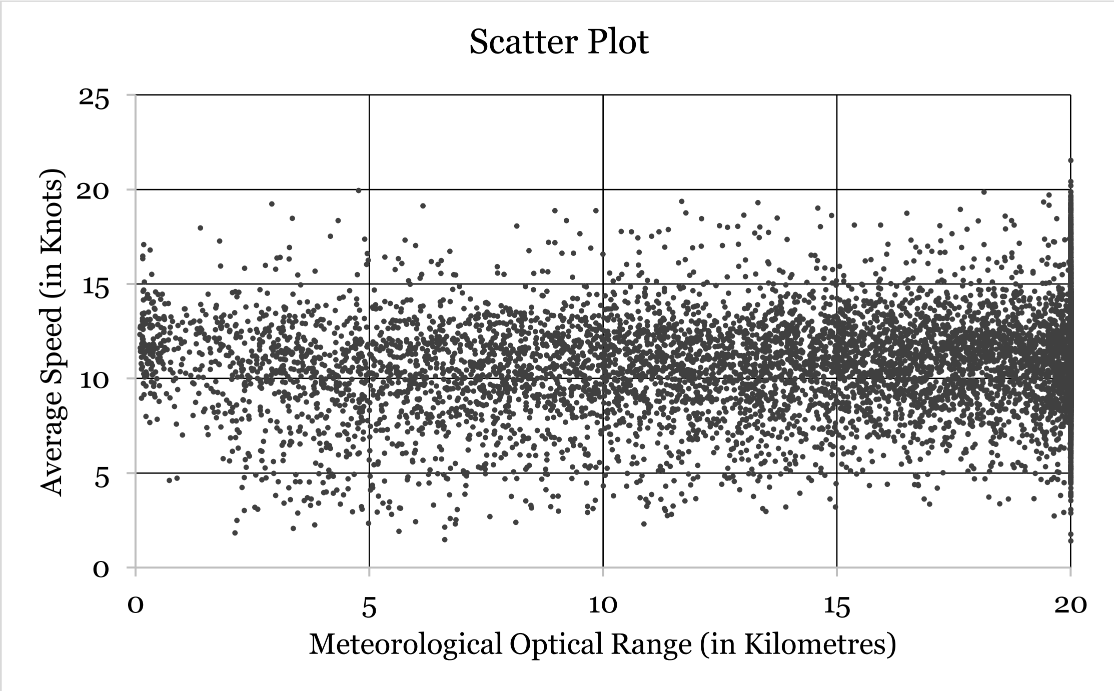

Figure 12: Scatter plot. The different dots represent the average speeds and visibility for each transit.

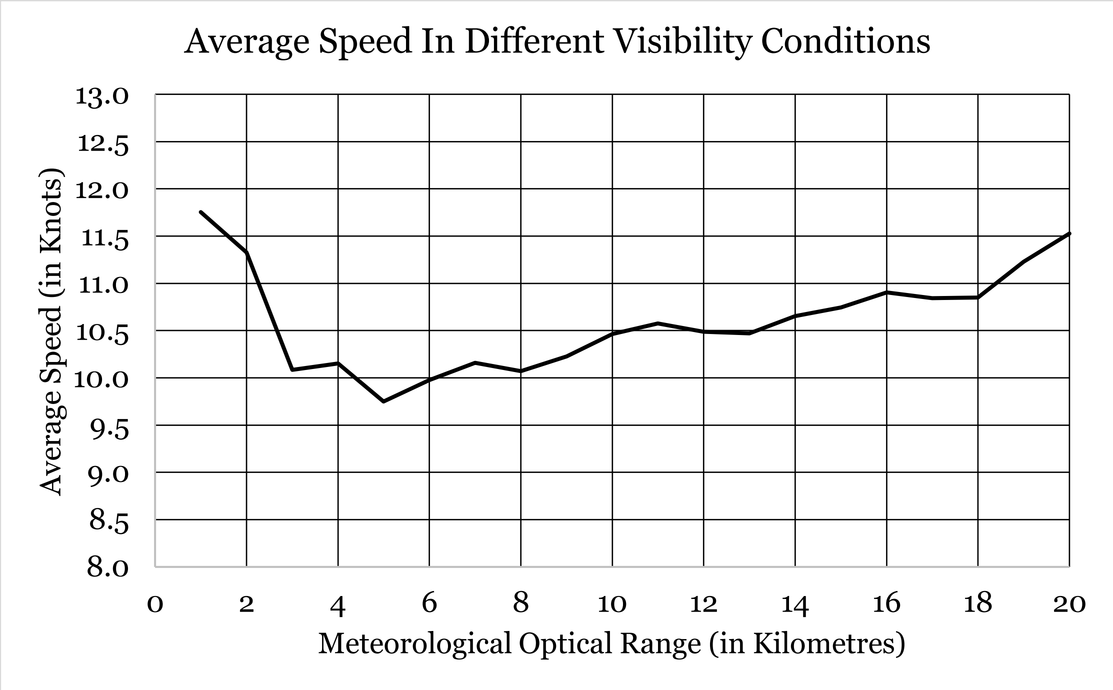

Figure 13: Graph showing the average transit speeds in different visibility ranges.

Article 2 therefore highlights that the problem of quantifying the safe speed of a vessel in different conditions is not easily solvable by simply relying on historic AIS data to teach the AI that steers future MASSs.

6.3. Summary and Results of Article 3

Dreyer, L. O. (2023). Relation analysis of ship speed & environmental conditions: Can historic AIS data form a baseline for autonomous determination of safe speed? *The Journal of Navigation*, 1-35. https://doi.org/10.1017/S0373463323000127.

One of the findings of Article 2 – the fact that average speeds were highest in the worst visibility situation – lies in direct opposition with the current understanding of safe speed. With the data used in the research, the article was not able to provide reasoning for this phenomenon. However, the possible influence of other factors – such as wind and waves – was seen as a possible explanation to warrant further research.

Following the publication of Article 2, I was contacted regarding research questions that were not answered in Article 2 and which would be of interest to investigate in future articles. While the data in Article 2 came from a well-structured offshore traffic area, interest was being voiced in how vessel speeds behave in less structured coastal waters. The interest in how wind and waves affect vessel speeds was also shared via the academic correspondence that followed publication of Article 2.

The overall objective of Article 3 was similar to that of Article 2 (i.e. to investigate if AIS vessel speed data collected from conventional ships in various external environmental conditions can be assumed to resemble safe speeds and can therefore be used for training MASS intelligence). However, Article 3 expanded on the findings of Article 2 by including a second data collection area in coastal waters and including wind and wave data in the analysis. Specific research questions Article 3 aimed to answer are as follows:

1. What are the relationships between vessel speeds and visibility, wind, and waves in coastal waters[19] and in the open ocean?[20]
2. Do the observed speeds qualify as safe speeds under contemporary theoretical understandings of safe speed?

The methods employed are largely similar to those utilised in Article 2, with Article 3 expanding the narrative literature review and including both multiple

[19] This was called the Sotra Bridge study area.

[20] This was called the Gjøa A study area.

linear regressions and the t-test for statistical testing for differences for a dataset comprising a total of 47,490 unique vessel transits.

The results of the expanded narrative literature review demonstrate that the association between safe vessel speeds and the state of the wind and sea is not transparent. The importance of the state of the wind and sea is generally seen as less than that of the state of visibility.

Average vessel speeds in different visibility conditions were seen to be more constant in coastal waters (Figure 14). This means that, unlike what was observed in open waters, vessel speeds were not observed to be increasing in very poor conditions in coastal waters. This also means that the regression equation with average speed as the dependent variable and visibility as the independent variable explained 0.0% of the variation of vessel speeds in coastal waters. Therefore, there was no evidence supporting the proposition that vessel speeds would reveal a stronger correlation with visibility in an ill-structured coastal waterway.

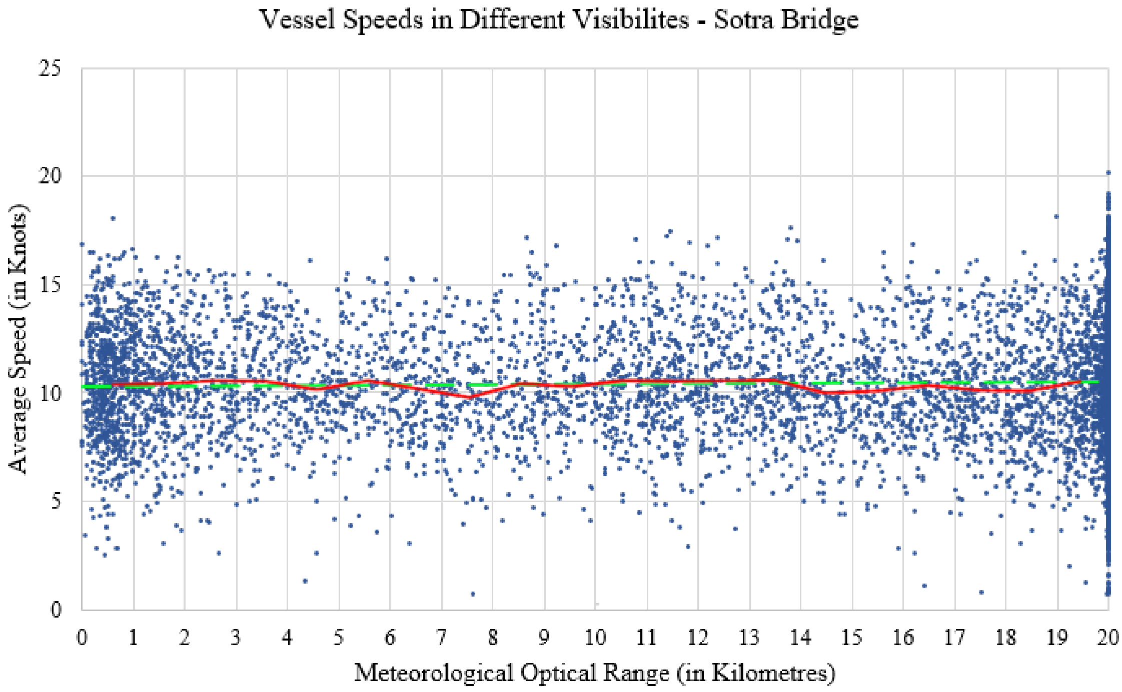

Figure 14: Speed/visibility scatter plot. The different dots represent the average speeds and visibilities for each transit through the coastal waters (Sotra Bridge) study area. The red line represents the average transit speeds through the area in different visibility ranges. The dashed green line represents the result of the regression equation.

Concerning the effect of wind and waves, their influence was starkly different in the two study areas. While wind had virtually no influence on average vessel speeds in coastal waters, the data reveals that average transit speeds in open waters decreased as waves got larger and winds picked up.

The simple linear regressions conducted for the open waters study area demonstrate that the R2 values for wave (9.5%) and wind (9.7%) are much higher than the R2 value for visibility (3.3%). The multiple linear regression combining all three factors had an R2 value of 13.1%. The R2 value for all regression analyses completed for the coastal waters area was 0.0%, indicating that no variation in average speed in the coastal waters area can be explained by variations in visibility or mean wind speed.

In an effort to explain the increase in average transit speeds in poor visibility in open waters, Article 3 provides a line graph presenting the average wind speed, wave height, and transit speed in different visibility conditions (Figure 15).

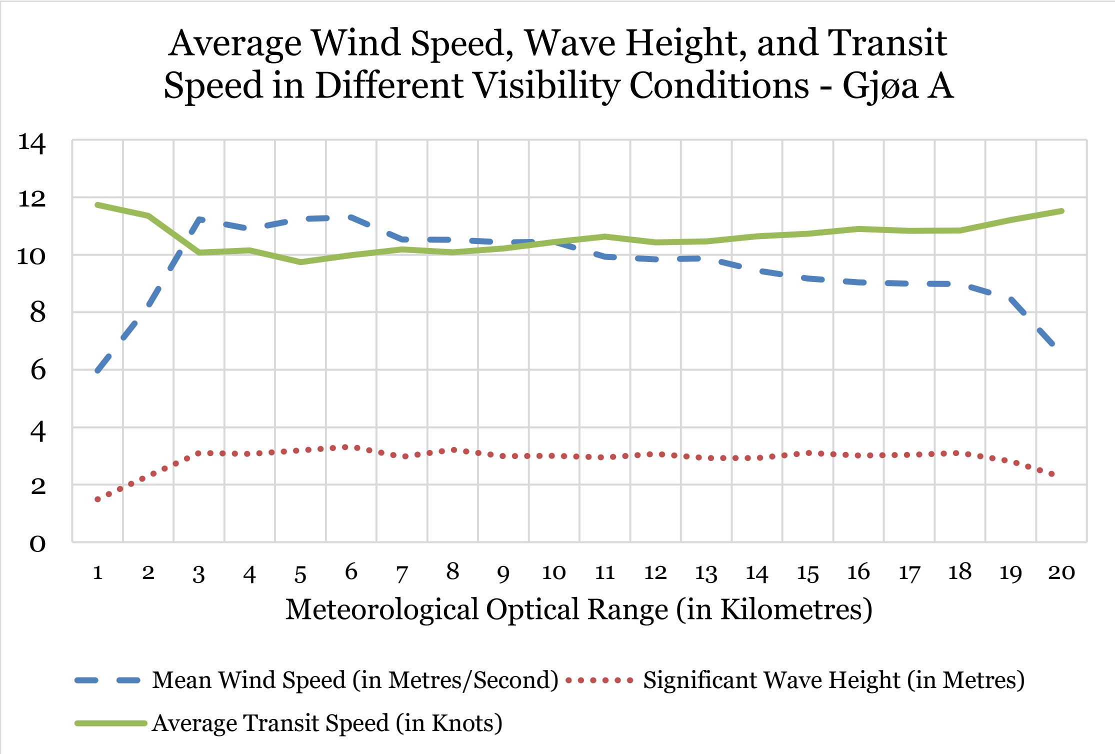

Figure 15: Line graph showing the average wind speed, wave height, and transit speed in different visibility conditions for the Gjøa A study area.

The graph reveals that the mean wind speeds and average significant wave heights recorded for transits that occurred in visibilities between 0 and 1,000 metres were approximately 50% lower than those recorded for transits that occurred in visibilities between 2,000 and 3,000 metres. This means that there is evidence that the increase in average vessel speeds observed in poor visibility in the open waters study area could be attributed to changes in the state of the wind and waves.

Finally, Article 3 indicates that the average transit speed in the coastal water study area (10.5 knots) was 0.7 knots lower than the average transit speed in the open water study area (11.2 knots). A concrete explanation for this difference was not determined.

The article concludes that vessel speeds do not behave as anticipated by our contemporary understanding of safe vessel speeds. The low R2 values observed indicate that there must be other, more influential factors affecting the speeds of vessels and that there may be a combination of effects that are not yet fully understood.

It is unclear if the results demonstrate that speed data collected from historic AIS data does not represent safe speeds in all conditions or if the contemporary understanding of what constitutes a safe speed is flawed. It is thus necessary to conduct more research towards gaining a deeper understanding of what constitutes safe vessel speeds.

6.4. Summary and Results of Article 4

Dreyer L. O. (2023). Safe Vessel Operations – The Tacit Knowledge of Navigators. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, 17(3)*, 579-586. http://doi.org/10.12716/1001.17.03.09

Article 1 concludes that a major challenge for MASSs is their ability to be compliant with the COLREGs, specifically with regard to the autonomous determination of safe speeds. Articles 2 and 3 reveal that this challenge cannot be solved by simply utilising historic AIS data to create a model of normalcy that MASSs can follow. Safe speed is a concept that is difficult to put your finger on.

To make progress on the issue, it was considered necessary to gain a better understanding of the conventional way navigators apply the COLREGs – and the requirement to proceed at a safe speed – in practice.

To achieve this objective, a qualitative study was designed based on interviews with a convenience sample of eight Norwegian navigators. The collected data was analysed using systemic text condensation.

The first important result of Article 4 is that navigators consider “safe speed” to be a juridical term that is disconnected from the conventional way seafarers determine safe speed in practice. Navigators recognise the term as being unclear but see this lack of clarity as a way to give navigators some leeway to navigate in a way that is most comfortable to them.

The study highlights that “the real-world problem of determining safe speed is too complex to be adequately captured by overly simplistic descriptions”. Safe speed is determined within a context that is often confused and complicated. Ranking different factors that influence safe vessel speeds by importance therefore makes little sense, as everything depends on the specific circumstances of the situation. Navigators stated that they do not determine safe speed by following Rule 6 of the COLREGs word for word but instead interpret it as a goal-based rule. A speed is considered to be safe when the navigator feels both comfortable with the ship and in control of the situation.

An important finding of the article is that safe vessel speeds refer to being in control not only in the current situation but also in the foreseeable future. Navigators are aware of situations where a change in speed does not affect the safety of navigation in the present but has an impact on the safety of navigation in the future. This means that taking a snapshot of a situation and determining the safe speed from this is not sufficient. The safe speed for a vessel proceeding in open waters and good conditions might be different depending on what the foreseeable future looks like. In this regard, participants in Article 4 mentioned that they would reduce speed in open waters in good conditions to avoid meeting other vessels in confined waters with possibly less favourable conditions.

While a reduction in speed was mentioned in that example, Article 4 highlights that a reduction in speed does not automatically make a speed safer. Indeed, as vessels generally lose their ability to manoeuvre when speed is reduced below a certain level, a reduction in speed may end up making the speed unsafe.

Finally, the navigators indicated that an important aspect of proceeding at a safe speed is being predictable. Navigators want to avoid creating the wrong signals, or signals that can be misunderstood, at all times. Vessel speeds should therefore follow the unwritten convention used by seafarers to determine safe vessel speeds.

Article 4 demonstrates – just like Articles 2 and 3 before it – that there is a gap between the work done by navigators and the work imagined by theorists and legal scholars on the topic of safe speed. While legal scholars conclude that it is unsafe to proceed at high speeds in low visibility, navigators have no problem proceeding through fog at high speeds, given that they are in open waters with no other traffic around. This misalignment of work as done and work as imagined can create serious challenges and risks at the sharp end of real operations. This highlights that determining the safe speed of a vessel is more complicated than is portrayed in the literature. Since MASSs will have to collaborate with conventional vessels for at least the foreseeable future, it is important that the control systems of MASSs are not programmed with only work as imagined in mind but that the work as done in practice is also considered.

Chapter 7.

Conclusions

Don’t raise your voice,
improve your argument.

Desmond Tutu

This is the final chapter of this thesis. It starts by highlighting how the different articles appended to this thesis fulfil the objectives and research questions of the thesis. It continues by presenting the main contributions of this thesis and some of the main research limitations. The chapter ends with recommendations for future research.

7.1. Fulfilment of Objectives and Research Questions

The objective of this thesis was to first identify which safety challenges exist for MASSs and then undertake an academic endeavour towards solving one of the identified safety challenges. In this regard, four research questions were established. The level to which these research questions were satisfied is indicated in Table 3 on the next page by the number of + symbols, with ++ indicating complete satisfaction.

Table 3: Level to which the research questions were satisfied in each of the appended articles.

	RQ 1	**RQ 2**	**RQ 3**	**RQ 4**
Article 1	++			
Article 2		++	++	+
Article 3		+	++	+
Article 4				++

Details regarding how the research questions were satisfied are provided as follows:

> **RQ 1.** What safety challenges for MASSs have been identified in previous research? What research gaps still need to be addressed to ensure safe MASS operations in the future?

Research Question 1 was answered in Article 1, which provides thorough information in investigating the safety challenges identified in previous research and regarding research gaps that must still be addressed to ensure safe MASS operations in the future. Details are provided in Chapter 6.1.

> **RQ 2.** Can historic data of conventional vessels be used as a reference for safe vessel behaviour? Could MASSs autonomously determine the safe speed in a given situation by utilising the historic AIS speed data of conventional vessels?

Research Question 2 is the focus of both Articles 2 and 3. Both of these articles conclude that the speeds conventional vessels were observed to be proceeding with in different environmental conditions would not be considered safe speeds according to our contemporary (i.e. legal) understanding of safe speed. The historic speed data of conventional vessels collected from AIS can therefore not be used as a reference for safe vessel behaviour and can also not be used in a database to teach MASSs to autonomously determine safe vessel speeds.

In Article 4, it was established that the safe speed of a vessel is not only dependent on the current situation the vessel is in but also on the situation the vessel will be in in the foreseeable future. Safe speed therefore exists in a context that is complex and that cannot be determined by using only a snapshot of the conditions at one particular instance.

RQ 3. How do factors such as visibility, wind, waves, and location affect the speeds of conventional vessels?

Research Question 3 is partially answered in Article 2, which focuses on the effect visibility had on the speeds of conventional vessels in one particular location. Article 3 expands on this with an analysis of the effects of visibility, wind, and waves on the speeds of conventional vessels in two different locations.

This quantitative approach was supplemented with qualitative data collected from the interviews conducted in Article 4. The results of this article reveal what effects visibility, wind, waves, and location (as well as other factors) have on how navigators determine safe vessel speeds.

RQ 4. How do human navigators interpret Rule 6 of the COLREGs covering the requirement to proceed at a safe speed?

Research Question 4 is the focus of Article 4. The article provides an in-depth view of how human navigators interpret Rule 6 and how different factors affect both how they determine safe speed and what speeds they would determine to be safe.

7.2. Contributions

Engineering well-functioning sociotechnical systems requires a sound understanding of human performance and contribution (Relling, 2020). Unfortunately, eliciting and representing the knowledge of experts has become a growing concern in systems design (de Vries, 2017; Hoffman & Lintern, 2006), resulting in even high-quality research sources struggling to correctly apply the COLREGs (Wróbel et al., 2022). Researchers investigating MASSs have thus sought a more advantageous understanding of the work done by navigators (Negenborn et al., 2023). This is where the main contributions of this thesis lie.

The research conducted in this thesis sheds light on the human contribution to safe vessel operations and especially on the importance of human input for a vessel following the COLREGs. The challenges surrounding the autonomous determination of a safe vessel speed were previously largely ignored, or the issue was falsely deemed trivial. The research conducted in this thesis contributes to theory by providing new knowledge about what speeds vessels actually proceed at in different situations and how navigators interpret the requirement to proceed at a safe speed. This knowledge can be valuable in ensuring that work as done is also considered when programming MASS control systems.

The knowledge presented in this thesis has several practical implications. Due to the importance of cooperation and transparency, MASSs cannot blindly follow the COLREGs word for word without also considering the unwritten conventions followed by human navigators. However, it is also not possible for MASSs to simply copy what manned vessels have been doing in the past by utilising historic AIS data as a guide. Since human navigators interpret the requirement to proceed at a safe speed as a goal-based rule – where the goal is to maintain control of the situation, it seems plausible that MASSs should follow a similar approach.[21] The designers of MASSs need to locate their own method of determining the safe speed for these vessels in different situations. The goal should not be limited to compliance with the rules but should rather ensure that the MASS is in control of the situation and that its actions are transparent and understandable to every other vessel in the area.

7.3. Research Limitations

The research conducted in this thesis has some limitations. Much of this has been discussed in both Chapter 3 and Section 5.4. Some important limitations are specifically listed in this section.

The first limitation relates to the interpretative rigour of this thesis. First, it must be noted that the findings of the research conducted in this thesis are based on limited samples. Data collection for Articles 2, 3, and 4 was limited to Norway, meaning that interpretative consistency dictates that the findings cannot be generalised to the whole world. Future research with different samples is needed if conclusions for larger parts of the shipping industry are desired. Second, most of the research conducted in this thesis was conducted by only one researcher. This limits the assessment of how much interpretative agreement exists on the topic. Due to my strong involvement in the qualitative data collection and analysis of the fourth article, researcher bias can be seen as a potential weakness and a source of some uncertainty. A correction for this would be if other researchers conducted similar studies in the future. This would allow for a comparison between the descriptions and claims made in this thesis and the interpretations of other researchers.

Finally, a limitation of this thesis is its strong focus on speed, specifically safe speed. This narrow focus is a clear limitation because decision systems for MASSs

[21] Adopting a goal-based approach also seems to be supported by the IMO, who are currently working on a *goal-based* MASS Code.

must be designed following a comprehensive and holistic approach that considers not only all of the different rules of the COLREGs but also multiple vessel situations and dynamic weather conditions. The results of this thesis cannot therefore be implemented in isolation but can only be used as a starting point for a holistic approach to a smart MASS decision system.

7.4. Recommendations for Future Work

When one observes Gartner's hype cycle, it seems as if MASSs are currently either in the trough of disillusionment or slowly on the way towards the slope of enlightenment. The initial timelines that were presented during the peak of inflated expectations have proven to be too optimistic: The *Yara Birkeland* was initially advertised as being capable of fully autonomous operations already in 2020, but in 2023 it is still operating with an onboard crew. Many challenges have proven to be more complicated than initially expected and therefore require continuous attention to be overcome. One of these challenges is the autonomous determination of a safe speed to allow COLREGs-compliant MASS operations.

Recommendations for future work directly related to the research conducted in this thesis include the undertaking of a field study where the behaviour of navigators is studied directly on board. The results of such a study could be compared with the results of the interview study conducted in Article 4 of this thesis. Further knowledge about the work done by navigators could also be gained through a simulator study. Here, different influencing factors could be manipulated to gain a deeper understanding of how they affect the determination of safe speed by navigators.

Finally, future work should address some of the limitations mentioned in Section 7.3. The recreation by other researchers of some of the research carried out in this thesis could provide valuable insight of the interpretive rigour of my research, and further work that aims to implement a holistic approach to designing MASS control systems could aid in utilising my findings in a larger setting.

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Appendix 1.

Safety Challenges for Maritime Autonomous Surface Ships: A Systematic Review

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Ergoship 2019 Conference, Haugesund, Norway.

Safety Challenges for Maritime Autonomous Surface Ships: A Systematic Review

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Abstract - **Background: While numerous studies have been carried out regarding the safety of merchant maritime autonomous surface ships, no prior systematic review synthesising their results exists.**
Objective: Systematic review of peer-reviewed journal articles to collect all safety challenges for merchant maritime autonomous surface ships identified therein.
Data Sources: Four databases –SCOPUS, Academic Search Elite, ScienceDirect and Web of Science – were utilised to search for relevant studies.
Results: The review has identified three main groups of challenges, namely technological, human factors and procedural challenges.
Conclusion: Further research is necessary in order to overcome the identified challenges. The qualitative nature of the collision regulations requires further research in order to ensure autonomous ships comply with legal requirements that are worded in a way that makes them open to interpretation.

Keywords
Autonomous; Challenges; MASS; Ship; Systematic Review; Unmanned; Vessel.

INTRODUCTION

Maritime Autonomous Surface Ships (MASS) – provisionally defined as ships "which, to a varying degree, can operate independent of human interaction" (Maritime Safety Committee, 2019) – have received a lot of attention in recent years. However, most of the research carried out on the topic has been focused on overcoming the technological (Banda, Ahola, Gelder, & Sonninen, 2018) and legal challenges involved (International Maritime Organization, 2018), leaving a research gap in how these vessels can safely be operated.

This review aims to summarise the safety challenges for MASS identified in previous research. The summary can be utilised by researchers to get an overview of the research gaps existing in the field, thereby facilitating the process of finding suitable measures to ensure safe operations of MASS.

METHODS

This paper is a systematic review of journal articles discussing safety challenges for MASS.

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Study Design

This review was designed using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement (Moher, Liberati, Tetzlaff, Altman, & PRISMA Group, 2009) as a guideline. A copy of the review protocol can be found in (Dreyer, 2018).

Search Strategy

The literature search was conducted using the databases SCOPUS, Academic Search Elite via EBSCOhost, ScienceDirect, and Web of Science. The search strings defined in Table 2 were run on 19 September 2018 in as many fields as the different databases allowed. Literature found by running these search strings was complemented by literature found by searching through their reference lists and bibliographies.

Selection Process

Papers were selected according to the inclusion/exclusion criteria defined in Table 1. Figure 1– based on the PRISMA four-phase flow diagram (Moher et al., 2009) – is utilised to highlight the selection process used in this systematic review, which was carried out by the main author of this review.

Table 1. Inclusion and exclusion criteria.

	Inclusion criteria	Exclusion criteria
1.	Published in or after 2008	Published prior to 2008
2.	Published in English	Published in a language other than English
3.	Article published in a peer-reviewed journal	Article not published in a peer-reviewed journal
4.	Full text copy of article available	Full text copy of article not available
5.	Article focuses on MASS and challenges related to their safety	Article does not focus on MASS and challenges related to their safety
6.	Search terms were used in the setting/for the meaning they were intended	Search terms were used in other setting/for other meanings
7.	Non-duplicate study	Duplicate study

After the completion of the selection process, the 14 studies presented in Table 4 remained and were included in the qualitative synthesis.

Table 2. Search strings and results in four databases.

Database	Search string	Results
SCOPUS	(ALL (ship* OR ((vessel* OR vehicle* OR craft*) AND (maritime* OR marine* OR sea OR ocean))) AND (autonom* OR unmanned OR automat*) AND (merchant OR cargo) AND (safe*) AND (manag* OR overcom* OR challeng* OR system*)) AND PUBYEAR > 2007 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (SRCTYPE , "j"))	779
Academic Search Elite via EBSCOhost	(ship* OR ((vessel* OR vehicle* OR craft*) AND (maritime OR marine OR sea OR ocean))) AND (autonom* OR unmanned OR automat*) AND safe* AND (manag* OR overcom* OR system* OR challeng*) AND (merchant OR cargo)	91
ScienceDirect	(ship* OR ((vessel* OR vehicle* OR craft*) AND (maritime OR marine OR sea OR ocean))) AND (autonom* OR unmanned OR automat*) AND safe* AND (manag* OR overcom* OR system* OR challeng*) AND (merchant OR cargo)	43
Web of Science	"TS=((ship* OR ((vessel* OR vehicle* OR craft*) AND (maritime OR marine OR sea OR ocean))) AND (autonom* OR unmanned OR automat*) AND safe* AND (manag* OR overcom* OR system* or challeng*) AND (merchant OR cargo))Refined by: LANGUAGES: (ENGLISH)Timespan: 2008-2018. Databases: WOS, KJD, MEDLINE, RSCI, SCIELO.Search language=Auto "	30

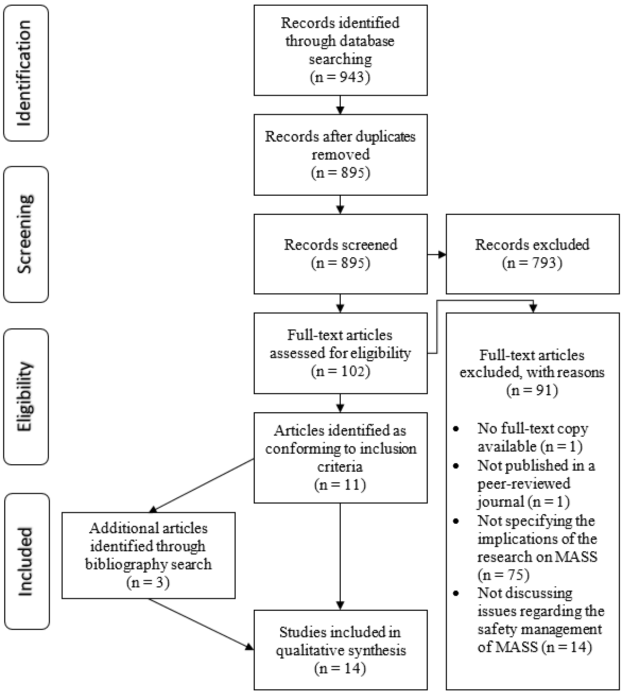

Figure 1. Flowchart of the selection process used in this systematic review.

Data Extraction

Data from the reviewed articles were manually extracted by the main author of this review. Principal data including author, year, title, country, design and outcomes are summarised in Table 4 below, while the identified safety challenges for MASS are discussed in more detailed in the results chapter.

Synthesis of Results

A narrative synthesis according to the guidance from Popay et al. (2006) was utilised in this review. The outcomes of the included studies and their methodological adequacy were described, explored and interpreted and when similarities emerged, they were be categorised as themes with explanations (Enya, Pillay, & Dempsey, 2018).

Quality Appraisal

The methodological quality of the identified studies that met the inclusion criteria were critically appraised using a set of screening questions utilised by Gillman and Pillay (2018), which were adapted from the Critical Appraisal Skills Programme (CASP) (Critical Appraisal Skills Programme, 2018).

The results of the quality appraisal and the risk of bias assessment can be obtained from (Dreyer, 2018).

RESULTS

Table 3. Main groups of challenges with sub-groups.

Main Groups	Sub-Groups
Technological	1. Hardware 1.1. Sensors 1.2. Communication 1.3. Fire Safety 1.4. Mooring 2. Software 2.1. Decision System 2.2. Software Errors 2.3. Cyber Security
Human Factor	1. Training 2. Effect of Technology on Human Operator 3. Human Centred System Design 3.1. Migration of Workplace 3.2. Presentation of Data
Procedural	1. Undesirable Events 1.1. Anticipated 1.2. Unanticipated 2. Standard Operations 2.1. Navigation 2.2. Maintenance 2.3. Cargo Care 2.4. Risk Assessment 2.5. Safety Controls 2.6. Absence of Regulations

Table 4. Characteristics and summary of reviewed articles.

Author(s)	Year	Title	Country	Design	Outcomes
Acanfora, M., Krata, P., Montewka, J., & Kujala, P.	2018	Towards a method for detecting large roll motions suitable for oceangoing ships	Finland, Poland, Italy	Case study	With the absence of seafarers on board, autonomous ships must have reliable methods for detecting critical operational conditions to be avoided. An alert must be raised when a roll motion starts to develop and an evasive manoeuvre must be executed immediately. This study therefore proposes a method providing for the avoidance of dangerous phenomena involving excessive motions of the ship.
Ahvenjärvi, S.	2016	The Human Element and Autonomous Ships	Finland	Exploratory	The paper highlights that the introduction of autonomous ships does not mean that there is no more human element involved in the navigation process and explores a number of select human factor issues that could be challenging in the safety management of autonomous ships.
Burmeister, H.-C., Bruhn, W., Rødseth, Ø. J., & Porathe, T.	2014	Autonomous Unmanned Merchant Vessel and its Contribution towards the e-Navigation Implementation: The MUNIN Perspective	Germany, Norway, Sweden	Exploratory	The development of advanced and integrated sensor systems for automated lookout, autonomous navigation systems incorporating the Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREGs) and safe operation in harsh weather, a safe and reliable ship-to-shore communication architecture as well as human-centred design of onshore monitoring stations are regarded as central challenges for MASS.
Burmeister, H.-C., Bruhn, W., & Walther, L.	2015	Interaction of Harsh Weather Operation and Collision Avoidance in Autonomous Navigation	Germany	Case study	Challenges for MASS identified in this paper include the requirement to decide independently how to react to unfavourable weather conditions and how to avoid collisions in accordance with the COLREGs. It highlights cargo care, the transiting of dense traffic and coastal areas, and the large number of interconnected requirements and dependencies in the system as problematic, meaning that different requirements must not be resolved independently. It further highlights that misbehaviour or negligence of other vessels must be taken into account and that a MASS must be able to realise when a departure from the rules is necessary.
Ghaderi, H.	2018	Autonomous technologies in short sea shipping: trends, feasibility and implications	Australia	Exploratory	The paper concludes that new skills and competencies are required to design, build and operate unmanned vessels, and highlights challenges in maintenance, compatibility in navigation support systems and cyber security.
Hogg, T., & Ghosh, S.	2016	Autonomous merchant vessels: examination of factors that impact the effective implementation of unmanned ships	Australia	Exploratory	The paper argues that the belief in complete reliability and trustworthiness of automation on ships is unrealistic. Numerous challenges are identified, including in the area of communications, human impact, legislation and standardisation, procedures, cyber security, and maintenance and prevention of technological failure.
Man, Y., Weber, R., Cimbritz, J., Lundh, M., & MacKinnon, S. N.	2018	Human factor issues during remote ship monitoring tasks: An ecological lesson for system design in a distributed context	Sweden	Case study	This study came to the realisation that a control centre cannot just copy the design of a conventional ships bridge. Instead, it is argued that ecological interface design should be utilised in order to create a virtual ecology that reflects the constraints in the work domain and supports user-environment coupling.
Rødseth, Ø. J., & Burmeister, H. C.	2015	Risk Assessment for an Unmanned Merchant Ship	Norway, Germany	Case study	A number of challenges – combined with some possible solutions – were identified in this paper. Hazards related to the interaction with other ships, errors in detection and classification of small/medium sized objects, detection of objects in low visibility, propulsion system breakdown and heavy weather are highlighted as being challenging to the safety management of MASS as no reliable control mechanisms have been identified yet.

Author(s)	Year	Title	Country	Design	Outcomes
Thieme, C. A., Utne, I. B., & Haugen, S.	2018	Assessing ship risk model applicability to Marine Autonomous Surface Ships	Norway	Theoretical review	This paper highlights that there is currently no appropriate risk model for MASS, which is a challenge for their safety management in itself, because a clear concept of risk is necessary to describe, communicate and manage risk.
Wróbel, K., Krata, P., Montewka, J., & Hinz, T.	2016	Towards the Development of a Risk Model for Unmanned Vessels Design and Operations	Poland, Finland	Case study	The outcome of this paper is that the safety of an unmanned ship as a system is made up of several features, most of which must not be considered separately from others, as the failure of one of the ships' subsystem can trigger a chain of events leading to potentially catastrophic consequences. This is visualised in the Bayesian network they created, which describes relationships between safety issues pertaining to unmanned vessels.
Wróbel, K., & Montewka, J.	2018	A method for uncertainty assessment and communication in safety-driven design - a case study of unmanned merchant vessel	Poland, Finland	Case study	The paper allocates levels of uncertainties to risk mitigation measures. Identified areas with particular uncertainties are the involvement of the remote operators, software solutions and the potential for so-called black swans.
Wróbel, K., Montewka, J., & Kujala, P.	2017	Towards the assessment of potential impact of unmanned vessels on maritime transportation safety	Poland, Finland	Causal	The results of this paper reveal that the likelihood of an unmanned ship being involved in a navigational accident would decrease, while the extent of consequences – particularly from non-navigational accidents – can be expected to be much larger. Numerous challenges to be addressed in order to allow for the safe operation of unmanned ships are identified in the paper.
Wróbel, K., Montewka, J., & Kujala, P.	2018	System-theoretic approach to safety of remotely-controlled merchant vessel	Poland, Finland	Case study	The results of this study indicate that ensuring the safety of MASS shall consist of executing various controls on regulatory, organisational and technical plains. As most safety constraint violations can be attributed to technical issues, mitigation of many hazards can be achieved by introducing redundancy to safety-critical systems. Examples of areas that are inherently different to traditional ships are navigation, power generation, fuel management, cargo conditioning and fire safety.
Wróbel, K., Montewka, J., & Kujala, P.	2018	Towards the development of a system-theoretic model for safety assessment of autonomous merchant vessels	Poland, Finland	Case study	The results of this paper indicate that software development and validation appear to be the parts of the system that are hampered most by significant uncertainties regarding safety performance. By applying a system-theoretic process analysis hazard mitigation measures were identified that can improve the safety performance of MASS. As a result, this paper highlighted a number of challenges related to their safety management.

The review has identified three main groups of challenges, namely **technological** (addressed in 13 different reviewed studies), **human factors** (addressed in 13 different reviewed studies) and **procedural** challenges (discussed in 13 different reviewed studies). These main groups were further split into sub-groups as shown in Table 3 above.

Technological Challenges

This sub-section presents the identified technological challenges, which can be split up into hardware and software.

Hardware

This section presents issues relating to the hardware of MASS, specifically to sensors, communication equipment, fire safety installations, apparatus for rendering assistance and mooring systems.

Sensors

MASS must be provided with an adequate sensor system capable of measuring a variety of different data available on-board. The importance of relevant sensors becomes apparent when looking at the consequences of their inadequacy. Due to the lack of "first-hand multi-sensory experience of a living person" (Hogg & Ghosh, 2016), a failure in the sensory system of a MASS would lead to it becoming blind, inevitably leading to it being unable to perform safely and efficiently (Wróbel, Montewka, & Kujala, 2018b). Such an inadequacy of the sensor system could be caused by "sensors' failures, installed sensors' inability to measure a required feature, unsuitable sensors being installed or their sub-optimal performance" (Wróbel et al., 2018b), which are all risks that must be addressed.

The literature generally distinguishes between sensors for sensing the environment outside the vessel (Burmeister, Bruhn, Rødseth, & Porathe, 2014; Burmeister, Bruhn, & Walther, 2015; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme, Utne, & Haugen, 2018; Wróbel, Krata, Montewka, & Hinz, 2016; Wróbel, Montewka, & Kujala, 2018a; Wróbel et al., 2018b), and sensors that measure the current state of the vessel (Burmeister et al., 2015; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b). The following critical areas in which adequate sensor data must be ensured have been identified: Lookout (Burmeister et al., 2014; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme et al., 2018; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b), external environmental data (e.g. meteorological and oceanographic) (Burmeister et al., 2015; Wróbel et al., 2018a, 2018b), internal stability data (e.g. motion and stress) (Burmeister et al., 2015; Wróbel et al., 2018a), and internal system data (Wróbel et al., 2016; Wróbel et al., 2018a, 2018b).

Lookout data refers to any data used for the observation of the sea for hazards, other ships, land, wreckage and distress signals, and is used to prevent collisions and detect persons in distress. When lookout data is combined with external environmental data such as depth readings from the echo sounder, an image of the external environment of the vessel can be constructed. However, to ensure safe navigation, internal stability data must be gathered and analysed as well. By combining external environmental data and internal stability data, dangerous situations that could lead to loss or damage to the ship or its cargo can be either anticipated and avoided, or realised and corrected.

Internal system data refers to data taken from the different internal systems on board, e.g. machinery data, fire sensor data and data to evaluate damage to the ship.

Communication

Another hardware challenge related to the operation of MASS is their communication capability. The reviewed literature generally agrees that the communication architecture of a MASS must be safe and reliable and distinguishes between two different types of communication: "Ship-to-shore" (Burmeister et al., 2014; Ghaderi, 2018; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme et al., 2018; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b), and "ship-to-ship" (Burmeister et al., 2014; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Thieme et al., 2018).

The architecture of the communication system of a MASS is critical for both safety and security (Wróbel et al., 2016) and requires specialised systems with sufficient redundancy and backup operations (Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Wróbel et al., 2018a). It must be ensured that MASS are provided with the necessary hardware to ensure reliable communication both with the remote control centre (Hogg & Ghosh, 2016; Thieme et al., 2018) and the monitoring and navigational systems used in ports (Ghaderi, 2018), even in regions where only restricted satellite bandwidth is available (Burmeister et al., 2014).

Means for communication with conventional vessels must also be provided (Hogg & Ghosh, 2016), which may prove to be challenging as this type of communication must be catered to humans on the bridges of the conventional vessels.

The uncertainties in the capabilities of the current technical communication solutions available lead Wróbel et al. (2018b) to conclude that communication – which is considered to be a major part of the whole system – requires further study.

Fire Safety

Depending on the type of MASS, the design of a technical system capable of preventing or handling fires in all possible scenarios was identified by Wróbel, Montewka, and Kujala (2017) to be an extremely difficult challenge. However, as major subsystems of a MASS are heavily reliant on one another, the performance of such a fire protection system has a direct impact on the vessels machinery systems and navigational capabilities (Wróbel et al., 2016). Therefore it is concluded that MASS fire safety must be carefully addressed (Wróbel et al., 2018a).

Rendering Assistance

MASS may find themselves in a situation where they have to assist another vessel. They must be able to assist in the distress response and be able to pick up and accommodate survivors even in the absence of on-board crewmembers (Wróbel et al., 2016; Wróbel et al., 2017).

Mooring

Seven reviewed papers expect MASS to have a crew on board for the port-related activities, including departure and approach (Burmeister et al., 2014; Burmeister et al., 2015; Ghaderi, 2018; Rødseth & Burmeister, 2015; Wróbel et al., 2017, 2018a, 2018b). In case a MASS operator plans to enter port without having any crew on board, special mooring infrastructure must be provided (Hogg & Ghosh, 2016; Thieme et al., 2018). Such mooring equipment must ensure a safe mooring process for both the ship itself as well as any shore personnel involved in the operation.

Software

The identified challenges regarding the decision system of a MASS, potential software errors and ensuring cyber security are presented in this section.

Decision System

A number of challenges have been identified regarding the decision system that will need to be installed on a MASS designed with a navigation automation system. The two challenges that have been discussed the most is the ability of a MASS to avoid collisions with other traffic in accordance with the COLREGs (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016; Man, Weber, Cimbritz, Lundh, & MacKinnon, 2018; Rødseth & Burmeister, 2015; Wróbel et al., 2018b), and the ability to avoid and react to unfavourable weather conditions (Acanfora, Krata, Montewka, & Kujala, 2018; Burmeister et al., 2014; Burmeister et al., 2015; Rødseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel et al., 2017).

The primary challenge is to ensure that MASS operate in compliance with the COLREGs. This has been fundamentally questioned by Hogg and Ghosh (2016) as they consider MASS as being incapable of mimicking the foresight a human navigator has on the bridge of a conventional vessel. As such, it must be ensured that good seamanship practice is replaced by methods and criteria (Acanfora et al., 2018; Wróbel et al., 2018b) sufficient to ensure that MASS can comply with the COLREGs.

While the COLREGs theoretically apply to all vessels upon the high seas (International Maritime Organization, 1972), misbehaviour or negligence of other vessels sometimes results in them not being applied in practice. The decision system of a MASS must therefore be able to avoid collisions with other vessels regardless of whether they follow COLREGs or not (Burmeister et al., 2015; Rødseth & Burmeister, 2015).

Another important part for ensuring safe navigation of MASS is the availability of reliable methods for detecting critical operational conditions that need to be avoided, both while planning the route and while monitoring the vessels progress along it (Acanfora et al., 2018). If a MASS encounters rough weather (Burmeister et al., 2014; Burmeister et al., 2015; Wróbel et al., 2016; Wróbel et al., 2017) or conditions that induce excessive motion and/or acceleration, her safety can be compromised.

It must be ensured that scenarios that can lead to damage of the ship or its cargo are determined both at the route planning stage and during the voyage execution stage (Acanfora et al., 2018). Detection of a potentially dangerous situation during the route planning stage should lead to the route being amended so that potentially dangerous sea areas are avoided (Acanfora et al., 2018), similar to how rough weather is avoided by utilising weather routing (Burmeister et al., 2015; Rødseth & Burmeister, 2015). During the voyage, the identification of a potentially dangerous situation should lead to the execution of mitigation actions, such as a change in course and/or speed and the raising of an alert to the controller (Acanfora et al., 2018).

When looking at the two challenges discussed above (i.e. reacting to traffic and reacting to environmental influences), it is highlighted that they cannot be resolved independently, as the required actions may be contradicting each other at times (Burmeister et al., 2015). Decisions made by one system module will inevitably have an effect on another. An example of such an effect is the need for a new route to be provided by the planning module if the control module of the MASS decides that it is necessary to deviate from the initially planned route (Acanfora et al., 2018). It is therefore essential that a holistic approach is adapted when designing the decision system in order to ensure the collaboration of the different components of the system (Wróbel et al., 2018b). As the proper functioning of the decision system depends on the quality of the input data (Wróbel et al., 2016), a stage where the quality of external- and sensor data is evaluated must be included in the system. Situations in which the indications of two or more sensors contradict each other must be identified and resolved in order to ensure the safe operational conduct of MASS (Wróbel et al., 2018a).

Further challenges that must be resolved are which action a MASS should take when all available options lead to undesirable outcomes, and ensuring that a MASS can adapt to unforeseen situations (Ahvenjärvi, 2016).

Software Errors

Even though the reliability and efficiency of the software utilised in MASS is of great importance to safety (Thieme et al., 2018; Wróbel et al., 2018b), there is a high probability that software errors will be present in their control system (Ahvenjärvi, 2016). This is considered to be a main risk for MASS (Rødseth & Burmeister, 2015). Proper software development and testing is therefore considered to be critical (Ahvenjärvi, 2016) and the introduction of technical standardisation, certification and inspection of the control system is encouraged (Hogg & Ghosh, 2016). Highlighted challenges are the revealing of software errors that are connected with abnormal situations (Ahvenjärvi, 2016) and the reduction of errors by reducing system complexity (Rødseth & Burmeister, 2015). Due to the presence of control algorithms in a large number of MASS system components, a lot of work needs to be done in this area (Wróbel et al., 2018a).

Cyber Security

Cyber security is considered critical for the safe operation of MASS (Ghaderi, 2018; Hogg & Ghosh, 2016). While virtually all system components are at risk of an attack (Wróbel et al., 2018a), the communication- and the information technology have been particularly highlighted by Ghaderi (2018). As devastating consequences may be expected if a breach in cyber security occurs (Wróbel et al., 2017, 2018b), ensuring the cyber security of MASS poses a major challenge that must be addressed appropriately.

Human Factor Challenges

The second group of identified safety for MASS are those related to human factors. This group is made up of challenges related to training, the effect of technology on the human operator, and human centred system design.

Training

Ensuring that all persons required to work with the new technology are adequately trained is mentioned as a challenge in a six different studies reviewed in this study (Ahvenjärvi, 2016; Ghaderi, 2018; Hogg & Ghosh, 2016; Man et al., 2018; Wróbel et al., 2018a, 2018b). The challenge to ensure proper training is not limited to seafarers (Ahvenjärvi, 2016) and shore-based operators (Wróbel et al., 2018b), but extends to naval architects (Ghaderi, 2018), technicians and engineers (Hogg & Ghosh, 2016) as well.

While Man et al. (2018) do not specifically state adjusted training requirements for MASS operators as a challenge, they do highlight that the required competencies of these operators have not been defined in regulations and that not enough research has been carried out on this topic. Hogg and Ghosh (2016) agree that new skills will be required and acknowledge the absence of regulation in this regard, but also highlight the importance of seagoing experience and question how the MASS operator of the future will gain the first-hand experience necessary to become an experienced Master when there are no more opportunities to work at sea.

As the implementation of operational trainings may have a positive effect on the influence humans have on the safety of MASS, ensuring proper training is of utmost importance (Wróbel et al., 2018a).

Effect of Technology on the Human Operator

None of the papers reviewed suggest that the implementation of MASS will remove the possibility of human error altogether, but the effect that humans will have on MASS has been discussed to a different extent. While Burmeister et al. (2015) and Ghaderi (2018) suggest that the introduction of MASS holds the potential to ultimately decrease human error, Ahvenjärvi (2016), Burmeister et al. (2014), Hogg and Ghosh (2016), Man et al. (2018), Rødseth and Burmeister (2015), Thieme et al. (2018), Wróbel et al. (2016), Wróbel and Montewka (2018), Wróbel et al. (2017), Wróbel et al. (2018a) and Wróbel et al. (2018b) argue that human factor issues will continue to be of significant importance in MASS operations.

The reviewed literature identifies a number of challenges related to the human factor that need to be managed in order to ensure MASS safety:

- Automation-induced complacency results in the operator being unable to detect malfunctions in the system, and is directly affected by the training received, the reliability of the system and the workload experienced (Hogg & Ghosh, 2016). If the operating system of a MASS is reliable, it is likely that the operator becomes over-confident in the system and loses vigilance. This negative effect of automation on the human operator has also been discussed in (Man et al., 2018; Wróbel et al., 2018a).

- Remote supervisory control may lead to out-of-the-loop syndrome (Man et al., 2018) and together with the lack of human connection to the MASS and absence of cues in an office-like environment may result in limited situational awareness of the remote operator (Ghaderi, 2018; Hogg & Ghosh, 2016; Man et al., 2018; Wróbel et al., 2018a), thereby possibly increasing the likelihood of an accident occurring (Wróbel et al., 2017). Furthermore, this leads to the inability for the operator to take over control in cases where the automation fails (Man et al., 2018) and has caused Hogg and Ghosh (2016) to question the effectiveness of the concept of supervising a MASS from a remote control centre altogether. This question gains more significance because humans are – due to their nature – not suitable for acting as a backup in human-automation interactions (Man et al., 2018).
- It is expected that the cognitive demands in the remote control centre will be higher than on the bridge of a conventional vessel (Hogg & Ghosh, 2016). If improperly managed, this may lead to information overload of the controller (Ghaderi, 2018). It is therefore considered essential that operators are kept at optimal mental work load levels (Hogg & Ghosh, 2016). In this regard Man et al. (2018) suggest if the pre-processing of raw data and flow may aid in reducing the demand of an operators cognitive resources.
- Another negative side effect of MASS implementation is the skill degradation of those charged with their remote supervision (Hogg & Ghosh, 2016; Wróbel et al., 2018a). Necessary steps must be taken to ensure that the remote operator will retain his or her skills in order to be able to take over control of the MASS when the situation so requires.

Human Centred System Design

Where the operator of a MASS is not stationed on board, the complete migration of the workspace away from the ship to must be duly considered in the design of the control centre. The presentation of data in a user-friendly way will be a challenge regardless of the location of the operator.

Migration of Workplace

One of the main results of the work of Man et al. (2018) is the realisation that the ecological changes related to the migration of the working place away from the ship must be considered when designing the remote control centre. The design of the technology in the control centre must be shaped for the new task of remote control and monitoring, meaning that current systems and practices cannot simply be transferred to the new location (Man et al., 2018). Ignoring the relationship between user and environment when designing the control centre may result in workplaces that are not suited for remote supervisory work and increase the gap between the demands of the work domain and the capabilities of the operator (Man et al., 2018).

Presentation of Data

A substantial amount of interaction between the MASS and its operators may be required at certain stages of a voyage (Thieme et al., 2018). Adapting a user-centred approach results in presenting the necessary data to the user according to his or her goals, tasks and needs (Hogg & Ghosh, 2016) will likely reduce the chance of him or her misinterpreting the data (Wróbel et al., 2017).

Utilising user-centred design in human-machine interfaces allows the operator to gain and maintain situational awareness (Ahvenjärvi, 2016; Thieme et al., 2018). Furthermore, it must be ensured that the data required by the operator is presented to him or her in all operating conditions, including unanticipated undesirable events. It is in these situations that automation functions may not reveal the true state of the system and provide the least help to the operator (Man et al., 2018). A central alarm management system including prioritisation of issues (Burmeister et al., 2014) may aid an operator in these cases, as he or she may not be able to make decisions due to information overflow and/or bad prioritisation of tasks (Wróbel et al., 2017).

Procedural Challenges

The final group of identified challenges is related to procedures, which is related to both undesirable situations and standard operations.

Undesirable Events

MASS can potentially experience undesirable events that have either been anticipated in advance (and therefore have contingency plans in place), or not.

Dealing with Anticipated Undesirable Events

It has been noted in the reviewed literature that even when considerable efforts are expended into ensuring excellent design and performance of MASS, it is likely that at some point a disaster might occur (Wróbel et al., 2017). A number of anticipated undesirable events have been identified in the literature. It is important that suitable measures will be in place to cope with these contingencies.

- Remote operators of MASS must anticipate the possibility of communication disconnections and ensure that suitable safeguards are in place in order to cope with such a situation (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel & Montewka, 2018; Wróbel et al., 2018a, 2018b). Fail-to-safe-functionalities that could potentially act as such safeguards have been discussed in (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Wróbel et al., 2018a).

- Ahvenjärvi (2016) identifies the situation of multiple and simultaneous sensor faults as a particularly challenging situation for autonomous ships. In fact, the failure of any of the technological equipment on-board the MASS must be addressed in order to prevent minor technological failures from causing an error chain that may lead to an accident (Hogg & Ghosh, 2016; Rødseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b).
- While the consequences of a marine accident involving a conventional vessel are usually reduced by the actions of on-board crew, an unmanned MASS will have to rely solely on the available technology to respond to an accident (Wróbel et al., 2018b). As operators will be unable to make necessary manual adjustments themselves (Wróbel et al., 2018a), the accident response relies heavily on the ability to anticipate potential accident scenarios in the design stage (Wróbel et al., 2016), as this will decide the response mechanisms that will be provided. While it has been stated that damage assessment and control is likely one of the biggest challenges for MASS, previous studies have not accounted for the possible absence of humans on board when evaluating response options to MASS accidents (Wróbel et al., 2017).

Dealing with Unanticipated Undesirable Events

If a MASS runs into an unanticipated undesirable situation, the operator must be alerted in due time. Suitable alert points must be defined in order to ensure that he or she has sufficient time before the situation develops to a point where nothing more can be done to remedy the situation (Hogg & Ghosh, 2016; Wróbel et al., 2016). Due to the unanticipated nature of the undesirable event, this will be a challenging task.

Regarding the accident response of an unmanned MASS, the presence of black swans – which are scenarios that for some reason have not been analysed – must be anticipated (Wróbel & Montewka, 2018; Wróbel et al., 2018a). As it is next to impossible to account for all potential accident scenarios in the design stage, MASS should be designed in a way that ensures a proper level of resilience (Ahvenjärvi, 2016; Wróbel et al., 2017, 2018b).

Standard Operations

The introduction of MASS will have a considerable impact on a number of standard operations, and numerous procedural challenges to ensuring safe operations of MASS have been identified in the reviewed literature. They have been categorised as challenges regarding navigation, maintenance, cargo care, risk assessment, safety control and absence of regulations.

Navigation

In the case of a MASS controlled or supervised from a remote control centre the following challenges regarding navigation have been identified.

- Utilising the traditional hierarchy of a conventional vessel in a remote control centre may not be suitable. Hogg and Ghosh (2016) argue that assigning the captain as the final decision-maker may not be a suitable solution, as he or she will be out of the loop and have difficulty developing proper situational awareness in an emergency. The shift from conventional navigation to MASS operation must therefore be based on a review of manned bridge procedures (Burmeister et al., 2015).
- The interaction between the operator and the MASS varies depending on the level of autonomy. Procedures must therefore be in place to ensure a safe transition when the operator takes control of the MASS (Wróbel & Montewka, 2018), and that the system and the operator are able to adapt quickly to the new operational mode (Thieme et al., 2018).
- As MASS will continue to coexist alongside other vessels in the foreseeable future, it has been suggested that aspects such as the interactions between conventional ships and MASS must receive more attention in the future (Thieme et al., 2018). One such interaction may be the dangerous utilisation of predictable MASS behaviour by conventional vessels, as humans who have regular contact with automated systems have a tendency to create new and risky habits (Ahvenjärvi, 2016).
- Thieme et al. (2018) argue that current navigational aids are designed to assist human navigators, and argue that further investigation is necessary to assess if they need to be changed in order to facilitate MASS navigation.

Maintenance

The absence of a crew on board an unmanned MASS leads to the realisation that there will be no one on board to carry out maintenance while the vessel is at sea (Ghaderi, 2018; Hogg & Ghosh, 2016; Thieme et al., 2018; Wróbel et al., 2018b), causing a number of maintenance related challenges (Wróbel et al., 2017). A rigorous preventive maintenance scheme must therefore be developed to ensure that no maintenance of ship components is necessary while the unmanned MASS is at sea (Burmeister et al., 2014; Thieme et al., 2018; Wróbel et al., 2016; Wróbel et al., 2018a, 2018b). As non-complex hardware problems can propagate and cause major problems (Rødseth & Burmeister, 2015; Wróbel et al., 2016) it must be ensured that sufficient backup solutions are available in case of a sub-system failure (Thieme et al., 2018).

Depending on the approach chosen to ensure that no maintenance needs to be carried out at sea, a number of different challenges have been identified in the literature. Hogg and Ghosh (2016), Thieme et al. (2018) and Wróbel et al. (2018b) declare that all MASS components will require extreme reliability. Any maintenance required will have to be carried out in port by specialised personnel (Ghaderi, 2018; Hogg & Ghosh, 2016; Thieme et al., 2018), introducing new implications for both port and ship operators (Ghaderi, 2018). It is even suggested that unmanned MASS will require new propulsion concepts, as conventional diesel engines are in need of frequent maintenance (Thieme et al., 2018).

Cargo Care

Current designs of MASS suggest that only cargo with low management requirements (i.e. stable, non-hazardous cargo that requires no maintenance or monitoring during the voyage) will be carried on unmanned MASS (Burmeister et al., 2014; Burmeister et al., 2015; Hogg & Ghosh, 2016). However, this view is not shared across the reviewed literature. Wróbel et al. (2016) can see issues arising from self-heating or self-igniting cargo, which suggests that they assume that such cargoes may be carried on board unmanned MASS. Wróbel et al. (2018b) are more direct assuming that more challenging cargoes can be accommodated if MASS are provided with the right functionalities. It should be noted that even if hazardous cargo was banned from being transported on unmanned MASS, undeclared dangerous cargoes may still end up on board (Wróbel et al., 2017). Safety issues regarding the carriage of hazardous cargo must therefore be addressed (Wróbel et al., 2017).

Risk Assessment

A number of the reviewed articles focus specifically on assessing the risk and uncertainty involved in MASS operation and highlight the difficulty in establishing a reliable risk model (Rødseth & Burmeister, 2015; Thieme et al., 2018; Wróbel et al., 2016; Wróbel & Montewka, 2018; Wróbel et al., 2017, 2018a, 2018b). However, a clear concept of risk is necessary to describe, communicate and manage risk (Thieme et al., 2018), and make feasible safety recommendations (Wróbel & Montewka, 2018). A number of key challenges that need to be overcome are outlined below:

- There is a widespread uncertainty regarding MASS in general, which means that reliable information regarding their actual design and operating circumstances is not available (Wróbel et al., 2016; Wróbel & Montewka, 2018; Wróbel et al., 2017). However, such information must be available if a generic and comprehensive risk model for MASS is to be developed (Thieme et al., 2018).
- Risk models in shipping have traditionally been quantified based on accident and incident data. However, due to absence of such data in a MASS context, such an approach is not viable for MASS risk models (Thieme et al., 2018). Furthermore, there is no empirical data pertaining to their performance (Wróbel & Montewka, 2018; Wróbel et al., 2018b), and areas that need special attention in the context of MASS operations have rarely been covered in depth in the literature (Thieme et al., 2018). If this absence of reliable data leads to incorrect assumptions, the assessment may lead to unjustified conclusions and incorrect decisions (Wróbel & Montewka, 2018). Circumventing this problem by utilising an existing model to assess risk is also described as questionable (Wróbel & Montewka, 2018).
- The concept of black swans described previously also has direct effects on the risk assessment models for MASS, as the likelihood of incomplete data leads to uncertain outcomes (Wróbel & Montewka, 2018; Wróbel et al., 2018a).
- Due to a lack of an officially defined acceptable risk level, the outcome of the existing risk models cannot be suitably utilised to assess MASS safety (Wróbel et al., 2016; Wróbel et al., 2017).

Safety Controls

Ensuring suitable safety controls systematically from higher organisational levels ensures that hazards are controlled at each point of the system structure (Wróbel et al., 2018a). However, mitigating hazards does not only involve the provision of safe control actions; it must also be ensured that those safety controls are applied at the right time and for the right period of time, and that they are applied in the correct sequence (Wróbel & Montewka, 2018; Wróbel et al., 2018a).

A further challenge is to ensure that safety and cost-effectiveness are suitably balanced (Rødseth & Burmeister, 2015; Wróbel et al., 2016; Wróbel et al., 2018a), as the reduction of cost is one of the most important arguments for MASS (Ahvenjärvi, 2016; Ghaderi, 2018; Rødseth & Burmeister, 2015; Wróbel et al., 2017, 2018a).

Absence of Regulations

Due to the absence of a regulatory framework regarding the many aspects involving MASS (Hogg & Ghosh, 2016; Man et al., 2018), it must be ensured that suitable operational procedures are available, relevant training is being organised and that the maintenance of on-board systems is properly managed (Wróbel et al., 2018a).

CONCLUSIONS

As mentioned in Banda et al. (2018), much technological research has been done regarding MASS. A great example is the push for satellite-based high-speed internet that is being developed by several major companies to reduce the likelihood of communication failure with MASS (Coldewey, 2019). However, with increased availability and reliability on internet communication systems, Ghaderi (2018) has identified cyber security as "the biggest challenge facing the maritime industry". The likelihood of unauthorised control of the ship can only be drastically reduced if proper design of communications, position sensing and on-board control systems is ensured (Rødseth & Burmeister, 2015).

A very real concern for MASS operations lays in the decision system, with "real-time intelligent algorithms for collision avoidance combining multiple vessel situations, dynamic weather conditions and COLREGS compliance is yet to be developed" (Hogg & Ghosh, 2016, p. 218). This is further complicated as the requirements of the COLREGs are sometimes open to interpretation (Vartdal, Skjong, & St.Clair, 2018). An obvious example of this is rule 6 of the COLREGs, which requires vessels to "proceed at a safe speed" (International Maritime Organization, 1972), without quantifying what is meant by the term "safe speed". MASS compliance with the COLREGs is therefore reliant on smart methods and criteria (Acanfora et al., 2018; Wróbel et al., 2018b) that have not been developed yet and therefore warrant further research.

Finally the realisation that humans are – due to their nature – not suitable for acting as a backup in human-automation interactions (Man et al., 2018) results in a challenge that need to be overcome if MASS are designed to be supervised from a remote control centre.

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Appendix 2.

Safe Speed for Maritime Autonomous Surface Ships – The Use of Automatic Identification System Data

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European Safety and Reliability Conference, Angers, France

Safe Speed for Maritime Autonomous Surface Ships – The Use of Automatic Identification System Data

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Introduction: All vessels are required by law to proceed at a safe speed while at sea. However, there is no acceptable method of determining what value of speed could be considered safe. One way of determining safe speeds in different conditions could be the utilization of Automatic Identification System (AIS) data to create a safe speed model that maritime autonomous surface ships (MASS) could follow.
Objectives: Investigate if MASS can determine the safe speed without human support by utilizing historic AIS speed data of other vessels. Investigate further if AIS and visibility data show a strong relationship between visibility and vessel speeds, and if vessels generally show a reduction of speed in restricted visibility.
Methods: AIS and visibility data was collected and merged in an area off Western Norway in the period between 27 March 2014 and 31 December 2020. A simple linear regression was calculated and supplemented by two graphical methods for revealing relationships between two variables.
Results: A significant regression equation between visibility and speed was found. This relationship was not strong. Average transit speed was highest when visibility was below 1,000 meters.
Conclusion: The problem of quantifying the safe speed of a vessel in different conditions does not seem to be solvable by only using historic AIS data to create a model of normalcy which a MASS can follow.

Keywords: MASS, AIS, Safe, Speed, COLREG, Visibility.

1. Introduction

The International Regulations for the Prevention of Collisions at Sea (COLREGs) lay out the basis of agreed practices for avoiding collisions at sea. They have to be followed by all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels (IMO 1972). As such, the COLREGs would apply to any maritime autonomous surface ship (MASS) navigating the seas in the future.

The COLREGs include a large number of qualitative terms such as “early” and “substantial” (Porathe 2019) which leaves much of the rule-system up to the interpretation of the navigator. This ambiguity is said to be the necessary price of applicability, as a completely prescriptive and rigid rule-system would be infinitely complicated (Taylor 1990). The ambiguity of the COLREGs can be seen as problematic, as collision avoidance to a large extend depends on each ship understanding the actual, likely and potential actions of the other (Taylor 1990). Collision avoidance is seen as a game of co-ordination where navigators on different vessels have to independently choose mutually compatible strategies (Cannell 1981). Already today, the interaction between traditional ships is seen as problematic (Porathe 2019), and collisions do still occur. It is warned that autonomous ships following a machine interpretation of the COLREGs may lead to even more uncertainty in the future, possibly causing more navigational problems (Porathe 2019).

One particular point of concern is the requirement of Rule 6 of the COLREGs, requiring every vessel to proceed at a safe speed at all times (Dreyer and Oltedal 2019). Nowhere in the rules is it further quantified what speed could be considered “safe”. While attempts have been made, no acceptable method of determining what value of speed could be considered to be “safe” has been put forward by the International Maritime Organization (IMO) (Cockcroft and Lameijer 2012). It is therefore up to the navigator to determine the “safe” speed in the prevailing conditions.

As unsafe speed has been highlighted as either the immediate or contributory cause in 11.6% of 248 analyzed collision, close quarters & contact cases between 2002 and 2016 (Acejo et al. 2018), it is important to find a reliable way autonomous ships can determine the safe speed in the absence of a human navigator.

One tool that could help extract the knowledge of which speeds navigators consider to be safe in different conditions could be the Automatic Identification System (AIS). AIS is a communications system that provides automatic reporting between ships and to shore by exchanging information such as identity, position, time, course and speed (IALA 2016). Other researchers have already utilized historic AIS data to build models of normalcy for traffic patterns (Yan et al. 2020). These models are being used both to generate what is described as “safe paths” that MASS can follow (Xu, Rong, and Guedes Soares 2019), as well as to identify so-called “high risk” vessels that do not follow the predicted pattern (Yan et al. 2020). Historic AIS data can therefore be utilized to create a model of normalcy for the speed of different types of vessels.

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An important assumption of the approach described above is that that historic AIS data – on average – shows safe vessel behaviors. It is taken for granted that the common patterns extracted from historic AIS data resemble safe speeds. This assumption can be tested by comparing the common patterns of vessel speeds observed from AIS data with accepted interpretations of what constitutes a safe speed.

Research on what speeds can be considered "safe" in different conditions is rather sparse. The COLREGs themselves define safe speed by the vessels ability to "take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions" (IMO 1972). They also provide a number of factors that shall be taken into account when determining the safe speed, with the state of visibility listed first (IMO 1972).

The importance of visibility is echoed in the available guides and commentary to the COLREGs. Kavanagh (2001) concludes his inquiry into safe speed by stating that the primary consideration in determining safe speed is visibility. Cockcroft and Lameijer (2012) state that visibility is "obviously of major importance" and that the need to moderate speed generally applies in restricted visibility. Rutkowski (2016) simply states that it is dangerous to go fast when visibility is poor.

For this paper, visibility is classified according to the national meteorological service of the United Kingdom, the Met Office. The definitions of their marine forecasts glossary can be seen in Table 1.

Table 1. Definition of visibility terms (Met Office 2021).

Term:	Meaning:
Very poor	Visibility less than 1,000 meters
Poor	Visibility between 1,000 meters and 2 nautical miles (3,704 meters)
Moderate	Visibility between 2 and 5 nautical miles (3,704 meters and 9,260 meters)
Good	Visibility more than 5 nautical miles (9,260 meters)

If speed patterns extracted from historic AIS data are to be used to aid MASS in determining safe speed, it must first be verified that the extracted speed patterns themselves represent safe speeds. Referring back to the contemporary guides and commentary on the COLREGS, a pattern which indicates the safe speed in different circumstances requires a strong correlation with visibility and should generally show a reduction of speed in restricted visibility.

This paper therefore combines historic AIS data with visibility data for the area to answer the following research question: **Can MASS autonomously determine the safe speed by utilizing historic AIS speed data of other vessels?**

This is done by investigating if speed data gathered through AIS show speeds that contemporary research would consider to be safe. To do so, the following research sub-questions were formulated:

(i) Does AIS and visibility data show a strong relationship between visibility and vessel speeds?

(ii) Does AIS data show a trend of vessels proceeding at a reduced speed in restricted visibility?

2. Description of Study Area, Collected Data, and Research Approach

This section introduces the reader to the study area, gives an overview of the collected data and describes the research approach of this study.

2.1. *Study area*

To decide which area this paper would utilize as the study area, the following requirements were set: The area had to be in open sea close to normal shipping routes and have both historic AIS- and visibility data.

The study area used in this study is located off Bulandet, an archipelago in the sea off the mainland coast of Western Norway, as shown in Figure 1. It is to the east of the "Gjøa A" platform – where the historic visibility data utilized in this study is measured – between the traffic separation scheme (TSS) Off Stad in the north and TSS Off Sotra in the south. The study area is approximately 4.2 by 4.2 nautical miles in size.

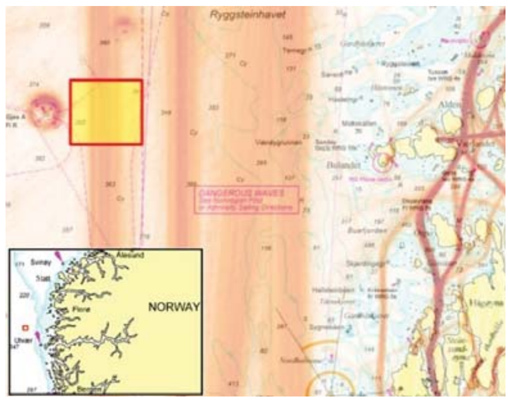

Fig. 1. Location of study area: West of Bulandet, off the mainland coast of Western Norway. AIS density plot overlay shows common shipping routes.

Note that the weather measuring station is located outside the study area. While this may result in visibility data reported by the measuring station differing slightly from the actual visibility within the study area, this decision was taken due to two reasons. Firstly, to reduce the possible disturbing effects of having large navigational hazards located inside the study area, and secondly to ensure that the study area is located within a normal shipping lane. As can be seen from the AIS density plot overlay in Figure 1, the study area covers traffic transiting southbound along the Norwegian west coast, while avoiding most of the non-transit traffic around the Gjøa A platform. Collected data

The data utilized in this study consists of two parts and covers the period from 27 March 2014 to 31 December 2020. Firstly, vessel speeds were drawn from AIS data, which was collected via the Kystdatahuset service provided by the Norwegian Coastal Administration (NCA).

Secondly, the visibility data – which was collected on the Gjøafeltet platform – was accessed via the Norwegian Climate Service Center. This section introduces the AIS data first, then gives more information on the visibility data, and finally explains how the two were merged.

2.1.1. *AIS data*

The AIS data used for analysis in this study was collected via the Kystdatahuset AIS tool by the NCA. The NCA has established an AIS receiving infrastructure consisting of approximately 70 base stations for receiving AIS data from vessels sailing within 40 to 60 nautical miles from the Norwegian baseline. It registers three types of information, namely dynamic (position, course, speed), static (identity, vessel type, dimensions) and voyage related (destination, estimated time of arrival, cargo, draught) (The Norwegian Coastal Administration 2011).

AIS data that can be accessed via the Kystdatahuset website is "cleaned", meaning that positions that are almost certainly erroneous are removed. The service includes historic AIS data going back to 2013 (Kystdatahuset 2021).

Since its inception, AIS data has become more accurate. While in 2004 10.4% of all vessels transmitted errors, this value decreased to 3.5% in 2007 (Shu et al. 2017; Harati-Mokhtari et al. 2007; Bailey, Ellis, and Sampson 2008). Furthermore, Shu et al. (2017) have concluded that dynamic vessel data was generally more accurate than static and voyage related data, with speed over ground only making up 0.8% of the errors.

Vessel speed data was extracted for the study area depicted in Figure 1 in the period from 27 March 2014 to 31 December 2020, resulting in a total of 38,820 data points.

This data was provided in form of a Microsoft Excel sheet, and included the following information: Start and end time, Maritime Mobile Service Identity Number (MMSI)[a], IMO Number[b], ship name, ship type, gross tonnage (GT)[c], length, draft, minimum- average- and maximum speed and number of transmissions received. Presumably due to interferences in transmission, some datapoints did not include all information. Where possible, missing information was added manually by the researcher. This included actions like utilizing a vessels IMO number to look-up and add information like the ship type to the dataset.

Ship type information was then utilized to filter the dataset to only include cargo ships such as bulk carriers, tankers, containerships, general cargo ships and ro-ro vessels in the dataset. This resulted in the removal of other types of vessels such as anchor handling vessels, cable layers, diving support ships, fishing vessels, dredgers and standby safety vessels. These vessels are expected to be constrained more by the nature of their assignment, then by external conditions such as visibility. For example, an increase in visibility is not expected to result in a standby safety vessel increasing its speed while standing by next to a platform.

While it was noted that most vessels had one datapoint for each time they passed the study area, this was not always the case: In some instances, a single passing would result in several datapoints being created. To prevent a skewed dataset, datapoints were merged in these instances, resulting in a dataset with a single datapoint for each unique transit of the study area. In practice this meant that all AIS transmissions received from a vessel transiting the study area within a period of five hours were combined to give a single datapoint for the whole transit. This datapoint included information of the vessel, the average transit speed, as well as the times of when the transit started and ended.

After removing datapoints showing dubious speeds (such as 102.3 knots), and datapoints where no visibility data was available, the final amount of AIS datapoints was 14,420.

2.1.2. *Visibility data*

The visibility data was collected by the Gjøafeltet measuring station, which is located approximately 1.6 nautical miles west of the study area. It was extracted utilizing the observations and weather statistics tool provided by the Norwegian climate service center.

The weather element selected for visibility data was "MOR visibility 1 min", which gives a visibility value between 0 and 20,000 meters every 10 minutes. MOR stands for meteorological optical range, which is an objective measurement of the transparency of the atmosphere. Instruments for the measurement of MOR sample a relatively small region of the atmosphere, and therefore provide an accurate measurement of MOR only when the volume of air they sample is representative of the atmosphere around the point of measurement. While the measurement can therefore be misleading in situations of patchy fog or rain, experience has shown that such situations are not frequent (World Meteorological Organization 2018).

2.1.3. *Merging of research data*

As each AIS datapoint was provided with a start and an end time, it was possible to look-up the average visibility for that time frame from the visibility dataset. This information was then merged with the AIS dataset, resulting in a dataset combining vessel speed with information on the prevailing visibility conditions. Table 2 in section 3.2.3 provides an overview of the different average transit speeds in various visibility ranges.

2.2. *Research approach*

Research data was handled in Microsoft Excel, and the tools available within the program were used to analyze the data. To get an overview of the data, the first step in the research was the creation of several graphs to visualize the contents of the dataset.

[a] An MMSI is a unique nine digit number used by certain marine radio communications equipment (such as AIS) to uniquely identify a ship (Navigation Center 2021).

[b] An IMO number is a unique reference number permanently associated to the hull of a ship (Retsch 2021).

[c] Gross tonnage is a measure of the overall size of a ship (Pearn 2000).

A commonly used graphical method for revealing relationships or associations between two variables is the scatter plot (NIST/SEMATECH 2013). Average transit speeds and average visibility during transit are therefore initially visualized in a scatter plot, with visibility on the x-axis, and average vessel speeds on the y-axis. The Pearson correlation coefficient is plotted as a trendline on the scatter plot, indicating the strength of the association between visibility and speed. If the vessel speeds collected from AIS data represent our current understanding of safe vessel speeds, a clear relationship should be visible, with a clear reduction of vessel speeds in restricted visibility.

Following the graphical representation of the research data in a scatter plot, a simple linear regression was then calculated in Microsoft Excel to predict vessel speeds based on visibility. Regression analysis is the study of relationships between two or more variables, and is usually conducted when we either want to know whether any relationship between two or more variables actually exists, or when we are interested in understanding the nature of the relationship between two or more variables (McIntosh, Sharpe, and Lawrie 2010).

Finally, datapoints were sorted into 20 different visibility groups, each covering a different range of 1,000 meters from 0 to 20,000. This allowed for the calculation of the average transit speeds of vessels in different visibility conditions, and the comparison of – for example – the average transit speed of vessels passing the study area in visibilities between 1,000 and 2,000 meters, and 12,000 and 13,000 meters. An X/Y scatter plot with straight lines was created to visualize the difference in average speeds in different visibility conditions.

3. Results

This section presents the results of this study. In the first subsection general findings are presented, followed by more detailed findings with regards to the effect of visibility on the average transit speeds in the second subsection.

3.1. *General findings*

In the period from 27 March 2014 to 30 December 2020, a total of 14,420 unique transits by 3,438 unique cargo ships through the study area were recorded. The highest number of unique transits by a single vessel was 230, while the lowest was 1. The vessels differed greatly in size, with the smallest vessel having a gross tonnage of 532 and the largest vessel having a gross tonnage of 176,490.

Transits took an average of 22:05 minutes (standard deviation: 09:17 minutes) and happened in visibilities between 88 and 20,000 meters. The recorded average transit speeds through the study area were between 1.4 and 21.6 knots, with an average of 11.2 knots and a standard deviation of 2.4 knots.

Histograms representing the distribution of gross tonnage (Figure 2), transit time (Figure 3), visibility (Figure 4) and average transit speed (Figure 5) can be seen below. Interestingly, even though both the gross tonnage (Figure 2) and visibility distributions (Figure 4) are extremely skewed, the average transit speed histogram (Figure 5) seems to be close to normally distributed.

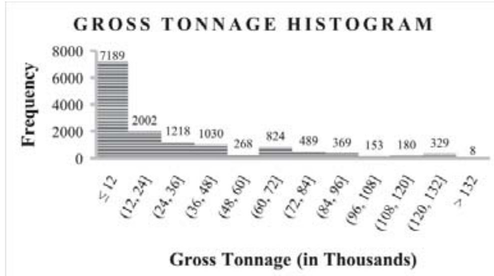

Fig. 2. Gross Tonnage Histogram. Number on top of each bar represents the total number of transits of vessels with different GT.

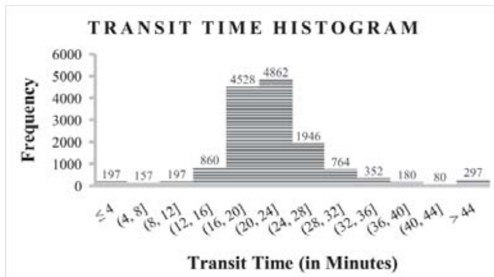

Fig. 3. Transit Time Histogram. Number on top of each bar represents the total number of transits of different length.

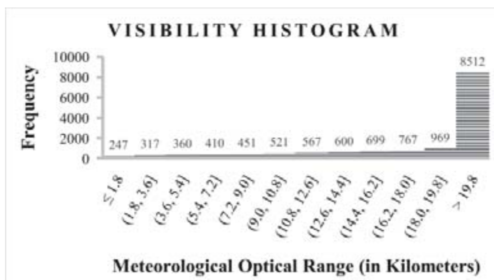

Fig. 4. Visibility Histogram. Number on top of each bar represents the total number of transits in different visibility conditions.

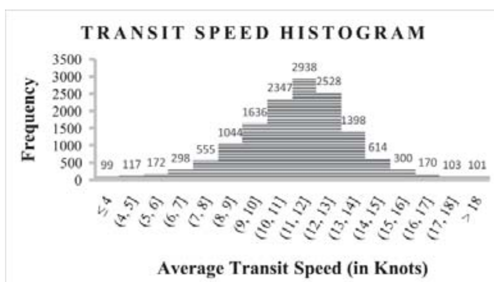

Fig. 5. Transit Speed Histogram. Number on top of each bar represents the total number of transits at different average speeds.

3.2. ***Effect of visibility on average transit speed***

As described in section 2.2 above, three different methods were utilized to investigate the effect of visibility on the average transit speed of vessels through the study area. The results of the scatter plot, the regression analysis, and the representation of average transit speeds in different visibility ranges are presented below.

3.2.1. ***Scatter plot***

Figure 6 shows a scatter plot of the average transit speed of vessels passing through the study area in different visibility conditions. The Pearson correlation coefficient – sometimes referred to as Pearson's r – was calculated to be 0.18. This value is displayed as a dashed line in Figure 6.

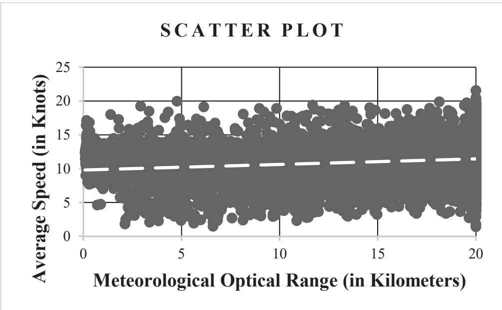

Fig. 6. Scatter plot. The different dots represent the average speeds and visibilities for each transit. Pearson correlation coefficient displayed as a dashed line.

3.2.2. ***Regression analysis***

The result of the simple linear regression calculated in Microsoft Excel, with average speed as the dependent variable, and visibility as the independent variable was as follows: A significant regression equation was found ($F(1, 14{,}418) = 489.647$, $p < 0.000$), with an R^2 of 0.033. The predicted average speed is equal to $9.807 + 0.0822$ (MOR) knots when MOR is measured in kilometers. Average speed increased by 0.0822 knots for each kilometer of MOR.

3.2.3. ***Average speeds in different visibility ranges***

Table 2 shows how the dataset was divided into different groups based on the visibility range during transit.

For each different visibility range, the total number of transits, and the average transit speed of all transits in that visibility range is shown. Details regarding how the AIS and visibility data were combined to create this table were given in section 2.1.3.

The information contained in Table 2 is visualized in Figure 7. Note that the number of datapoints per visibility range is not constant. Only 94 transits occurred in the visibility range of 1 – 2 kilometers, while the visibility range of 19 – 20 kilometers had a total of 9,019 transits.

In the maximum visibility range of 19 – 20 kilometers the average transit speed was 11.53 knots. The data shows that average transit speeds lessen as visibility is reduced, reaching its lowest value in the visibility range of 4 – 5 kilometers. After this, average transit speeds increase sharply even as visibility is further reduced. The highest average transit speed of the whole range of visibility from 0 – 20 kilometers was in the visibility range of 0 – 1 kilometers, with an average transit speed of 11.75 knots.

Table 2. Table showing the average transit speeds in different visibility ranges.

Visibility Range (in Meters):	Number of Transits:	Average Transit Speed (in Knots) in This Visibility Range:
0 – 1,000	174	11.75
1,001 – 2,000	94	11.33
2,001 – 3,000	164	10.08
3,001 – 4,000	211	10.15
4,001 – 5,000	199	9.75
5,001 – 6,000	224	9.98
6,001 – 7,000	220	10.16
7,001 – 8,000	256	10.07
8,001 – 9,000	243	10.23
9,001 – 10,000	267	10.46
10,001 – 11,000	317	10.58
11,001 – 12,000	329	10.49
12,001 – 13,000	286	10.47
13,001 – 14,000	364	10.65
14,001 – 15,000	348	10.74
15,001 – 16,000	400	10.90
16,001 – 17,000	409	10.84
17,001 – 18,000	434	10.85
18,001 – 19,000	462	11.23
19,001 – 20,000	9,019	11.53

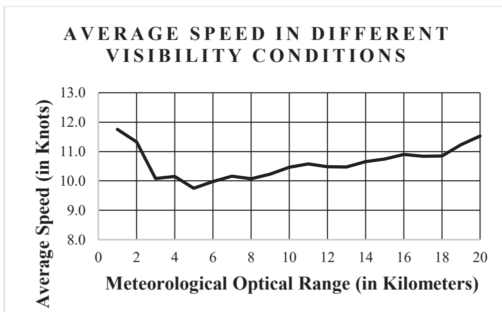

Fig. 7. Graph showing the average transit speeds in different visibility ranges.

4. Discussion

Contemporary commentary on safe speed at sea designates visibility as the primary influencing factor. Furthermore, it is generally agreed that the safe speed in restricted visibility is lower than in perfect visibility. If historic AIS data is to be used to aid MASS in determining the safe speed for the prevailing conditions without human intervention, it must first be ascertained that speed data taken from AIS represents speeds that can be considered safe. This section will discuss whether trends from AIS data can be classified as safe speeds under the contemporary understanding of what constitutes safe speed at sea.

4.1. *Scatter plot*

No clear relationship between visibility and speed can be readily ascertained from the scatter plot (Figure 6), something that is manifested in the lack of predictability in determining the average transit speed from a given visibility value. Looking at the scatter plot, the average transit speed of a vessel passing when the MOR is 10 kilometers could be anywhere between 7 and 18 knots.

Pearson's correlation coefficient was calculated as being 0.18. While a positive value of Pearson's correlation coefficient generally indicates that both visibility and speed increase and decrease together, the strength of relationship is generally judged to be non-existent or very weak when it is below 0.3 (Moore, Notz, and Fligner 2021).

4.2. *Regression analysis*

While the scatter plot did not show a clear relationship between visibility and speed, the regression analysis was able to find a significant regression equation, with the P-value of 1.008×10^{-106} indicating a statistically significant relationship between visibility and speed. This is in line with the expectation that a reduction in visibility should cause a reduction in the speeds of vessels. Nevertheless, the regression equation only has an R^2 value of 0.033. R^2 is the fraction by which the variance of the errors in the model is less than the variance of the dependent variable, meaning that it indicates the percent of variance explained by the model (Nau 2020). This means that the regression analysis found that only 3.3% of variation in average speed can be explained by the variation in visibility.

This can hardly be interpreted as visibility being the primary influencing factor on vessel speeds. Instead, the data shows that there must be other, more influential factors influencing the speeds of vessels. These could be the other factors directly named in the COLREGs, such as traffic density, maneuverability, background light at night, the state of wind, sea and current, the proximity of navigational hazards and the draft in relation to the available depth of water. However, other factors that are unrelated to the goal of proceeding at a safe speed could also have large influences on the speeds that vessels proceed at.

From research into road safety, we know that almost all drivers want to drive faster than the speed that they themselves consider to be a safe speed (Goldenbeld and van Schagen 2007). Reasons for speeding in a road context are diverse and include – among others – temporary motives (such as being in a hurry or adapting the speed to the general traffic stream) and permanent personality characteristics (such as proneness to risk taking or general enjoyment of driving fast) (European Commission 2018). Human perceptual skills and limitations play a role as well, with some situations making it easy to underestimate one's own driving speed. These include situations when a high speed has been maintained for a long period, as well as situations where there is little peripheral visual information (ETSC 1995; Martens, Comte, and Kaptein 1997; Elliott, McColl, and Kennedy 2003). It is easy to find maritime examples for situations that provide little peripheral information, such as navigating in the open sea, at night, or – maybe most importantly in this context – in fog.

Additionally, we have learned from Rasmussen (1997) that "human behavior in any work system is shaped by objectives and constraints which must be respected by the actors for work performance to be successful". The navigators setting the speed on the different vessels are not only bound by safety related constraints, but by administrative and functional constraints as well. The decision at which speed a vessel will proceed is therefore not only influenced by factors relating to safety, but by factors relating to efficiency and reduction of effort as well. Speed decisions made by navigators on board a vessel can be seen as being under immense outside pressure, with standard ocean shipping contracts requiring vessels to proceed at 'utmost dispatch', and first-come, first-served berthing policies adding additional incentives for navigators to proceed at full speed (Alvarez, Longva, and Engebrethsen 2010).

With only 3.3% of the speed variation in the dataset being able to be explained by changes in visibility, it seems prudent to explore the possible impact of non-safety related influences on the speed that vessels proceed at, before utilizing speed data from AIS to teach MASS what constitutes safe speed.

The other interesting value of the regression equation is the coefficient of 0.0822. For each kilometer of increased visibility, vessel speed only seems to be increasing by 0.0822 knots. With the difference between what the Met Office describes as good and very poor visibility being 8.26 kilometers, this means that the regression equation predicts a vessel experiencing a deterioration of visibility from good to very poor to reduce its speed by approximately 0.7 knots (0.0822 x 8.26).

Cockcroft and Lameijer (2012), whose Guide to the Collision Avoidance Rules is described as the essential reference to safe operation of all vessels at sea, provide an example on safe speed in restricted visibility from the legal case of the collision between the *Hagen* and the *Boulgaria*. Here it was stated that a radar equipped vessel normally capable of proceeding at 13.5 knots would be expected to reduce its speed to about 8 to 9 knots when proceeding in visibility of approximately 1.1 kilometers. Note that this expected speed reduction was stated for a vessel equipped with radar, i.e. a vessel that was not solely reliant on human senses such as sight and hearing but could instead utilize technology to perceive its environment. This example is therefore well-suited for application to MASS, which will also rely on technology – and not on human senses – to perceive their surroundings. When comparing this expected speed reduction of 4.5 – 5.5 knots with the 0.7 knots expected by the regression equation of the AIS dataset, it becomes clear that the reduction of speed in reduced visibility observed in the AIS data is not nearly enough to be classified as sufficient by our current understanding of safe speed.

4.3. *Average speeds in different visibility ranges*

Perhaps the most interesting finding of this study is visualized in Figure 7. While commentary on the safe speed requirement of the COLREGs states that the need to moderate speed generally applies in restricted visibility and that it is dangerous to go fast when visibility is poor, the AIS data shows that the average transit speed of vessels passing the study area in very poor visibility conditions was higher than that of any other visibility range.

Starting at the maximum measured MOR of 20 kilometers, average transit speeds in the different visibility ranges gets smaller as visibility is reduced. This trend continues until the measured MOR reaches 4 kilometers, at which point average transit speeds increase as visibility is reduced.

Referring to the visibility definitions by the Met Office stated in Table 1, we can see that the visibility range of 3,704 meters to 9,260 meters is called moderate visibility. The data therefore shows that in moderate to good visibility, the measured average transit speeds decreased as visibility deteriorated, while in very poor to poor visibility, the measured average transit speeds increased as visibility deteriorated.

This phenomenon of vessel speeds increasing as visibility decreases in very poor to poor visibility conditions is in direct opposition to our current understanding of safe speed. This is therefore another indicator that vessel speeds collected via AIS do not represent safe vessel speeds in the prevailing circumstances.

To understand why average vessel speeds are highest in very poor visibility conditions, more research is necessary. It is possible to hypothesize that more influential factors on vessel speeds – such as the influence of wind and waves – are greatly reduced in situations of very poor visibility. For example, light winds increases the likelihood of fog forming, while high wind generally prevents for from forming (Haby 2021).

5. Conclusion

This research paper had the following research question:
Can MASS autonomously determine the safe speed by utilizing historic AIS speed data of other vessels?
To find an answer to the research question, AIS speed data was scrutinized to ascertain if it could be taken to represent safe speed. As visibility is stated to be of major importance when determining the safe speed and the need to reduce speed generally applies in restricted visibility, this process was conducted by answering the following research sub-questions:

(i) Does AIS and visibility data show a strong relationship between visibility and vessel speeds?
(ii) Does AIS data show a trend of vessels proceeding at a reduced speed in restricted visibility?

The regression analysis conducted in this study found a statistically significant relationship between visibility and speed. However, the regression equation is only able to explain 3.3% of the speed variation in the dataset with changes in visibility. Factors other than visibility are therefore likely to have a larger influence on vessel speeds observed on AIS. Furthermore, the regression equation predicts the average speeds of vessels transiting the study area in good and very poor conditions to only differ by approximately 0.7 knots.

By dividing transits into different visibility groups, this study showed that average transit speeds in very poor visibility are the highest of any visibility group. Instead of showing a reduction of speed in restricted visibility, the data shows that the average transit speeds actually increase as visibility deteriorates in poor to very poor visibility conditions.

Vessel speed data taken from AIS therefore shows that while there is a statistically significant relationship between visibility and speed, it is not particularly strong. Moreover, vessels do not show a reduction of speed in restricted visibility. It can therefore be concluded that there is a difference between the predicted changes in vessel speeds – based on contemporary theoretical understanding of safe speed – and the actual differences in vessel speeds in different visibility conditions. This difference can be either due to our contemporary understanding of safe speed being flawed, or because speed data taken from AIS does not represent safe speeds in all conditions. This is because the speeds of vessels are not only influenced by factors relating to safety, but by factors relating to efficiency and reduction of effort as well.

The problem of quantifying the safe speed of a vessel in different conditions therefore does not seem to be easily solvable by simply using historic AIS data to create a model of normalcy which a MASS can follow. More research in this area is necessary to gain a deeper understanding of what a safe speed constitutes and how this knowledge can be transferred to any MASS sailing the seas in the future.

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Appendix 3.

Relation Analysis of Ship Speed & Environmental Conditions: Can Historic AIS Data Form a Baseline for Autonomous Determination of Safe Speed?

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RESEARCH ARTICLE

Relation analysis of ship speed & environmental conditions: Can historic AIS data form a baseline for autonomous determination of safe speed?

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Abstract
As no internationally agreed-upon method for determining safe speed values currently exists, collecting vast amounts of information on conventional ship behaviour could be used to train autonomous ship intelligence in determining safe speeds in different conditions. This requires speed data collected from conventional ships to resemble what can be described as safe speeds. To test this, the Automatic Identification System (AIS) and environmental data – namely visibility, mean wind speed and significant wave height – were collected and merged for two study areas in Norway in the period between 27 March 2014 and 1 January 2021. Regression analyses based on 47,490 unique vessel transits were conducted and supplemented by two graphical methods for revealing relationships between variables. Contrary to the contemporary understanding of safe speed, reduced visibility did not lead to significantly reduced transit speeds. Wind and waves caused a reduction in speed in the open ocean, but not in coastal waters. Transit speeds were lower in coastal waters than in the open ocean.

1. Introduction

Autonomous shipping has been one of the hot topics in shipping for the past few years. The topic has received widespread attention by academia, regulatory bodies, and private companies alike. With projects such as the *Yara Birkeland*, we now have actual cargo ships in operation that are online to operate fully autonomously by the year 2024 (Raza, 2022). The International Maritime Organization (IMO) – the United Nations specialised agency with responsibility for the safety and security of shipping – has responded to the push for autonomy by conducting a regulatory scoping exercise on Maritime Autonomous Surface Ships (MASS), which was finalised in May 2021. With so much development happening in the field of autonomous shipping, the need for research in the area is as vital as ever.

A systematic review of the safety challenges for MASS published in 2019 (Dreyer and Oltedal, 2019) highlighted a number of areas that needed further research, among them the development of smart methods and criteria that support MASS compliance with the International Regulations for the Prevention of Collisions at Sea (COLREGs), which state the basis of agreed practices for avoiding collisions at sea. The need for smart methods and criteria lies in the nature of the COLREGs, which relies on a large number of qualitative terms [such as ‘early’ and ‘substantial’ (Porathe, 2019)], thereby delegating much of the rule-system to the interpretation of the navigator. This constant requirement to interpret qualitative terms included in the rules is exemplified by the requirement for all vessels to proceed at a safe speed at all times (IMO, 1972). The rules do not provide any quantification as to what speeds could be considered ‘safe’, and while attempts have been made at quantification, the IMO has not agreed upon an acceptable method for determining what value of speed could be considered 'safe' (Cockcroft and Lameijer, 2012). It is unlikely that the rules will be amended in a way that removes these qualitative terms in the near future, for two reasons. Firstly, ambiguity is said to be the necessary price of applicability, as a completely prescriptive and rigid rule-system would be infinitely complicated (Taylor, 1990). Secondly, the IMO has stated in the recently published outcome of the regulatory scoping exercise on the use of MASS 'that COLREG in its current form is still the reference point and should retain as much of its current content as possible' (IMO, 2021, p. 86).

As collision avoidance is seen as a game of coordination where navigators on different vessels must independently choose mutually compatible strategies (Cannell, 1981), it is of utmost importance to ensure that MASS behave in a way that is coherent to human navigators. Already today, the interaction between traditional ships is seen as problematic (Porathe, 2019), and collisions do still occur. It is warned that autonomous ships following a machine interpretation of the COLREGs may lead to even more uncertainty in the future, possibly causing more navigational problems (Porathe, 2019).

A proposed solution to this problem is the utilisation of deep-learning in autonomous ship system intelligence. Under this approach, vast amounts of information on conventional ship behaviour – including vessel speed and external environmental conditions – is collected as big data sets that are used for training autonomous ship intelligence. Humans essentially train the autonomous vessels, causing them to exhibit similar behaviour in similar circumstances (Perera, 2018). The deep-learning solution is seen as promising, as a similar approach in driverless cars has achieved promising results in terms of navigating with the required safety levels (Liu et al., 2017). Note that the deep-learning approach – which essentially envisions MASS mimicking conventional ship behaviour – hinges on conventional ship behaviour being both safe and legal. However, contemporary research on the application of deep-learning in autonomous ship intelligence commonly ignores this requirement. Instead, historic data is regularly utilised to build models of normalcy (Yan et al., 2020), where adherence to the model is seen as a sign of safety (Xu et al., 2019) and deviation is seen as a sign of high-risk behaviour (Yan et al., 2020).

This paper therefore explores whether vessel speed data collected from conventional ships in various external environmental conditions actually resemble safe speeds, and can therefore be used for deep-learning purposes in MASS. This is done by comparing the data with accepted interpretations of what constitutes a safe speed.

The research questions this paper aims to answer are as follows:

1. What are the relationships between vessel speeds and visibility, and wind and waves in coastal waters and in the open ocean?
2. Do the observed speeds qualify as safe speeds under the contemporary theoretical understanding of safe speed?

2. Safe speed determination

As mentioned in the Introduction, rule 6 of the COLREGs requires that 'every vessel shall at all times proceed at a safe speed', without ever quantifying what speeds could be considered 'safe' in different conditions (IMO, 1972). Neither is there an internationally agreed-upon method for determining safe speed values. So, what constitutes a safe speed? The COLREGs themselves define it as a speed where a vessel 'can take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions' (IMO, 1972). Examples of factors that shall be taken into account when evaluating the prevailing conditions include visibility, traffic density, manoeuvrability, background light and proximity of navigational hazards, as well as the state of wind, sea and current. Visibility is listed first among the factors to be taken into account (IMO, 1972).

This apparent importance of visibility is reverberated in various available guides and commentary to the COLREGs. In his inquiry into safe speed, Kavanagh (2001) notes that there is a general rule of thumb where vessels are proceeding at a safe speed when they can be stopped within half the distance of the visibility. While he does not agree that this 'half-visibility' rule should be adopted as a starting

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point for assessing a safe speed, he does conclude with the statement that visibility is the primary consideration in determining safe speed. In their guide to the collision avoidance rules, Cockcroft and Lameijer (2012) assert that 'visibility is obviously of major importance' (Cockcroft and Lameijer, 2012, p. 20), and that it is 'in restricted visibility that the need to moderate the speed generally applies' (Cockcroft and Lameijer, 2012, pp. 17–18). Rutkowski (2016) simply declared that it is dangerous to go fast when visibility is poor.

To get an understanding of what it means for visibility to be poor, the visibility classification of the national meteorological service of the United Kingdom – the Met Office – can be utilised. The definitions included in their marine forecasts glossary can be accessed in the Appendix, Table A1.

When it comes to other environmental factors – such as wind and waves – less guidance is available. In their comments to rule 6 of the COLREGs, Cockcroft and Lameijer (2012) do not mention wind at all and sea state only in combination with visibility, as high waves may hinder the detection of other vessels by radar. Kavanagh (2001) sees the state of wind and sea as an important consideration in the determination of safe speed, but also couples these factors to visibility. In his legal inquiry, Kavanagh noted that precedent requires a reduction of speed in a hurricane, where waves reach up to 15 metres in height and visibility is reduced to zero due to spray and foam in the air (Kavanagh, 2001).

When looking at the contemporary guides, commentary and research on the COLREGs and safe speed, our current understanding of safe speed requires vessel speeds to adhere to the following general pattern: Safe vessel speeds have a strong correlation with the prevailing visibility conditions, and generally require a reduction of speed when visibility is restricted. The association between safe vessel speeds and the state of wind and sea is less transparent – while the importance of the state of wind and sea is said to be less than that of the state of visibility, vessel speeds should be reduced in conditions of strong winds and high seas to remain safe.

3. Description of research approach, study area and collected data

This section first discusses the research approach of this paper, then introduces the reader to the geographical areas for which data was collected, and finally provides an overview of the data collected.

3.1. Research approach

The wide availability of historic Automatic Information System (AIS) data has meant that these data have been used as the big data basis in research projects on MASS autonomous navigation (Gao et al., 2022). AIS is a communications system that provides automatic reporting between ships and to shore by exchanging information such as identity, position, time, course and speed (IALA, 2016). However, if speed data collected from conventional ships in various external environments are to be used to teach MASS how safe speed is determined, it must first be verified that the data themselves represent both safe and legal speeds. By analysing vessel speed data received from AIS with respect to data on the external environmental conditions, this paper looks closer at whether vessel speed data collected from AIS would contemporarily be considered safe speeds.

Dreyer (2021) collected AIS and visibility data in open waters off the Norwegian coast, and looked at whether the AIS and visibility data show a strong relationship between visibility and vessels speeds, and whether the AIS data shows a trend of vessels proceeding at a reduced speed in restricted visibility. In this paper, the visibility data collected offshore are supplemented by wind and wave data. Additionally, AIS, wind, and visibility data were collected for an additional location in a Norwegian sound, allowing for comparison of vessel speed behaviour in locations with different traffic densities and proximity to navigational hazards. This inclusion of additional data advances the previous research, as more factors that the COLREGs commands to be considered are included in the analysis. More information on the data collected, and where they were collected, is given in Sections 3.2 and 3.3.

The research data were handled in Microsoft Excel, and the tools available within the program were used to analyse the data. Analysis included both visual means in the form of graphs, and simple linear

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regression analyses for predicting vessel speeds based on different variables. Regression analysis is the study of relationships between two or more variables and is usually conducted when we either want to know whether any relationship between two or more variables exists or when we are interested in understanding the nature of the relationship between two or more variables (McIntosh et al., 2010). The result is a regression equation:

$$Y = \beta_0 + \beta_1 X \tag{1}$$

where Y is the dependent variable, X is the independent variable, β_0 is the Y intercept, and β_1 is the slope coefficient. A regression equation was deemed to be significant when the calculated p-value[1] was less than $0 \cdot 05$.

The data analysis is presented in Section 4, the results highlighted in Section 5 and a discussion follows in Section 6. In the discussion, the focus will be on determining whether our contemporary understanding of safe speed would consider the data to represent safe vessel speeds.

3.2. Study areas

This section introduces the two study areas in which AIS and external environmental data were collected.

3.2.1. Gjøa A

The first area, which is identical to the study area described in the previous research conducted by Dreyer (2021), is located approximately 18 nautical miles off the coast of Western Norway. This area was chosen due to its location in open sea close to normal shipping routes, combined with the availability of historic AIS and external environmental data. Due to its proximity to the 'Gjøa A' platform – where the historic external environmental data were measured – the area will be called the Gjøa A study area in this paper. Figure 1 depicts the location of the Gjøa A study area.

The Gjøa A study area is approximately 4 · 2 by 4 · 2 nautical miles in size, located to the east of the Gjøa A platform between the traffic separation scheme (TSS) Off Stad in the north and TSS Off Sotra in the south. As can be seen in Figure 1, the measuring station for external environmental data is located outside the Gjøa A study area. While this may have the negative consequence of the external environmental data measured at the measuring station differing slightly from the actual external environmental data within the Gjøa A study area, the decision to place the study area to the east of the platform was taken to ensure two things. First, the Gjøa A study area was chosen due to its location in open sea, and having a large platform located within the study area may cause disturbing effects that are difficult to control. Second, moving the study area to the east of the external environmental data measuring station ensures that the location of the Gjøa A study area is within a normal shipping lane. As can be seen from the AIS density plot overlay in Figure 1, the study area covers traffic transiting southbound along the Norwegian west coast, while avoiding most of the nontransit traffic around the Gjøa A platform. The water depth in the study area is approximately 350 metres. The dangerous waves that might be encountered at Værøygrunnen, which is approximately 10 nautical miles east of the Gjøa A study area, are unlikely to affect vessels navigating in the Gjøa A study area. This is because while the water depth at Værøygrunnen is rapidly decreasing to shallow waters, water depths in the Gjøa A study area are uniform and deep.

3.2.2. Sotra Bridge

The second area for which data were collected in this paper is an area centred around the Sotra Bridge, a suspension bridge that crosses the Knarreviksund in Western Norway. It was chosen because it covers normal shipping routes in coastal waters, with readily available AIS and external environmental data. As the area is centred around the Sotra Bridge, it will be called the Sotra Bridge study area in this paper. Figure 2 depicts the location of the Sotra Bridge study area.

[1] If the p-value is above 0.05, a straight-line model in X does not help predicting Y (Alexopoulos, 2010).

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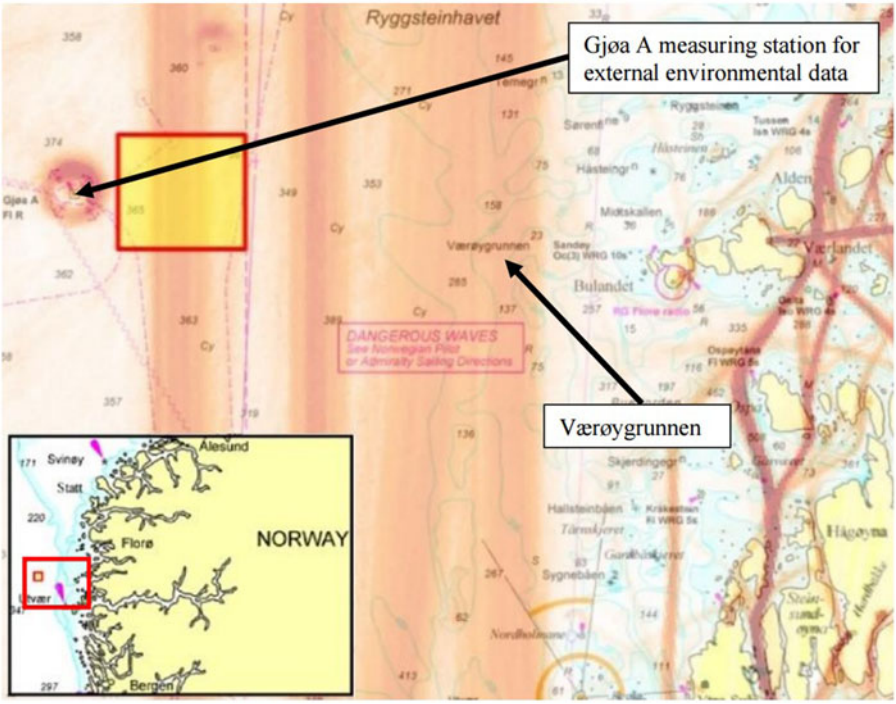

Figure 1. *Location of study area: West of Bulandet, off the mainland coast of Western Norway. AIS density plot overlay (in orange) shows common shipping routes.*

The Sotra Bridge study area is approximately 1 by 2 nautical miles in size, covering the 'Y-junction' between the Byfjord, Hjeltefjord and Raunefjord. As such, the area is crossed by vessels navigating between Bergen to the east, the Hjeltefjord to the north and the Raunefjord to the south. The measuring station for the external environmental data is on the Sotra Bridge, located in the centre of the study area. The AIS density plot overlay in Figure 2 show that the traffic pattern in the Sotra Bridge study area is more complex than that of the Gjøa A study area. Water depths in the Sotra Bridge study area vary depending on the distance from shore in the middle of the fairway; they are approximately 80 metres south of the bridge and 140 metres north of the bridge. Tidal currents in the area are described as not very strong (Kartverket Sjødivisjonen, 2018).

3.3. Collected data

This section introduces the type of data collected for the research in this paper. This includes AIS data providing the speeds of vessels transiting the study areas, as well as environmental data – including data on visibility, wind and waves – for the period from 27 March 2014 to 01 January 2021.

3.3.1. AIS data

The Norwegian national AIS network consists of both shore- and satellite-based AIS, where the shore-based AIS network consisting of about 90 base stations that monitor coastal traffic up until approximately 40 to 60 nautical miles from the coast (Norwegian Coastal Administration, 2022). The AIS data collected by the Norwegian Coastal Administration (NCA) include three types of information, namely dynamic (position, course, speed), static (identity, vessel type, dimensions) and voyage related (destination, estimated time of arrival, cargo, draught) and can be universally accessed via the NCA's Kystdatahuset service. Any data accessible here have been 'cleaned', meaning that datapoints that almost certainly are erroneous have automatically been removed (Kystdatahuset, 2022).

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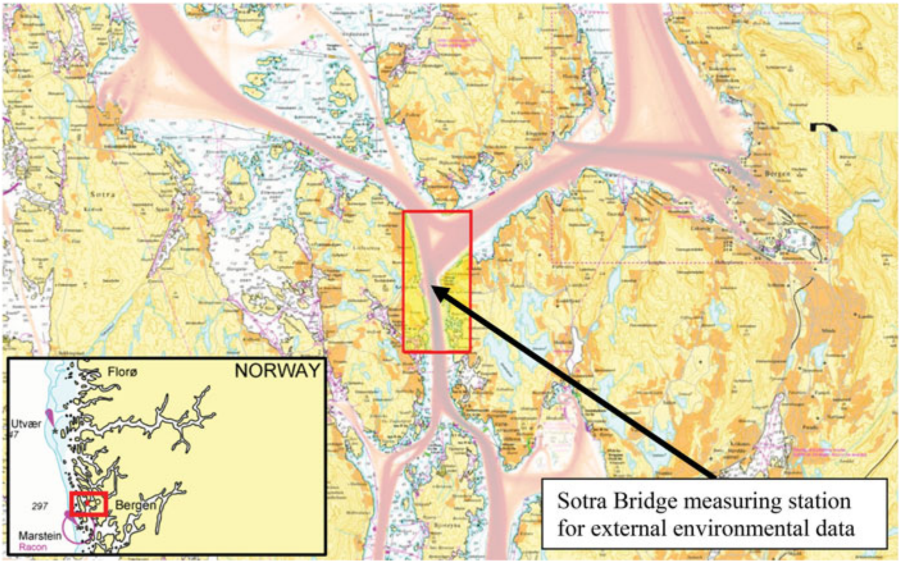

Figure 2. *Location of study area: West of Bergen, in coastal waters of Western Norway. AIS density plot overlay (in orange) shows common shipping routes.*

Even though the NCA automatically removes datapoints that most certainly are erroneous, it must be noted that since its inception, AIS data have become more accurate: Erroneous transmissions from vessels have decreased from 10 · 4% in 2004 to only 3 · 5% in 2007 (Harati-Mokhtari et al., 2007; Bailey et al., 2008; Shu et al., 2017). From the three types of information conveyed via AIS, dynamic vessel data were the most accurate, with errors in the transmission of speed over ground only making up 0 · 8% of the errors (Shu et al., 2017).

Two independent AIS datasets were collected from the Kystdatahuset service: One for the Gjøa A study area and one for the Sotra Bridge study area. The AIS dataset for the Gjøa A study area included a total of 38,820 datapoints between 27 March 2014 and 30 December 2020. The AIS dataset for the Sotra Bridge study area included a total of 187,581 datapoints between 15 March 2016 and 01 January 2021.

The AIS data were provided by the Kystdatahuset service of the NCA in a Microsoft Excel sheet, and included the following information for the timeframe in which each vessel was within the study area: Start and end time, Maritime Mobile Service Identity Number (MMSI)[2], IMO Number[3], ship name, ship type, gross tonnage (GT)[4], length and draft, plus minimum, average, and maximum speed, and number of transmissions received.

The researcher scanned the dataset manually for any datapoints including missing/erroneous data, which were removed from the dataset. Furthermore, the ship type information was utilised to filter the dataset to only include cargo ships, such as bulk carriers, tankers, containerships, general cargo ships and ro-ro vessels[5] in the dataset. This resulted in the removal of other types of vessels, such as anchor handling vessels, cable layers, diving support ships, fishing vessels, dredgers and standby safety vessels, as these vessels are expected to be constrained more by the nature of their assignment than by external conditions, such as visibility. For example, an increase in visibility is not expected to result in a standby safety vessel increasing its speed while standing by next to a platform.

While most vessels had one datapoint for each time they passed the study area, this was not always the case: In some instances, a single passing would result in several datapoints being created. To prevent a

[2]An MMSI is a unique nine-digit number used by certain marine radio communications equipment (such as AIS) to uniquely identify a ship (Navigation Center 2021).

[3]An IMO number is a unique reference number permanently associated to the hull of a ship (Retsch 2021).

[4]Gross tonnage is a measure of the overall size of a ship (Pearn 2000).

[5]Ro-ro stands for roll-on/roll-off and describes vessels that transport wheeled cargo.

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Table 1. Weather station information (Norwegian Centre for Climate Services, 2022).

Station name	Gjøafeltet	RV555 Sotrabrua VInd
Station number (id)	SN76954	SN50526
Height above mean sea level	0 metres	50 metres
Latitude	$61 \cdot 3322$°N	$60 \cdot 3725$°N
Longitude	$3 \cdot 897$°E	$5 \cdot 1738$°E

skewed dataset, datapoints were merged in these instances, resulting in a dataset with a single datapoint for each unique transit of the study area. In practice, this meant that all AIS transmissions received from a vessel transiting the study area within a period of five hours were combined to give a single datapoint for the entire transit. This datapoint included information about the vessel and the average transit speed, as well as the times of when the transit started and ended. The final dataset included a total of 14,498 unique vessel transits by 3,475 unique cargo ships through the Gjøa A study area, and a total of 32,992 unique vessel transits by 1,004 unique cargo ships through the Sotra Bridge study area.

3.3.2. Environmental data

The Norwegian Centre for Climate Services (NCCS) provides historic data of observations and measurements from Norway's weather stations. Environmental data utilised in this study were collected at station number SN76954 (Gjøafeltet) for the Gjøa A study area and at station number SN50526 (RV555 Sotrabrua VInd) for the Sotra Bridge study area. More information on the weather stations is detailed in Table 1.

Data for the following weather elements were collected in 10-minute intervals between 27 March 2014 and 31 December 2020 at both weather stations: Meteorological Optical Range (MOR) visibility 1 min[6] and mean wind speed[7]. In addition, data for significant wave height[8] were collected in 10-minute intervals in the same timeframe only at station number SN76954 (Gjøafeltet), as this weather element was not recorded at station number SN50526 (RV555 Sotrabrua VInd). The final database of environmental data was made up of 354,563 datapoints collected from station number SN76954 (Gjøafeltet) and 206,733 datapoints collected from station number SN50526 (RV555 Sotrabrua VInd).

3.3.3. Merging of research data

As each AIS datapoint was provided with both a start and end time, it was possible to look up the average environmental conditions for each vessel transit through the study areas from the environmental dataset. This allowed for the AIS dataset and the environmental dataset to be merged into one dataset. To ensure a smooth dataset, any vessel transits for which no or faulty environmental data were available were removed from the final dataset.

The final dataset included 14,498 vessel transits with available environmental data through the Gjøa A study area, and 32,992 transits with available environmental data through the Sotra Bridge study area.

[6]"MOR visibility 1 min" gives a visibility value between 0 and 20,000 metres every 10 minutes. MOR stands for meteorological optical range, which is an objective measurement of the transparency of the atmosphere. Instruments for the measurement of MOR sample a relatively small region of the atmosphere, and therefore provide an accurate measurement of MOR only when the volume of air they sample is representative of the atmosphere around the point of measurement. While the measurement can therefore be misleading in situations of patchy fog or rain, experience has shown that such situations are not frequent (World Meteorological Organization 2018).

[7]"Mean wind speed" is registered as a mean value of the wind speed over the last ten minutes before the observation time at 10 metres above ground (Norwegian Centre for Climate Services 2022a).

[8]"Significant wave height" is a statistic computed from wave measurements and corresponds to the average height of the highest one-third of the waves, where the height is defined as the vertical distance from a wave trough to the following wave crest (Norwegian Centre for Climate Services 2022a).

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4. Data analysis

This section presents the data analysis of this study, intitially providing an overview of the dataset in Table 2.

Histograms representing the distribution of gross tonnage, visibility, mean wind speed, significant wave height and transit speed can be accessed in the Appendix, Figures A1–A9. It is noteworthy that the average transit speed histograms for both study areas seem to be close to normally distributed.

The analysis of the effect of environmental factors on average transit speeds will be presented by utilising visual means and statistical analysis. For the visual means, scatterplots are employed and supplemented by a red-line graph showing the average transit speeds in different environmental conditions. To achieve this, the dataset was divided into different groups based on the environmental conditions present during transit. Numerical data, including information on the total number of transits and quartiles in each environmental range, can be accessed in the Appendix, Tables A4–A8 and Figure A10–A14. In this regard, note that the number of datapoints used to calculate the average transit speeds vary. Where average transits speeds are based on a larger sample size, greater precision can be expected. The calculated regression equations are illustrated as a dashed-green line in the scatterplots, and more detailed information on the results of the regression analyses can be accessed in the Appendix, Tables A9–A12.

4.1. Visibility

This section presents the analysis of the relationship between visibility and average transit speeds. A simple linear regression analysis, with average speed as the dependent and visibility as the independent variable, was conducted for both study areas. The significant regression equation with an R^2 value of $3 \cdot 3\%$ for the Gjøa A study area is provided in Equation (2), while the significant regression equation with an R^2 value of $0 \cdot 0\%$ for the Sotra Bridge study area is provided in Equation (3):

$$Y = 9 \cdot 81 + 0 \cdot 08\ X_1 \tag{2}$$

$$Y = 10 \cdot 31 + 0 \cdot 01\ X_1 \tag{3}$$

where Y is average speed estimated in knots, and X_1 is meteorological optical range measured in kilometres. The Pearson correlation coefficient was calculated to be $0 \cdot 18$ for the Gjøa A study area, and $0 \cdot 02$ for the Sotra Bridge study area (Figures 3 and 4).

4.2. Mean wind speed

This section presents the analysis of the relationship between mean wind speed and average transit speeds. A simple linear regression, with average speed as the dependent and mean wind speed as the independent variable, was conducted for both study areas. The significant regression equation with an R^2 value of $9 \cdot 7\%$ for the Gjøa A study area is provided in Equation (4), while the significant regression equation with an R^2 value of $0 \cdot 0\%$ for the Sotra Bridge study area is provided in Equation (5):

$$Y = 12 \cdot 61 - 0 \cdot 19\ X_2 \tag{4}$$

$$Y = 10 \cdot 55 - 0 \cdot 01\ X_2 \tag{5}$$

where Y is average speed estimated in knots and X_2 is mean wind speed measured in metres/second. The Pearson correlation coefficient was calculated to be $-0 \cdot 31$ for the Gjøa A study area, and $-0 \cdot 01$ for the Sotra Bridge study area (Figures 5 and 6).

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Table 2. Overview of the dataset.

	Gjøa A study area				Sotra Bridge study area			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Unique transits by single vessel	4	12	1	230	33	82	1	960
Gross tonnage	26,830	31,000	532	176,490	3,093	2,742	132	25,609
Average transit speed (in knots)	11·2	2·4	1·4	21·6	10·5	2·4	0·7	20·1
Visibility (in metres)	16,740	5,267	88	20,000	18,544	4,395	0	20,000
Wind speed (in metres/second)	7·7	4·0	0	27·7	5·2	3·6	0·2	22·5
Wave height (in metres)	2·5	1·4	0·3	11·5	*No data available*			

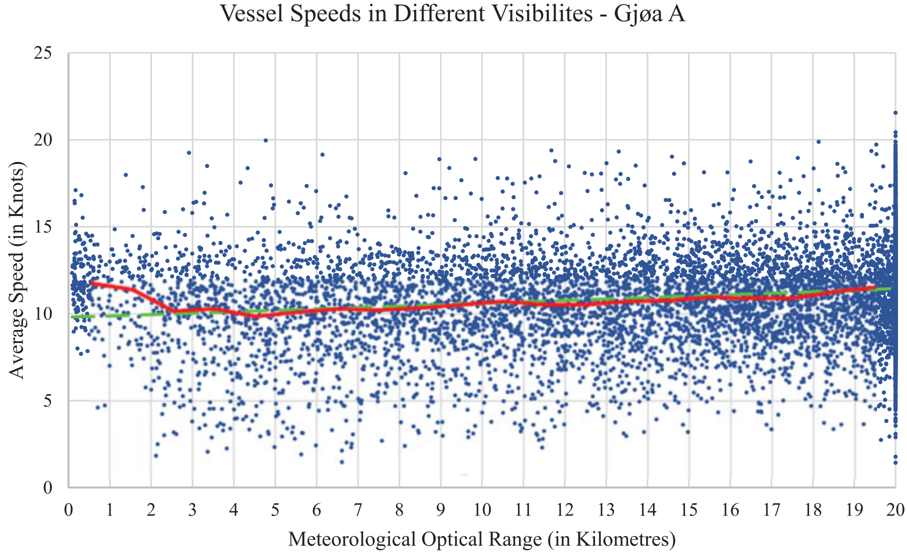

Figure 3. *Speed/Visibility scatterplot. The different dots represent the average speeds and visibilities for each transit through the Gjøa A study area. The red line represents the average transit speeds through the area in different visibility ranges. The dashed green line represents the result of regression Equation (2).*

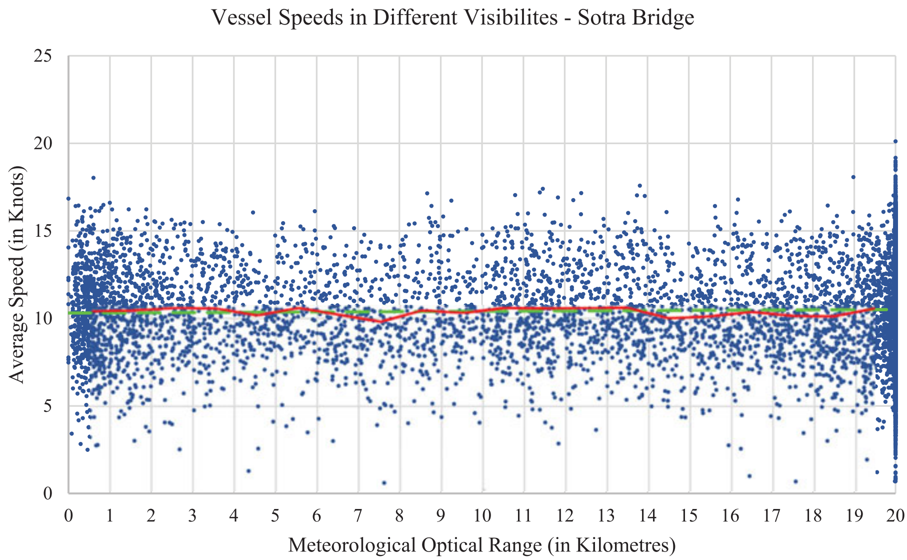

Figure 4. *Speed/Visibility scatterplot. The different dots represent the average speeds and visibilities for each transit through the Sotra Bridge study area. The red line represents the average transit speeds through the area in different visibility ranges. The dashed green line represents the result of regression Equation 3) above.*

4.3. Significant wave height

This section presents the analysis of the relationship between significant wave height and average transit speeds. A simple linear regression, with average speed as the dependent and significant wave height as the independent variable, was conducted only for the Gjøa A study area, as no data on significant wave height was available for the Sotra Bridge study area. The significant regression equation with an R^2

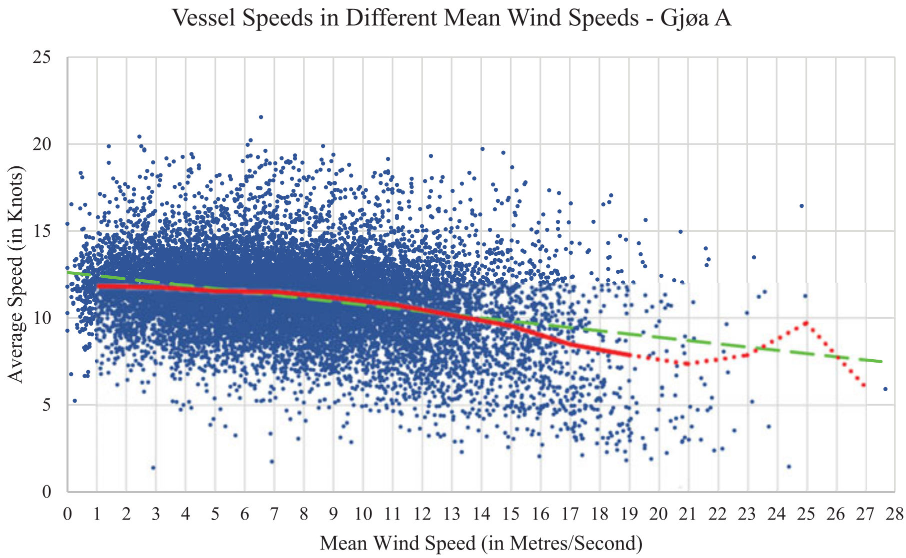

Figure 5. *Speed/Mean Wind scatterplot. The different dots represent the average speeds and mean wind speeds for each transit through the Gjøa A study area. The red line represents the average transit speeds through the area in different mean wind speed ranges. Where fewer than 50 datapoints were used to calculate the average, the red line is displayed as a dotted line. The dashed green line represents the result of regression Equation (4).*

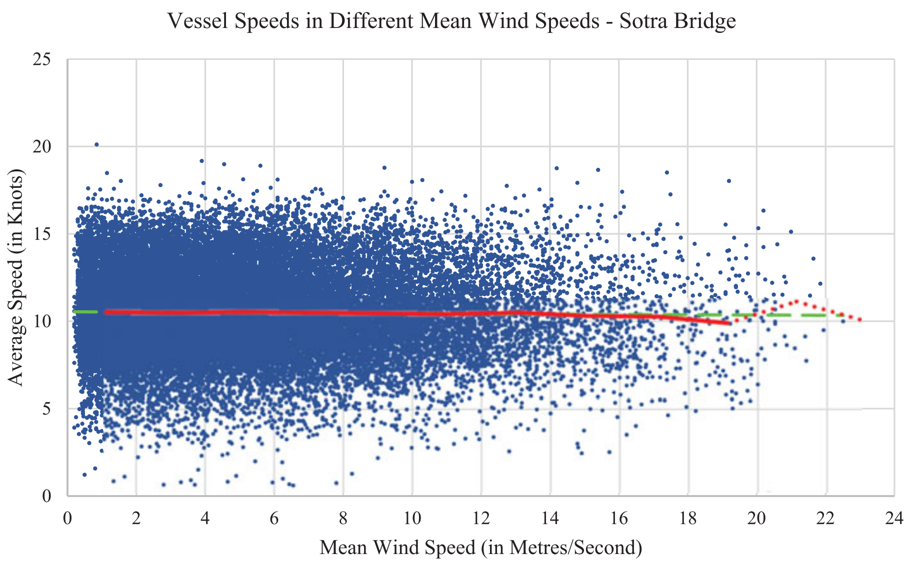

Figure 6. *Speed/Mean Wind scatterplot. The different dots represent the average speeds and mean wind speeds for each transit through the Sotra Bridge study area. The red line represents the average transit speeds through the area in different mean wind speed ranges. Where fewer than 50 datapoints were used to calculate the average, the red line is displayed as a dotted line. The dashed green line represents the result of regression Equation (5).*

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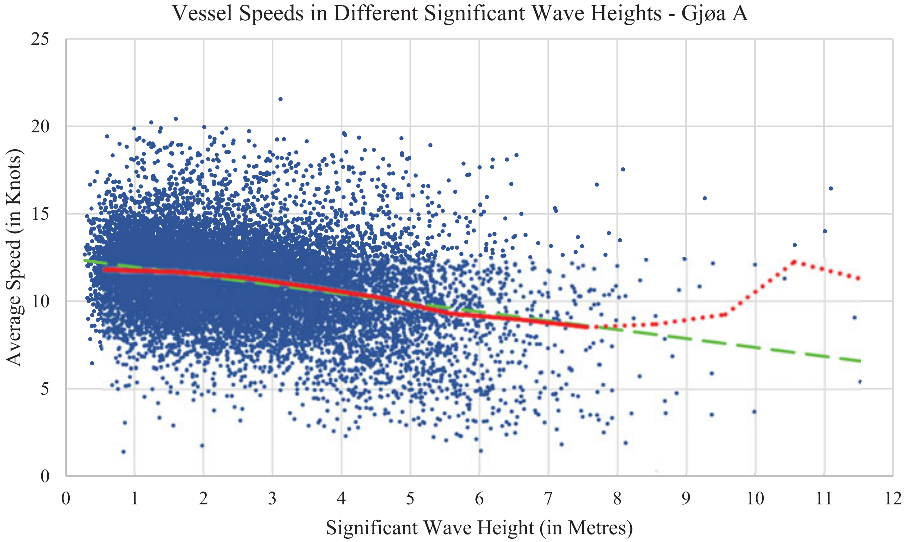

Figure 7. Speed/Wave scatterplot. The different dots represent the average speeds and significant wave heights for each transit through the Gjøa A study area. The red line represents the average transit speeds through the area in different significant wave height ranges. Where fewer than 50 datapoints were used to calculate the average, the red line is displayed as a dotted line. The dashed green line represents the result of regression Equation (6).

value of $9 \cdot 5\%$ is provided in Equation (6).

$$Y = 12 \cdot 47 - 0 \cdot 51\ X_3 \tag{6}$$

where Y is average speed estimated in knots, and X_3 is significant wave height measured in metres. The Pearson correlation coefficient was calculated to be $-0 \cdot 31$ (Figure 7).

4.4. Combination of different environmental factors

In addition to the simple linear regressions reported, multiple linear regressions were used to test whether the different environmental factors can be combined to predict average transit speeds through the study areas. For the Gjøa A study area, the multiple linear regression included visibility, mean wind speed and significant wave height, while the multiple linear regression for the Sotra Bridge study area only included visibility and mean wind speed. The resulting significant regression equations with an R^2 value of $13 \cdot 1\%$ for the Gjøa A study area, and an R^2 value of $0 \cdot 0\%$ for the Sotra Bridge study area are provided in Equations (7) and (8), respectively:

$$Y = 12 \cdot 13 + 0 \cdot 04\ X_1 - 0 \cdot 10\ X_2 - 0 \cdot 33\ X_3 \tag{7}$$

$$Y = 10 \cdot 37 + 0 \cdot 01\ X_1 - 0 \cdot 01\ X_2 \tag{8}$$

where Y is average speed estimated in knots and X_1 is meteorological optical range measured in kilometres; X_2 is mean wind speed measured in metres/second; and X_3 is significant wave height measured in metres. It was found that for the Gjøa A study area, all three independent variables (visibility, mean wind speed and significant wave height) significantly predicted average transit speed when presented in the same combined model. However, when presenting visibility and mean wind speed in the same combined model for the Sotra Bridge study area, only visibility was found to significantly

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predict average transit speed. Mean wind speed on the other hand was found to not significantly predict average transit speed.

4.5. Comparison of the Gjøa A and Sotra Bridge study areas

The average transit speeds through the Gjøa A and Sotra Bridge study areas were recorded to be 11 · 18 knots (standard deviation: 2 · 4 knots) and 10 · 50 knots (standard deviation: 2 · 4 knots), respectively, a difference of 0 · 68 knots. A two-sample t-test was performed to compare the average transit speeds through the Gjøa A and Sotra Bridge study areas. There was a significant difference in average transit speeds between the Gjøa A study area and the Sotra Bridge study area; $t(47{,}488) = 1 \cdot 960$, $p = <0 \cdot 0001$.

5. Results

This section briefly summarises the results from the data analysis presented in Section 4.

Visibility does not have a large influence on vessel speeds. When looked at in isolation, visibility explains only 3 · 3% and virtually nothing (0 · 0%) of the variation in speed in the Gjøa A and Sotra Bridge study areas, respectively. While the significant linear regression equations were found in both areas, these regression equations predict a reduction in vessel speeds of only 0 · 08 and 0 · 01 knots for each kilometre visibility deteriorates in the Gjøa A and Sotra Bridge study areas, respectively. The graphical representation of the relationship between visibility and average transit speeds show that average transit speeds do not decrease significantly in restricted visibility.

The influence of mean wind speed on vessel speeds was vastly different in the two study areas. When considered in isolation, the mean wind speed explains 9 · 7% of the variation in speed in the Gjøa A study area, but virtually nothing (0 · 0%) in the Sotra Bridge study area. Significant linear regression equations were found in both study areas, but the magnitude of the slope coefficient differed considerably. An increase in mean wind speed of 1 metre/second is predicted to decrease transit speeds by 0 · 19 knots in the Gjøa A study area, but only 0 · 01 knots in the Sotra Bridge study area. This difference in the effect of mean wind speed on average transit speeds is also apparent in the graphical representations of the relationship between mean wind speed and average transit speeds in the two study areas. In the Gjøa A study area, an increase in mean wind speed shows a clear reduction in average transit speeds, but in the Sotra Bridge study area, the average transit speed remains virtually unchanged throughout all mean wind speed ranges. Common for both study areas is the large variation in transit speeds in the same wind conditions. For example, the scatter plot shows that transit speeds at mean wind speeds of approximately 7 metres/second were between roughly 6 and 19 knots in the Gjøa A study area, and 4 to 17 knots in the Sotra Bridge study area.

Like mean wind speed in the Gjøa A study area, significant wave height had a clear influence on average transit speeds. When looked at in isolation, significant wave height explains 9 · 5% of the variation in average transit speed. The significant linear regression equation predicts a decrease of 0 · 51 knots in average transit speed for each metre increase in significant wave height. This clear reduction in average transit speeds in higher wave conditions can also be seen on the graphical representation of the relationship between significant wave height and average transit speeds. However, it must be said that for mean wind speed, the variation in transit speeds in the same wave conditions is quite high – thescatter plot shows that transit speeds at significant wave heights of approximately 3 metres were roughly between 6 and 18 knots.

When combining the different influencing variables together, visibility, wind and waves explain 13 · 1% of the variation in vessels speeds through the Gjøa A study area. For the Sotra Bridge study area, visibility and wind combined has virtually no (0 · 0%) explanatory power for the variation in vessel speeds through the area.

Finally, it was found that the average transit speed through the coastal Sotra Bridge study area was 0 · 68 knots lower than the average transit speed through the Gjøa A study area in open waters. This difference was statistically significant.

Table 3. Pearson's correlation coefficients.

	Gjøa A	Sotra Bridge
Visibility	0 · 18	0 · 02
Wave	–0 · 31	–
Mean wind speed	–0 · 31	–0 · 01

6. Discussion

This paper set out to explore whether vessel speed data collected from conventional ships in various external environmental conditions actually resemble safe speeds by comparing the data with accepted interpretations of what constitutes a safe speed. As was highlighted in Section 2, the COLREGS lists visibility, traffic density, manoeuvrability, blackground light and proximity of navigational hazards as well as the state of wind, sea and current as factors to be taken into account when determining safe speed. Contemporary guides and commentary to the COLREGs highlight visibility as being the most important factor when it comes to safe speed.

The data analysis and results presented in Sections 4 and 5 show the average transit speeds of conventional vessels in different visibility, wind and wave conditions. More indirectly, the effect of traffic density and proximity of navigational hazards on average transit speeds can be seen in the difference of average transit speeds through the Gjøa A study area in the open ocean, with less traffic in a more structured traffic pattern, and the Sotra Bridge study area in inland waters with higher traffic in a more abstruse pattern.

6.1. Scatterplots

Various scatterplots visualising the relationship between average transit speeds and external environmental conditions were presented for both the Gjøa A and the Sotra Bridge study areas. None of these scatterplots showed a precise relationship between the factor and average transit speed through the study area. While the scatterplots for wave height and mean wind speed in the Gjøa A study area show a reduction of spread in the average transit speeds from approximately 2–20 knots in the lower ranges to 2–15 knots in the higher ranges, these ranges are still too large to be used by a MASS to indicate an acceptable safe speed range. The scatterplots for visibility in both study areas and the scatterplots for mean wind speed in the Sotra Bridge study area showed no clear pattern at all.

This interpretation is supported by the calculated Pearson's correlation coefficients shown in Table 3.

While a positive value of Pearson's correlation coefficient generally indicates a positive correlation between the two variables, and a negative value of Pearson's correlation coefficient generally indicates a negative correlation between the two variables, the strength of the relationship is generally judged to be nonexistent or very weak when it is below 0 · 3, and weak when between 0 · 3 and 0 · 5 (Moore et al., 2021).

While the correlation coefficients in the Gjøa A study area are low and imply very weak relationships, the correlation coefficients in the Sotra Bridge study area are virtually zero. After presenting their paper on Safe Speed for Maritime Autonomous Surface Ships at ESReL 2021, Dreyer (2021) received the feedback that the very weak relationship between visibility and speed in the Gjøa A study area may be due to the well-structured traffic pattern in the area combined with the low likelihood of a close encounter with another ship, and that this very weak relationship may be stronger in coastal waters where the traffic pattern is confused. However, the results of this paper show that in the Sotra Bridge study area – an area in coastal waters with confused traffic patterns and high likelihood of close quarter encounters with both commercial and leisure vessels – there is virtually no correlation between visibility and average transit speeds.

Table 4. *R^2 values of regression equations.*

	Gjøa A	Sotra Bridge
Visibility	$3 \cdot 3\%$	$0 \cdot 0\%$
Wave	$9 \cdot 5\%$	–
Mean wind speed	$9 \cdot 7\%$	$0 \cdot 0\%$

6.2. Regression analyses

The following two subsections discuss the results of the conducted simple and multiple linear regression analyses.

6.2.1. Simple linear regressions

In contrast to the ambiguous scatterplots and Pearson's correlation coefficients, significant regression equations were found for the simple linear regressions calculated for each of the environmental factors in both study areas. It must be noted, however, that the R^2 values of these regression equations are quite small, as can be seen in Table 4.

R^2 is the fraction by which the variance of the errors in the model is less than the variance of the dependent variable, meaning that it indicates the percent of variance explained by the model (Nau, 2020). This means that only $3 \cdot 3\%$, $9 \cdot 5\%$ and $9 \cdot 7\%$ of variation in average speed in the Gjøa A study area can be explained by the variation in visibility, wave and mean wind speed, respectively. More surprisingly, variations in visibility and mean wind speed explain $0 \cdot 0\%$ of the variation in average speed in the Sotra Bridge area.

6.2.2. Multiple linear regressions

The simple linear regressions discussed are only useful for estimating the relationship between a dependent variable and a singular explanatory variable in isolation. Multiple linear regressions on the other hand are carried out to analyse the relationship between a dependent variable and multiple explanatory variables. As average transit speed is dependent on more than just one singular factor, multiple linear regressions were calculated for both study areas. The final multiple linear regression for the Gjøa A study area was a statistically significant regression where visibility, mean wind speed and significant wave height all significantly predicted average transit speed. However, the R^2 value indicates that only $13 \cdot 1\%$ of the variation in average speed can be explained by the variation of these three factors. For the Sotra Bridge study area, the multiple linear regression analysis highlighted that only visibility significantly predicted average transit speeds, albeit the R^2 value indicating that literally no variation in average speed in the Sotra Bridge study area can be explained by variations in visibility or mean wind speed.

In other words, there must be other, more influential factors influencing the speeds of vessels. These could be other factors related to the goal of achieving a safe speed, but it could also be that other factors unrelated to the goal of proceeding at a safe speed have a large influence.

From research into road safety, we know that almost all drivers want to drive faster than the speed that they themselves consider to be a safe speed (Goldenbeld and van Schagen, 2007). Reasons for speeding in a road context are diverse and include – among others – temporary motives (such as being in a hurry or adapting the speed to the general traffic stream) and permanent personality characteristics (such as proneness to risk taking or general enjoyment of driving fast) (European Commission, 2018). Human perceptual skills and limitations play a role as well, with some situations making it easy to underestimate one's own driving speed. These include situations when a high speed has been maintained for a long period, as well as situations where there is little peripheral visual information (ETSC, 1995; Martens et al., 1997; Elliott et al., 2003). It is easy to find maritime examples for situations that provide little peripheral information, such as navigating in the open sea, at night or in fog.

Additionally, we have learned from Rasmussen (1997) that 'human behavior in any work system is shaped by objectives and constraints which must be respected by the actors for work performance to be successful'. The navigators setting the speed on the different vessels are not only bound by safety-related constraints, but by administrative and functional constraints, as well. The decision at which speed a vessel will proceed is therefore not only influenced by factors relating to safety, but by factors relating to efficiency and reduction of effort as well. Speed decisions made by navigators onboard a vessel can be seen as being under immense outside pressure, with standard ocean shipping contracts requiring vessels to proceed at 'utmost dispatch', and first-come, first-served berthing policies adding additional incentives for navigators to proceed at full speed (Alvarez et al., 2010).

When looking at the coefficients of the final multiple linear regression in the Gjøa A study area, we see that vessel speed is predicted to increase by $0 \cdot 04$ knots for each kilometre of increased visibility, decrease by $0 \cdot 10$ knots for each metre/second increase in mean wind speed, and decrease by $0 \cdot 33$ knots for each metre increase in significant wave height.

With the difference between what the Met Office describes as good and very poor visibility being $8 \cdot 26$ kilometres (Met Office, 2021b), this means that the regression equation predicts a vessel experiencing a deterioration of visibility from good to very poor to reduce its speed by only approximately $0 \cdot 3$ knots $(0 \cdot 04 \times 8 \cdot 26)$.

Likewise, a change from calm to gale force winds of 17 metres/second is predicted to decrease vessel speeds by approximately $1 \cdot 7$ knots $(0 \cdot 10 \times 17)$, and a change from what the Met Office (Met Office, 2021b) describes as a smooth sea state of waves less than $0 \cdot 5$ metres to a very rough sea state of waves between 4 to 6 metres is predicted to decrease vessel speeds by approximately $1 \cdot 1$ knots $(0 \cdot 33 \times 3 \cdot 5)$.

The regression equation of the only statistically significant predictor for average transit speeds in the Sotra Bridge study area – visibility – had a coefficient which predicts an increase of $0 \cdot 01$ knots for each kilometre of increased visibility. This converts to a predicted reduction of speed of less than $0 \cdot 1$ knots $(0 \cdot 01 \times 8 \cdot 26)$ by a vessel experiencing a degradation of visibility from good to very poor in the Sotra Bridge study area.

To compare this data with our current understanding of safe speed, it will now be compared with a specific example from commentary related to safe speed. Cockcroft and Lameijer (2012), whose *Guide to the Collision Avoidance Rules* is described as the essential reference to safe operation of all vessels at sea, provide an example on safe speed in restricted visibility from the legal case of the collision between the ships *Hagen* and *Boulgaria*. Here it was stated that a radar-equipped vessel normally capable of proceeding at $13 \cdot 5$ knots would be expected to reduce its speed to about 8 to 9 knots when proceeding in visibility of approximately $1 \cdot 1$ kilometres. Note that this expected speed reduction was stated for a vessel equipped with radar (i.e. a vessel that was not solely reliant on human senses, such as sight and hearing but could instead utilise technology to perceive its environment). This example is therefore well-suited for application to MASS, which will also rely on technology – and not on human senses – to perceive their surroundings. When comparing this expected speed reduction of $4 \cdot 5$–$5 \cdot 5$ knots with the $0 \cdot 3/0 \cdot 1$ knots expected by the regression equation of the AIS dataset, it becomes clear that the reduction of speed in reduced visibility observed in the AIS data is not nearly enough to be classified as sufficient by our current understanding of safe speed.

6.3. Average speeds in different environmental condition ranges

The graphs illustrating average transit speeds in different environmental condition ranges are markedly different in each study area. While the graphs in the Sotra Bridge study areas are virtually flat and indicate similar average transit speeds in the different environmental condition ranges, the graphs for the Gjøa A study area show changes in average speeds in different environmental conditions.

Commentary on the COLREGs states that the need to moderate speed generally applies in restricted visibility and that it is dangerous to go fast when visibility is poor. The results of this paper show that

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conventional ships do not behave that way. Figure 4 shows that there is no decrease in average transit speeds of vessels passing through the Sotra Bridge study area in poor visibility, and – curiously – Figure 3 shows that average transit speeds of vessels passing through the Gjøa A study area in very poor visibility conditions was higher than that of any other visibility range. Indeed, when MOR is less than 4 kilometres, average transit speeds seem to be increasing as visibility deteriorates. This might be explained by the sharply reduced mean wind speeds and significant wave heights experienced by vessels transiting the study area in low visibilities. As can be seen in the Appendix, Figure A15 and Table A13, the average mean wind speeds and average significant wave heights for transits that occurred in visibilities of 0 to 1 kilometres were $6 \cdot 0$ metres/second and $1 \cdot 5$ metres, respectively. This a reduction of approximately 50% when compared to the average mean wind speeds and average significant wave heights of $11 \cdot 2$ metres/second and $3 \cdot 1$ metres, respectively, for transits that occurred in visibilities of 2 to 3 kilometres.

When it comes to average transit speeds in different wave and mean wind speed conditions in the Gjøa A study area, the results do not seem surprising. The data shows that average transit speeds decrease as waves get larger and winds pick up. At first glance, the sharp increase in average transit speeds at extremely high wave and wind conditions is surprising. However, the increased average transit speeds at extremely high wave and wind conditions are based on a very low number of transits and are, therefore, considered to be erratic outliers.

The same observation was not done at the Sotra Bridge study area – here average transit speeds remained stable throughout all wind ranges. A possible explanation for this may be the sheltered nature of the study area. When in the open ocean, added resistance due to waves is one of the major components that affect ship performance. The magnitude of added resistance is about 15–30% of calm-water resistance, meaning that a ship's forward speed decreases, compared to that in calm sea, when encountering waves (Seo et al., 2013). Wave development is significantly affected by not only wind speed but also fetch – the distance that wind travels over open water. As the Sotra Bridge study area is located in coastal waters sheltered from the open ocean, strong winds likely do not cause the same high waves in the Sotra Bridge study area as they would in the open Gjøa A study area. This, in turn, would mean less added resistance – and less speed reduction – for ships passing through the Sotra Bridge study area in stronger winds. However, due to the absence of wave height data for the Sotra Bridge study area, this hypothesis was not tested in this paper.

6.4. Difference in transit speed through the Gjøa A and Sotra Bridge study areas

There was a significant difference in average transit speeds between the Gjøa A and Sotra Bridge study areas. At $10 \cdot 50$ knots, the average transit speed through the Sotra Bridge study area was $0 \cdot 68$ knots lower than the $11 \cdot 18$ knots average transit speed through the Gjøa A study area.

As mentioned in the descriptions of the study areas, the Gjøa A study area is characterised by its location in open ocean, in an area of structured traffic. The Sotra Bridge area, on the other hand, is located in coastal waters, with completely encircled by shoreline. There is more traffic in this area, which is also less structured. One could, therefore, argue that of the factors to be taken into account when determining safe speed mentioned in the COLREGs, the factors of traffic density, background light at night and proximity to navigational hazards are more pronounced in the Sotra Bridge study area. These differences may explain the 6% difference in average transit speeds through the two study areas.

7. Conclusion

This paper investigated whether vessel speed data collected from conventional ships in various external environmental conditions actually resembles safe speeds, and can therefore be used for deep-learning purposes in MASS. This was done by comparing the data with accepted interpretations if what constitutes a safe speed.

Contemporary commentary to the COLREGs consider visibility the dominant factor to be considered when determining safe speed and acknowledge that poor visibility demands reduced vessel speeds. However, the analysis of the AIS data show that ships do not actually behave as anticipated. While the regression analyses, with speed as the dependent and visibility as the independent variable, found significant regression equations, both the coefficients and R^2 values were small to negligible. The problem of quantifying the safe speed of a vessel in different conditions, therefore, does not seem to be easily solvable by simply using historic AIS data to create a model of normalcy which a MASS can follow. The regression equations predict a speed reduction of $0 \cdot 1$ to $0 \cdot 3$ knots when visibility deteriorates from good to very poor, and the low R^2 values mean that only 0 to $3 \cdot 3\%$ of the variation in speed can be explained by the variation in visibility. Note that the effect of visibility on transit speeds was even less pronounced in the coastal waters study area of the Sotra Bridge, a finding that directly contradicts the expectations of some experts in the field.

While the speed reductions observed in higher wind and wave conditions in the Gjøa A study area fall into what may be expected, these speed reductions were not observed in the Sotra Bridge study area. Again, this seems to indicate that there are combination effects that are not fully understood yet.

It can, therefore, be concluded that there is a difference between the predicted changes in vessel speeds that are based on our contemporary theoretical understanding of safe speed, and the actual differences in vessel speeds observed in different environmental conditions. Contrary to contemporary understanding of safe speed, reduced visibility did not lead to significantly reduced transit speeds.

This difference may be either due to our contemporary understanding of safe speed being flawed, or because speed data taken from AIS does not represent safe speeds in all conditions. This is because the speed of vessels is not only influenced by factors relating to safety, but by factors relating to efficiency and reduction of effort as well.

The problem of quantifying the safe speed of a vessel in different conditions, therefore, does not seem to be easily solvable by simply using historic AIS data to create a model of normalcy which a MASS can follow. More research in this area is necessary to gain a deeper understanding of what a safe speed constitutes and how this knowledge can be transferred to any MASS sailing the seas in the future.

8. Limitations and further research

The data collected and analysed in this paper shows that vessels behave markedly differently in similar conditions. Since all vessel data collected in this study was combined for the analysis, a limitation of this research is the fact that differences between different vessel types and sizes were not considered. Further research is warranted to investigate whether vessel type and size influences vessel speeds in different environmental conditions. Furthermore, the possibility of smaller vessels choosing different paths when the weather is unfavourable should also be explored.

The analysis of the effect of wind and waves on vessels speeds conducted in this paper did not consider the relative direction of wind and waves to the vessels. Since different hazards are posed to the vessel depending on the angle in which waves interact with the vessel, further research that includes the relative wind and wave directions in the analysis is encouraged.

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Competing interests. None.

Availability of data and material. Data can be downloaded via the websites mentioned.

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A. Appendix

A1. Qualitative descriptions of visibility, wind and waves

Table A1. *Qualitative description of visibility (Met Office, 2021b).*

Term	Meaning
Very poor	Visibility less than 1,000 metres
Poor	Visibility between 1,000 metres and 2 nautical miles (3,704 metres)
Moderate	Visibility between 2 and 5 nautical miles (3,704 metres and 9,260 metres)
Good	Visibility more than 5 nautical miles (9,260 metres)

Table A2. *Qualitative description of mean wind speed (Met Office, 2021a).*

Term	Meaning
Calm	Wind speed less than 1 m/s
Light air	Wind speed of 1 to 2 m/s
Light breeze	Wind speed of 2 to 3 m/s
Gentle breeze	Wind speed of 4 to 5 m/s
Moderate breeze	Wind speed of 6 to 8 m/s
Fresh breeze	Wind speed of 9 to 11 m/s
Strong breeze	Wind speed of 11 to 14 m/s
Near-gale	Wind speed of 14 to 17 m/s
Gale	Wind speed of 17 to 21 m/s
Strong gale	Wind speed of 21 to 24 m/s
Storm	Wind speed of 25 to 28 m/s
Violent storm	Wind speed of 29 to 32 m/s
Hurricane	Wind speed of more than 33 m/s

Table A3. *Qualitative description of wave height (Met Office, 2021b).*

Term	Meaning
Smooth	Wave height less than $0 \cdot 5$ metres
Slight	Wave height of $0 \cdot 5$ to $1 \cdot 25$ metres
Moderate	Wave height of $1 \cdot 25$ to $2 \cdot 5$ metres
Rough	Wave height of $2 \cdot 5$ to $4 \cdot 0$ metres
Very rough	Wave height of $4 \cdot 0$ to $6 \cdot 0$ metres
High	Wave height of $6 \cdot 0$ to $9 \cdot 0$ metres
Very high	Wave height of $9 \cdot 0$ to $14 \cdot 0$ metres
Phenomenal	Wave height of more than $14 \cdot 0$ metres

A2. Diagrams representing data collected for the Gjøa A study area

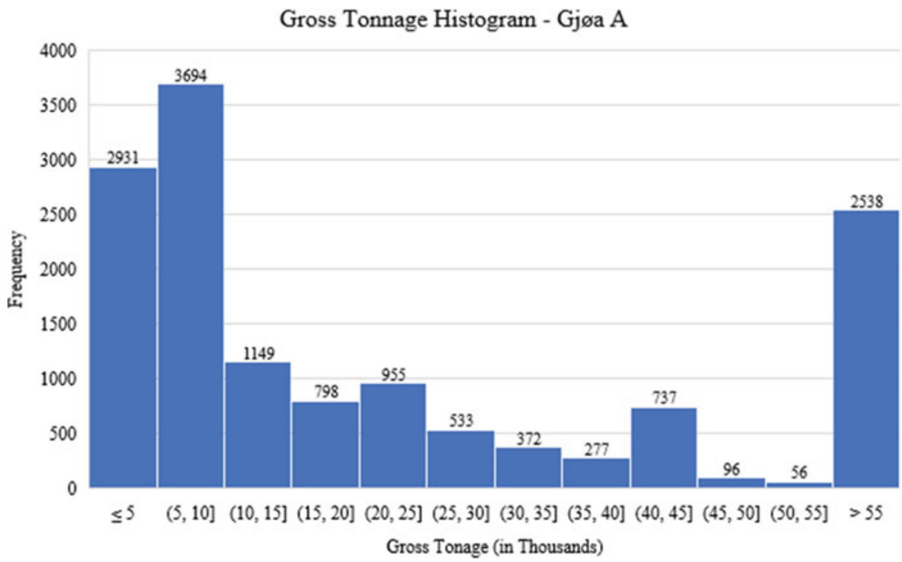

Figure A1. *Gross Tonnage histogram for Gjøa A. Number on top of each bar represents the total number of transits of vessels with different GT. Average GT in the array above 55,000: 84,129.*

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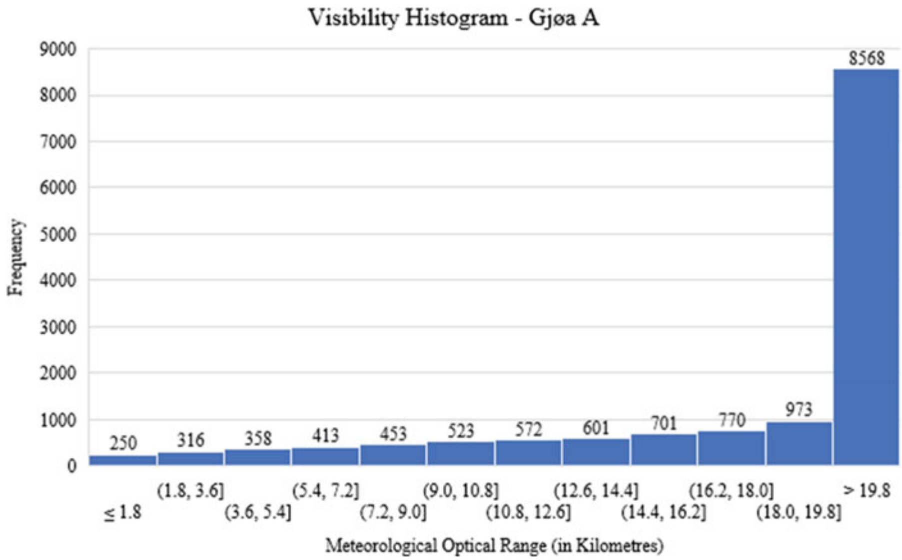

Figure A2. *Visibility histogram for Gjøa A. Number on top of each bar represents the total number of transits under different visibility conditions.*

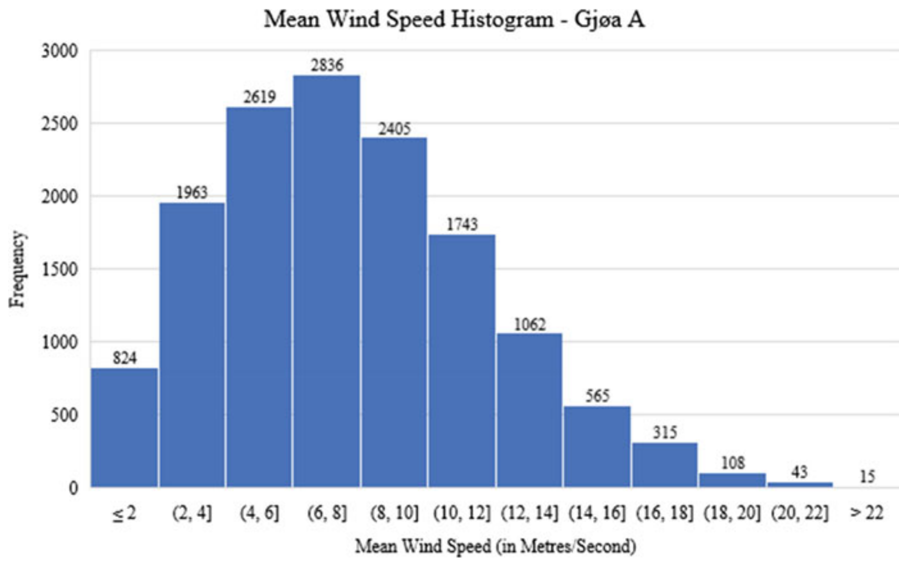

Figure A3. *Mean Wind Speed histogram for Gjøa A. Number on top of each bar represents the total number of transits under different mean wind speed conditions. Average mean wind speed in the array above 22 metres/second: 23.6 metres/second.*

https://doi.org/10.1017/S0373463323000127 Published online by Cambridge University Press

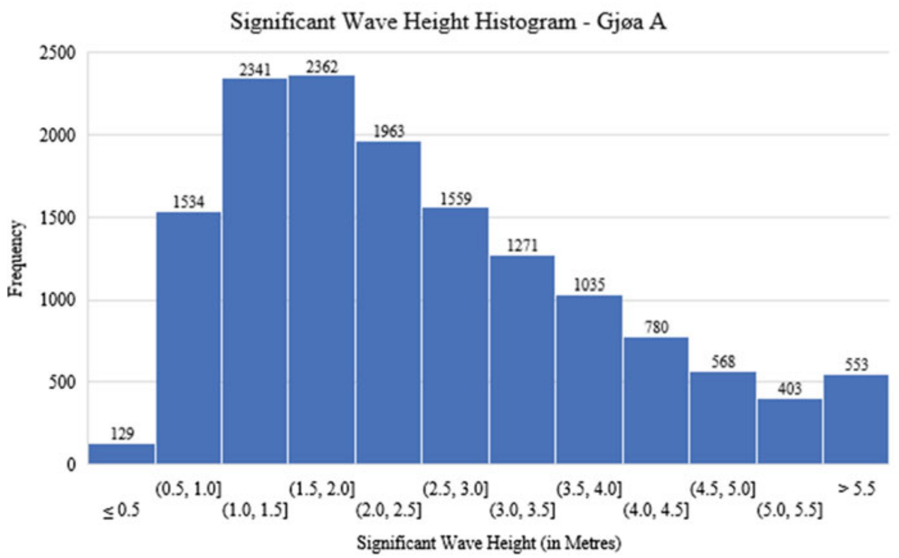

Figure A4. *Significant Wave Height histogram for Gjøa A. Number on top of each bar represents the total number of transits under different significant wave height conditions. Average wave height in the array above 5.5 metres: 6.4 metres.*

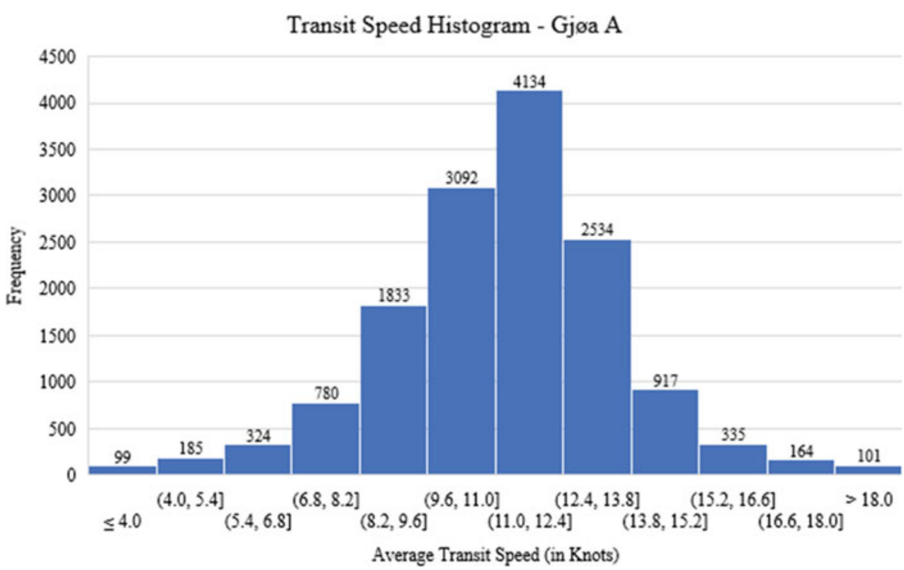

Figure A5. *Transit Speed histogram for Gjøa A. Number on top of each bar represents the total number of transits at different average speeds. Average transit speed in the array above 18 knots: 18.7 knots.*

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A3. Diagrams representing data collected for the sotra bridge study area

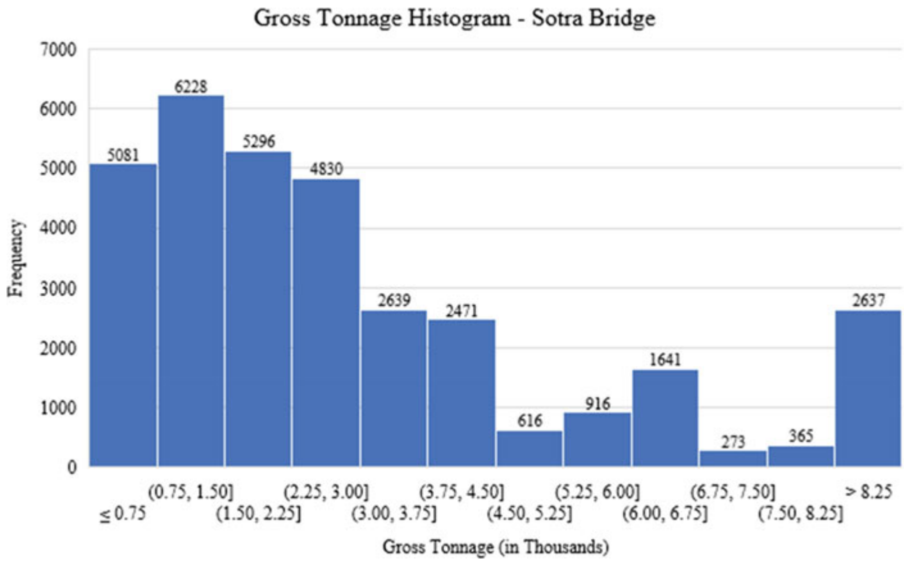

Figure A6. *Gross Tonnage histogram for Sotra Bridge. Number on top of each bar represents the total number of transits of vessels with different GT. Average GT in the array above 8,250: 10,104.*

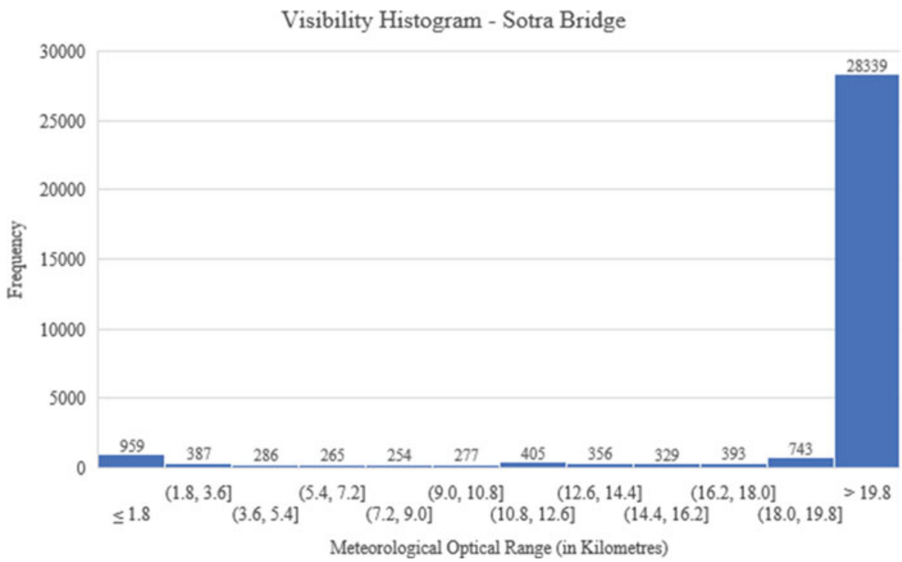

Figure A7. *Visibility histogram for Sotra Bridge. Number on top of each bar represents the total number of transits under different visibility conditions.*

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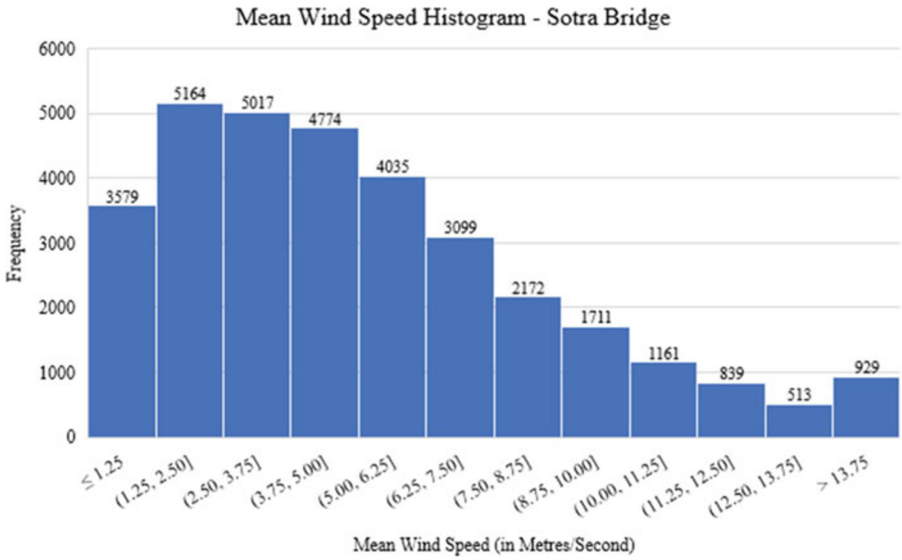

Figure A8. *Mean Wind Speed histogram for Sotra Bridge. Number on top of each bar represents the total number of transits under different mean wind speed conditions. Average mean wind speed in the array above 13 · 75 metres/second: 16 · 0 metres/second.*

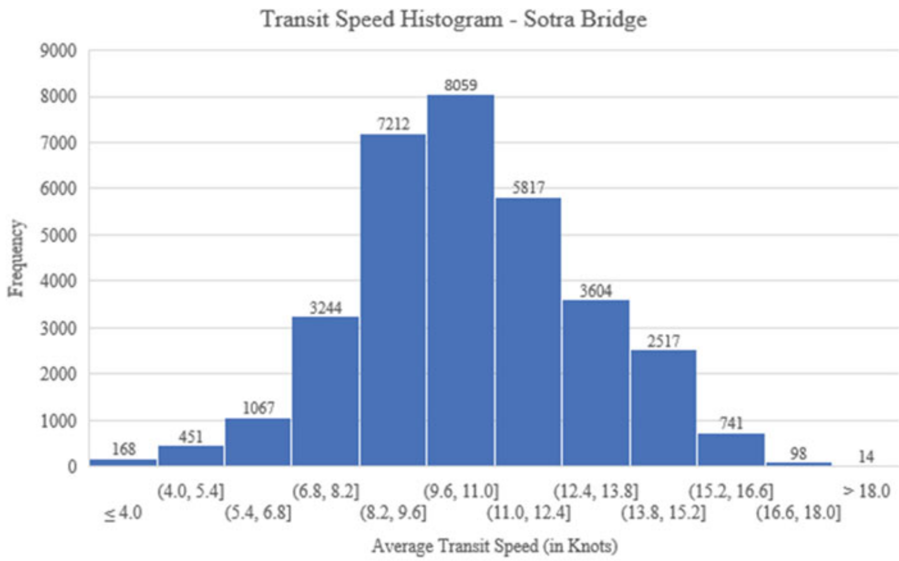

Figure A9. *Transit Speed histogram for Sotra Bridge. Number on top of each bar represents the total number of transits at different average speeds. Average transit speed in the array above 18 knots: 18 · 6 knots.*

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A4. Average transit speeds through the Gjøa A study area in different environmental conditions.

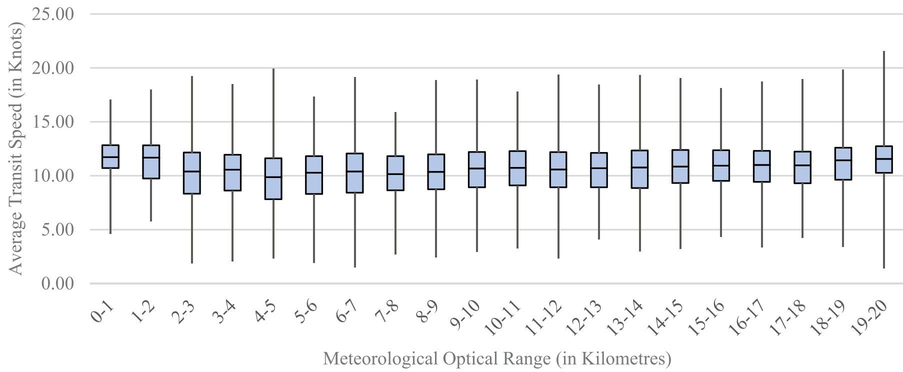

Figure A10. *Box-and-whisker chart showing the quartiles of the average transit speed through the Gjøa A study area in different visibility ranges.*

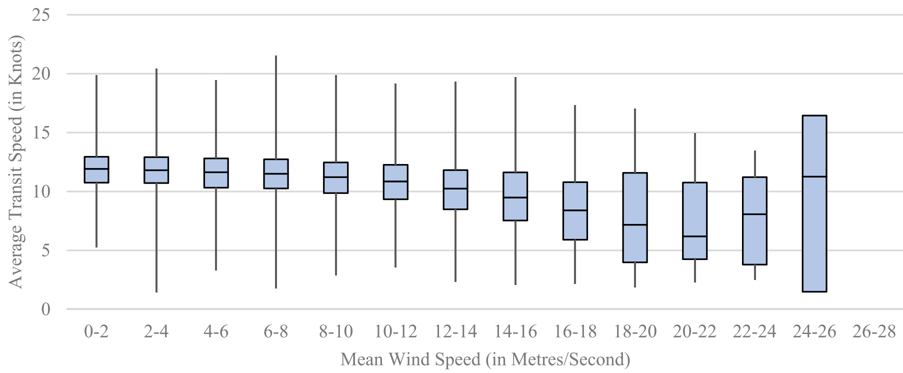

Figure A11. *Box-and-whisker chart showing the quartiles of the average transit speed through the Gjøa A study area in different mean wind speed ranges.*

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Table A4. *Table showing the average transit speeds through the Gjøa A study area in different visibility ranges..*

Visibility Range (in Kilometres)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Number of Transits	176	95	165	209	196	225	223	256	245	265
Average Transit Speed (in Knots) in This Visibility Range	11·73	11·35	10·07	10·15	9·74	9·98	10·19	10·08	10·22	10·44
Minimum Recorded Transit Speed (in Knots) in This Visibility Range	4·62	5·78	1·85	2·08,	2·35	1·93	1·49	2·71	2·41	2·92
25% Quartile (in Knots)	10·71	9·74	8·33	8·62	7·82	8·31	8·43	8·65	8·73	8·92
50% Quartile (in Knots)	11·73	11·67	10·39	10·55	9·87	10·28	10·39	10·16	10·36	10·68
75% Quartile (in Knots)	12·83	12·82	12·16	11·94	11·62	11·81	12·06	11·82	11·98	12·20
Maximum Recorded Transit Speed (in Knots) in This Visibility Range	17·10	17·98	19·25	18·49	19·96	17·34	19·14	15·94	18·88	18·89

Visibility Range (in Kilometres)	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20
Number of Transits	321	331	288	365	352	400	409	436	463	9,078
Average Transit Speed (in Knots) in This Visibility Range	10·63	10·43	10·47	10·64	10·73	10·89	10·83	10·84	11·21	11·53
Minimum Recorded Transit Speed (in Knots) in This Visibility Range	3·26	2·32	4·13	2·98	3·22	4·34	3·37	4·21	3·38	1·43
25% Quartile (in Knots)	9·10	8·92	8·93	8·85	9·32	9·52	9·43	9·30	9·62	10·27
50% Quartile (in Knots)	10·74	10·58	10·69	10·77	10·85	10·93	11·00	10·97	11·44	11·56
75% Quartile (in Knots)	12·29	12·19	12·12	12·34	12·39	12·36	12·30	12·23	12·60	12·74
Maximum Recorded Transit Speed (in Knots) in This Visibility Range	17·80	19·39	18·47	19·32	19·03	18·13	18·75	18·95	19·88	21·55

Table A5. *Table showing the average transit speeds through the Gjøa A study area in different mean wind speed ranges.*

Mean Wind Speed Range (in Metres/Second)	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24	24–26	26–28
Number of Transits	824	1,963	2,620	2,837	2,404	1,742	1,062	568	312	108	43	11	3	1
Average Transit Speed (in Knots) in This Mean Wind Speed Range	11 · 88	11 · 82	11 · 61	11 · 53	11 · 22	10 · 81	10 · 15	9 · 56	8 · 48	7 · 83	7 · 30	7 · 83	9 · 73	5 · 91
Minimum Recorded Transit Speed (in Knots) in This Mean Wind Speed Range	5 · 24	1 · 43	3 · 27	1 · 78	2 · 90	3 · 57	2 · 33	2 · 08	2 · 15	1 · 85	2 · 27	2 · 52	1 · 49	5 · 91
25% Quartile (in Knots)	10 · 75	10 · 71	10 · 32	10 · 26	9 · 86	9 · 34	8 · 49	7 · 53	5 · 90	3 · 99	4 · 25	3 · 79	1 · 49	-
50% Quartile (in Knots)	11 · 92	11 · 80	11 · 63	11 · 50	11 · 22	10 · 86	10 · 25	9 · 48	8 · 40	7 · 18	6 · 19	8 · 07	11 · 26	5 · 91
75% Quartile (in Knots)	12 · 94	12 · 91	12 · 80	12 · 73	12 · 46	12 · 26	11 · 81	11 · 63	10 · 79	11 · 58	10 · 75	11 · 21	16 · 44	-
Maximum Recorded Transit Speed (in Knots) in This Mean Wind Speed Range	19 · 88	20 · 43	19 · 43	21 · 55	19 · 89	19 · 14	19 · 32	19 · 72	17 · 34	17 · 05	14 · 96	13 · 49	16 · 44	5 · 91

Table A6. *Table showing the average transit speeds through the Gjøa A study area in different significant wave height ranges.*

Significant Wave Height Range (in Metres)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11	11–12
Number of Transits	1,663	4,703	3,522	2,306	1,348	622	223	80	18	7	2	4
Average Transit Speed (in Knots) in This Significant Wave Height Range	11·83	11·72	11·35	10·79	10·18	9·23	8·89	8·45	8·62	9·17	12·26	11·24
Minimum Recorded Transit Speed (in Knots) in This Significant Wave Height Range	1·43	1·78	3·22	2·61	2·33	2·08	1·49	1·85	1·93	3·56	11·30	5·44
25% Quartile (in Knots)	10·71	10·51	10·04	9·29	8·39	7·16	6·03	5·10	4·67	3·72	-	6·34
50% Quartile (in Knots)	11·93	11·72	11·35	10·87	10·22	9·39	8·95	9·04	9·09	10·85	12·26	11·53
75% Quartile (in Knots)	12·93	12·86	12·62	12·17	11·86	11·15	11·49	10·73	11·50	12·17	-	15·83
Maximum Recorded Transit Speed (in Knots) in This Significant Wave Height Range	19·88	20·43	19·96	21·55	19·61	18·92	18·35	16·67	17·54	15·88	13·21	16·44

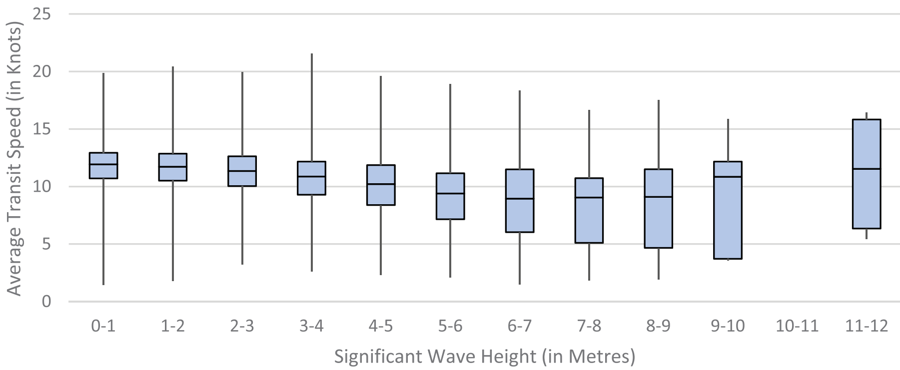

Figure A12. *Box-and-whisker chart showing the quartiles of the average transit speed through the Gjøa A study area in different significant wave height ranges.*

A5. Average transit speeds through the Sotra Bridge study area in different environmental conditions

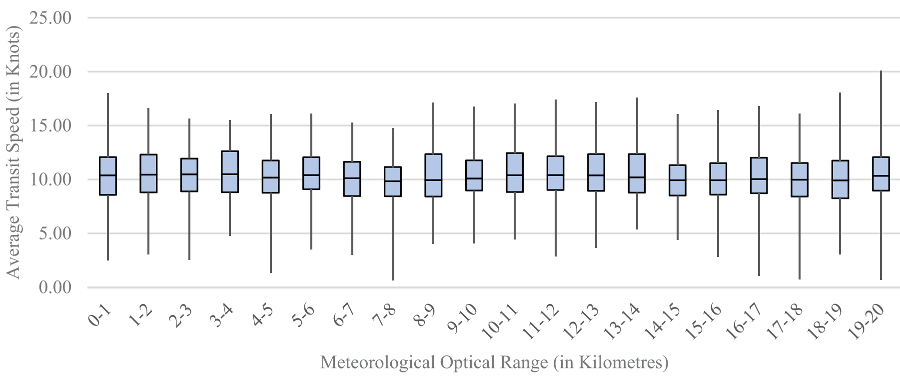

Figure A13. *Box-and-whisker chart showing the quartiles of the average transit speed through the Sotra Bridge study area in different visibility ranges·.*

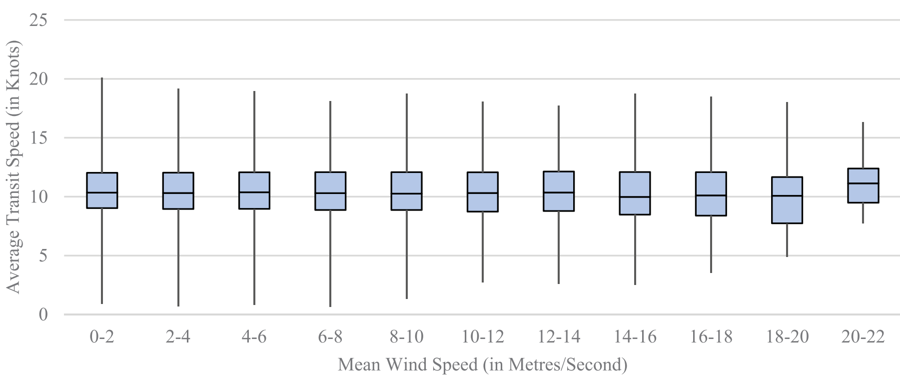

Figure A14. *Box-and-whisker chart showing the quartiles of the average transit speed through the Sotra Bridge study area in different mean wind speed ranges.*

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Table A7. *Table showing the average transit speeds through the Sotra Bridge study area in different visibility ranges..*

Visibility Range (in Kilometres)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Number of Transits	647	368	222	169	159	143	150	144	148	128
Average Transit Speed (in Knots) in This Visibility Range	10·35	10·42	10·56	10·54	10·14	10·55	10·15	9·75	10·42	10·26
Minimum Recorded Transit Speed (in Knots) in This Visibility Range	2·50	3·04	2·56	4·78	1·32	3·52	3·03	0·65	4·05	4·08
25% Quartile (in Knots)	8·56	8·79	8·89	8·80	8·77	9·09	8·46	8·44	8·41	8·98
50% Quartile (in Knots)	10·38	10·44	10·48	10·49	10·17	10·41	10·11	9·84	9·94	10·09
75% Quartile (in Knots)	12·07	12·31	11·93	12·63	11·75	12·06	11·63	11·15	12·35	11·77
Maximum Recorded Transit Speed (in Knots) in This Visibility Range	18·03	16·61	15·63	15·50	16·05	16·12	15·27	14·78	17·14	16·73

Visibility Range (in Kilometres)	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20
Number of Transits	193	241	186	219	163	188	202	240	313	28,769
Average Transit Speed (in Knots) in This Visibility Range	10·55	10·54	10·55	10·57	9·96	10·06	10·32	10·10	10·08	10·52
Minimum Recorded Transit Speed (in Knots) in This Visibility Range	4·47	2·89	3·66	5·38	4·37	2·79	1·04	0·73	3·04	0·70
25% Quartile (in Knots)	8·83	9·02	8·93	8·77	8·51	8·59	8·72	8·42	8·25	8·96
50% Quartile (in Knots)	10·40	10·41	10·38	10·20	9·93	9·93	10·04	9·98	9·91	10·34
75% Quartile (in Knots)	12·45	12·15	12·36	12·35	11·32	11·51	12·02	11·53	11·75	12·07
Maximum Recorded Transit Speed (in Knots) in This Visibility Range	17·05	17·41	17·16	17·59	16·07	16·42	16·80	16·11	18·08	20·12

Table A8. Table showing the average transit speeds through the Sotra Bridge study area in different mean wind speed ranges.

Mean Wind Speed Range (in Metres/Second)	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24
Number of Transits	6,631	8,119	7,045	4,813	2,943	1,723	886	447	234	115	35	1
Average Transit Speed (in Knots) in This Mean Wind Speed Range	10·54	10·49	10·54	10·49	10·46	10·43	10·49	10·29	10·26	9·87	11·16	9·99
Minimum Recorded Transit Speed (in Knots) in This Mean Wind Speed Range	0·90	0·70	0·82	0·65	1·32	2·75	2·60	2·50	3·55	4·91	7·74	9·99
25% Quartile (in Knots)	9·03	8·96	8·96	8·87	8·87	8·73	8·79	8·48	8·39	7·73	9·49	-
50% Quartile (in Knots)	10·34	10·31	10·37	10·30	10·26	10·31	10·36	9·98	10·11	10·07	11·13	9·99
75% Quartile (in Knots)	12·03	12·03	12·08	12·08	12·08	12·07	12·14	12·09	12·09	11·66	12·39	-
Maximum Recorded Transit Speed (in Knots) in This Mean Wind Speed Range	20·12	19·17	18·99	18·11	18·78	18·08	17·75	18·75	18·51	18·03	16·33	9·99

A6. Results of regression analyses

Explanation of symbols used in the tables below:

- X = independent variable
- β_0 = Y intercept
- β_1 = slope coefficient
- CI = 95% confidence interval
- F = F-statistic – indicates whether a group of variables is jointly significant
- p = p-value – indicates whether there is a significant relationship between dependent and independent variables.
- R^2 = coefficient of determination – indicates the proportion of variance in the dependent variable that can be explained by the independent variable.

Table A9. *Result of simple linear regression analysis for the Gjøa A study area, with average speed as the dependent variable (Y).*

X	β_0	β_1	CI [β_0]	CI [β_1]	F	P	R^2
Visibility	9·81	0·08	[9·68, 9·94]	[0·07, 0·09]	*487·78*	<0·0001	3·3%
Wind	12·61	−0·19	[12·53, 12·69]	[−0·20, −0·18]	1549·21	<0·0001	9·7%
Wave	12·47	−0·51	[12·40, 12·55]	[−0·54, −0·49]	1518·45	<0·0001	9·5%

Table A10. *Result of simple linear regression analysis for the Sotra Bridge study area, with average speed as the dependent variable (Y).*

X	β_0	β_1	CI [β_0]	CI [β_1]	F	P	R^2
Visibility	10·31	0·01	[10·20, 10·42]	[0·00, 0·02]	11·16	0·0008	0·0%
Wind	10·55	−0·01	[10·50, 10·59]	[−0·02, −0·00]	6·90	0·0086	0·0%

Table A11. *Result of multiple linear regression analysis for the Gjøa A study area, with average speed as the dependent variable (Y).*

X	β_0	β_1	CI [β_0]	CI [β_1]	F	P	R^2
Visibility	12·13	0·04	[11·96, 12·30]	[0·03, 0·05]	728·10 ($p < 0·0001$)	<0·0001	13·1%
Wind		−0·10		[−0·11, −0·09]		<0·0001	
Wave	−0·33	[−0·36, −0·30]	<0·0001				

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A7. Average wind speed, wave height, and transit speed in different visibility conditions for the GJØA A study area.

Table A12. Result of multiple linear regression analysis for the Sotra Bridge study area, with average speed as the dependent variable (Y).

X	β_0	β_1	CI [β_0]	CI [β_1]	F	p	R^2
Visibility	10 · 37	0 · 01	[10 · 23, 10 · 51]	[0 · 00, 0 · 01]	6 · 68 ($p = 0 \cdot 0013$)	0 · 0111	0 · 0%
Wind		−0 · 01		[−0 · 01, 0 · 00]		0 · 1391	

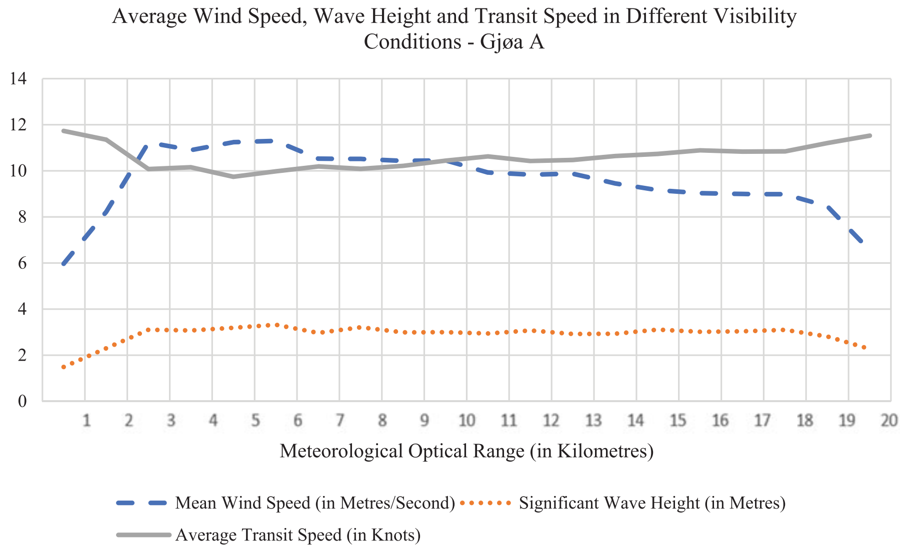

Figure A15. Line graph showing the average wind speed, wave height and transit speed in different visibility conditions for the Gjøa A study area.

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Table A13. Table showing the average wind speed, wave height and transit speeds through the Gjøa A study area in different visibility ranges..

Visibility Range (in Kilometres)	0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10
Average Mean Wind Speed (in Metres/Second) in This Visibility Range	5·97	8·22	11·23	10·90	11·24	11·30	10·53	10·52	10·43	10·45
Average Significant Wave Height (in Metres) in This Visibility Range	1·49	2·30	3·10	3·07	3·19	3·32	2·97	3·21	2·99	3·00
Average Transit Speed (in Knots) in This Visibility Range	11·73	11·35	10·07	10·15	9·74	9·98	10·19	10·08	10·22	10·44

Visibility Range (in Kilometres)	10–11	11–12	12–13	13–14	14–15	15–16	16–17	17–18	18–19	19–20
Average Mean Wind Speed (in Metres/Second) in This Visibility Range	9·93	9·84	9·87	9·45	9·17	9·03	8·99	8·99	8·46	6·55
Average Significant Wave Height (in Metres) in This Visibility Range	2·94	3·07	2·92	2·93	3·11	3·02	3·04	3·10	2·81	2·27
Average Transit Speed (in Knots) in This Visibility Range	10·63	10·43	10·47	10·64	10·73	10·89	10·83	10·84	11·21	11·53

Appendix 4.

Safe Vessel Operations – The Tacit Knowledge of Navigators

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Safe Vessel Operations – The Tacit Knowledge of Navigators

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ABSTRACT: The collision regulations include several qualitative terms without providing guidance as to how these terms could be understood in quantitative terms. These terms must therefore be interpreted by navigators, which poses a problem for autonomous ships. Extend the knowledge of how navigators interpret the collision regulations, with a specific focus on how they interpret the rule covering the requirement to proceed at a safe speed. Qualitative study based on interviews of a convenience sample of eight Norwegian navigators. Data was analysed with systematic text condensation. Navigators characterise safe speed as a speed in which they have control. Navigators do not look at different factors mentioned in the collision regulations in isolation, but within the context of the situation. Determining the safe speed of a vessel is more complicated than made out in the literature. As autonomous ships will have to cooperate with conventional vessels, their programming must include the knowledge of how the collision regulations are interpreted by human navigators.

1 INTRODUCTION

Collisions have been the second top cause for shipping casualties and incidents in 2022 [1]. The Norwegian Maritime Authority – which collects incident statistics that combine Norwegian vessels regardless of location, and foreign vessels operating in Norwegian waters – reports that in every year since 2011 at least 16 collisions have occurred [2].

To prevent collisions from occurring, the International Maritime Organization (IMO) has published the International Regulations for Preventing Collisions at Sea 1972 (COLREGs). These rules apply to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels [3]. As such, maritime autonomous surface ships (MASS) will also be required to follow these rules.

Having entered into force in 1977 – they were presumably written without having modern autonomous cargo vessels in mind. The COLREGs include various qualitative terms – such as “early”, “substantial” and “safe” – without providing any information as to how these terms could be understood in quantitative terms. The result is a rule system that relies heavily on the interpretation of the navigator. While ambiguity is a desired trait of the COLREGs (a completely prescriptive and rigid rule-system would be infinitely complicated [4]), it has led to a situation where there may be a large discrepancy between the legal interpretation of the COLREGs and the conventional way navigators avoid collisions [5]. In practice this means that navigators are pressured both to follow convention, in order to avoid collision, and the law, to avoid prosecution should anything go wrong [5].

This distinction between the legal interpretation and convention was highlighted in a study by Dreyer [6], where it was shown that vessel speeds predicted by legal interpretation of the COLREGs and actual observed vessel speeds did not align: The idea put forward by legal scholars that visibility is the most important factor when it comes to safe speed [7-9] was not mirrored in the data of actual ship behaviours.

As collision avoidance between vessels is seen as a game of coordination, where navigators on different vessels have to independently choose mutually compatible strategies [5], the control system of a MASS must not only be aware of the legal interpretation of the COLREGs, but also of the conventional way navigators apply the rules in practice. Indeed, if MASS are "too strict" in following the legal interpretation of the COLREGs they might – at times – jeopardize the safety of a ship encounter [10].

As a better understanding of the conventional way navigators apply the COLREGs in practice is necessary, this study aims to extend the knowledge of how navigators interpret the rules, with a specific focus on how they interpret the rule covering the requirement to proceed at a safe speed.

2 BACKGROUND

Rule 6 of the COLREGs deals with safe speed. It requires that "every vessel shall at all times proceed at a safe speed so that she can take proper and effective action to avoid collision and be stopped within a distance appropriate to the prevailing circumstances and conditions". To determine what speed may be considered safe, the COLREGs provide a number of factors that shall be among those taken into account, including visibility, traffic density, manoeuvrability of the vessel, background light, the state of wind, sea and current, the proximity of navigational hazards and the draught in relation to the available depth of water [11].

3 3 MATERIALS AND METHODS

3.1 *Participants*

A purposive sample of two fast ferry captains and six maritime pilots (eight men, no women) aged 33 – 61 years working in Norway participated in the study. The lack of gender difference largely reflects the situation in the maritime industry where the majority of seafarers are men [12]. The strategy for selecting the study subjects (purposefully) was influenced by homogenous sampling (in terms of professional background) and convenience sampling [13]. The concept of saturation was considered when deciding on the amount of interviews to conduct in this study [14]. Saturation is achieved "when gathering fresh data no longer sparks new theoretical insights, nor reveals new properties of your core theoretical categories" [15]. Following the eight semi-structured interviews that were conducted, saturation was achieved.

The professional seafaring experience of the participants ranged from 8 – 38 years. Seven participants had 21 years of experience or more.

3.2 *Interview Procedure*

The author conducted the interviews. One interview was conducted via the videotelephony software program Zoom Meetings, one interview was conducted in a meeting room at the interviewer's workplace and the rest of the interviews were conducted at the homes of the interviewees. The interviews lasted from 58 minutes to 2 hours and 6 minutes. A semi-structured interview guide was used as a tool to obtain detailed descriptions of the seafarers' experiences in order to grasp the tacit knowledge of seafarers that is so important in ensuring safe vessel operations. The main questions were: How do you ensure the safe and smooth operation of your vessel? What factors go into your decision for setting your vessels speed? How do you determine safe speed? Could you rank influencing factors by importance?

All interviews were recorded and transcribed.

3.3 *Data Analysis*

The data collected in this study was analysed by means of systematic text condensation [16]. The approach is described as a four-step procedure: (1) reading the transcripts to get an overall impression and identifying preliminary themes; (2) extracting meaning units from the transcripts and sorting them into codes and code groups; (3) condensing the meaning within each code group; (4) summarizing the content into meaningful descriptions [16, 17]. The author conducted all steps of the analysis. In this regard it must be noted that the author's background as a navigational watch officer with knowledge and experience within the field has influenced the process of collecting and interpreting data. As the final descriptions were developed and refined over time, the interview transcripts were read repeatedly to ensure that the constructed descriptions were grounded in the empirical data.

3.4 *Ethical Considerations*

The Norwegian centre for research data approved the study. The interviewees received an information letter and provided consent to participate. They were informed that they could withdraw from the study at any time (until publication) without providing any reason. Data was treated confidentially and information about the seafarers is presented in such a way that they are not identifiable.

4 FINDINGS

It was found that navigators predominantly experience a vessels speed to be safe when they feel comfortable with the ship and feel that they are in control. While COLREG rule 6 – the rule covering the safe speed requirement – mentions several factors, and legal scholars have pointed to visibility as being the most important factor, the navigators had a different view. Navigators highlight that the factors affecting safe speed are very dependent not only one another, but also the context of the situation. Indeed, as the context is often confused and complicated, ranking different factors by importance will likely be an oversimplification that does not cover all scenarios. While visibility is seen as an important factor, the impact visibility has on "safe" speed depends on the specific circumstances of the situation. These findings are elaborated below. The findings include authentic illustrative quotations (AIQ), which are not necessarily direct citations but descriptive synthesized quotations that aim to grasp the essence of the opinions voiced by all interviewees [16, 18].

4.1 *Ensuring Safe and Efficient Navigation*

When asked how they ensure safe and efficient navigation, interviewees responded by firstly mentioning one of the following two concepts: Comfortableness with the vessel, and knowledge of the area. How comfortable they are with the vessel they are on depends on both the manoeuvrability of the vessel itself, as well as outside factors affecting the vessel. When the navigator is comfortable with the vessel, less attention is required for keeping the vessel on course. This frees up mental capacities that can be focused on other important tasks such as overseeing the traffic situation.

If you are very comfortable with the vessel, and you encounter bad weather, then you do not need to use so many brain cells and energy on thinking about how to turn the vessel.

The same principle applies to being comfortable with the area the navigator is navigating in. Being well versed in the area includes being aware of the safe path(s) through the area, navigational aids and dangers as well as areas where encountering other traffic is likely.

If you know the area, the way, the courses, and the navigational aids, then you can function as a human sensor: even if there is a technical failure in the vessel's navigation equipment, you should still be able to find your way.

Actively utilising the available navigational aids means that navigators can traverse an area without having to constantly check the (electronic) navigational charts or relying on technical support. This both introduces redundancy as well as it frees up mental capacities which the navigator can then focus on other important tasks.

4.2 *The Meaning of Safe Speed*

When it comes to safe speed, it was difficult to get a clear definition of the concept. During some interviews it seemed as if the interviewees understanding of the concept was inconsistent.

Safe speed is a speed which allows you to stop before you get into a dangerous situation. If something suddenly appears in front of you, you must be able to stop. This would mean that you should not be underway when visibility is so poor that you cannot see past your own bow. But in reality, safe speed is so individual that it is difficult to define properly. We go through tight waterways with full speed because we feel like we are in control of the vessel. So maybe safe speed really is the speed that you as the navigator feel safe in.

The above AIQ illustrates how the interviewee initially thought of the legal understanding of the term safe speed, and later adjusted the meaning according to how they apply it in practice. This gap between legal interpretation and the conventional way seafarers determine safe speed was pointed out specifically by another interviewee.

Safe speed is quite juridical … I don't know, but that term is perhaps very broad. When I think about setting a speed that is safe, I don't usually think about the COLREGs. What I'm concerned about is that the vessel steers and moves as I want it to, and that I feel confident that I can navigate safely.

The importance of keeping control of the vessel and the situation was echoed by the majority of the interviewed navigators. Factors such as manoeuvrability of the vessel, traffic situation, external environmental factors and navigation area play a large role in this regard.

The most important thing is that you feel in control of the vessel and the situation around you. Going with full speed reduces your options and means you require more room to manoeuvre. Reducing the vessels speed generally increases your manoeuvrability and provides additional flexibility. It also means that you have more time to evaluate and execute the correct choices. But be careful to not reduce your speed too much – you will sacrifice your steering and lose control.

As the navigators tightly coupled safe speed to the feeling of being in control, they stated that for any situation there is no such thing as the one correct safe speed.

Safe speed is an unclear term. In the same situation one navigator may proceed at a safe speed of 10 knots, while another proceeds at 5 knots. It will be wrong to set any boundaries, as that may force some navigators to proceed at a speed that they do not feel comfortable with – which would also be dangerous. Maybe that is why the term is a bit unclear – to give navigators some leeway to navigate in a way that is most comfortable to them.

4.3 *Standard Speed and when to Deviate*

When setting the vessels speed in practice, the interviewees unveiled that full speed ahead is the default. The speed generally only gets adjusted when the navigator deems this necessary to stay comfortable and in control.

If there is no traffic you go with full speed. Sometimes you meet captains who want to reduce in certain areas, and that wish gets respected.

However, some interviewees shared that a reduction of speed may sometimes be a bureaucratic process that might involve repercussions. As a result, they sometimes feel pressured to proceed at speeds that they themselves deem unsafe. Examples of these situations were coupled solely to vessels with passengers on board.

In the passenger ferry industry, we proceed at high speeds because we must keep a schedule. People expect to arrive on time. There is a conflict of interest here: We don't want accidents, but we also have an obligation to get people from A to B on time. In practice this means that you only reduce speed for very special things – and as a result we don't reduce speed more than a couple of times a year. But you can see the same happening with cruise ships – 300-metre-long vessels going through the fjords at 25 knots, even in the middle of the night, just because the passengers should wake up in a new place the next morning. It's completely wild.

Consideration for others was also mentioned as a reason for reducing the vessels speed. A vessels wake can cause problems for other vessels, particularly small craft and moored vessels, and navigators highlighted that they would reduce their speed in particular areas to reduce the size of their wake – and thereby keep any disturbance to others to a minimum.

4.4 *Specific Moments to Consider when Setting a Safe Speed*

In the following subsections, different specific moments that navigators consider when setting a safe speed will be presented. This illustrates both what navigators deem important to consider, as well as highlight which conclusions navigators draw from the information they gather. When asked if there is some sort of hierarchy that determines that some moments are more important than others, some initially pointed to a specific moment that they deemed most impacting. This quickly changed however, and the interviewees pointed to how the factors are dependent on one another, and that the importance of the different moments depend on the context.

Fog is worse than anything else. But really this was back in the day – but nowadays we have such good equipment. Now visibility might be important in confined waters with much traffic, but not so much in open waters. When I think about it all these factors depend on the situation, the vessel you are on and where you are going. Any hierarchy of the factors is changing along with the conditions and is not constant.

Because of the many dependencies, interviewees were critical of the possibility of creating a general safe-speed-flowchart, which could be followed to determine the safe speed in that particular situation. One interviewed navigator voiced restrained optimism for the possibility of creating such a flowchart for one specific vessel in one specific location but also mentioned that a general flowchart would be complicated as there is so much variance in how the different factors affect which speed would be safe.

4.4.1 *Is Slower Safer?*

As mentioned in 4.2 above, the most important thing about safe speed is being in control. So, while reducing speed gives the navigator more time to evaluate and execute their options, it also amplifies the effect of external weather factors – such as wind and current – on the vessel. After reducing the vessels speed below a certain point, most vessels will even lose their ability to manoeuvre. As a result, the interviewed navigators disagree with the sentiment that a reduction of speed necessarily leads to a safe speed. Indeed, examples of the opposite have been shared by many interviewees.

In some of the Norwegian ports there are speed restrictions limiting speed to 5 knots. For many vessels, going at a speed of less than 5 knots in these ports is unsafe. Fast ferries are much easier to steer when going 10 to 12 knots, and some of the old cruise ships do not swing – but only go straight ahead – when going at less than 10 knots. The same applies for some of the other more confined areas – when you go too slow, the wind and current takes you and you run aground. Reducing to zero in these areas would be lunacy – so personally I like to keep a little higher speed to be in control of my own fate.

4.4.2 *Visibility*

Visibility is mentioned as the first factor to consider in the COLREGs and is generally seen as the most important factor for the determination of safe speed by the legal community, where it is stated that is not safe to go fast when visibility is poor. But when is visibility poor? While not all navigators provided the same values, they seemed to agree that more than 1 nautical mile visibility can be considered good, between 5 cables and 1 nautical mile they start to raise their alertness, and below 5 cables they would consider reducing speed. Additionally, the interviewees highlighted the following concepts as important: The size of the vessel you are on, the amount of navigable space around you and the reason for the reduced visibility.

900 metre visibility is completely fine on a vessel that is 100 metres long, but for a vessel that is 300 metres that same visibility does not seem so fine anymore. But it also depends on the area you are in: In open waters you have so much room to manoeuvre that a reduction in visibility really doesn't have an effect anymore – especially since we have such good equipment. With radar you can see even in thick fog. The only time where radar cannot help you in reduced visibility is when you encounter wet snow – then you get false echoes and cannot trust the radar picture.

The above AIQ highlights how navigators can – under specific circumstances – deem a visibility range of 900 metres as completely fine. The interviews highlighted that the importance of visibility is not independent, but instead depends on the context as well. Only when other safety margins are reduced – such as navigating in a narrow channel or in an area of high traffic – would navigators start to adjust their speed. If, however, they encountered reduced visibility in open waters with no other traffic, they would continue proceeding at their normal speed. In general, the interviewed navigators mentioned visibility less with regards to collision avoidance, but more with regards to keeping the vessel on track. They voiced their content with both the available and planned aids to navigation along the Norwegian coast and stated that they used classical i.e., visual navigation methods as their preferred way of navigating along the coast. A reduction in visibility would mean that they would need to switch to technical navigation methods instead.

You can obviously use the chart and radar to sail in this area, but we mostly use these tools to check for other traffic. The navigation happens mostly by eye: We use the aids to navigation that we have along the coast, as for example the sector lights. That is a very pleasant way of navigating. But when visibility is poor, we must switch to technical navigation. Then we must allocate more time to utilizing those tools and have less time for looking outside the window.

The danger of not being able to detect another vessel in poor visibility was not generally seen as great enough to warrant a reduction of speed no matter the context. Furthermore, it was pointed out that it is generally smaller pleasure craft that are most at risk of not being discovered in bad weather – and that these would generally not be out on the water in bad weather.

But this is a type of risk assessment. When it is dark, visibility is low and there are gale force winds that mean that I have a bit of wave clutter on the radar, then I do not expect small vessels to be out on the water. And then I don't reduce speed just because of the off chance that they could be there.

The above AIQ highlights the kind of risk assessment that takes place. While in that instance it was highlighted why a reduction of speed may not be necessary it was also highlighted by navigators that if they pass areas where they know the likelihood of encountering small vessels to be larger, they would either try to take a different route or reduce speed pre-emptively.

4.4.3 *Traffic*

While there is generally less traffic in Norway than in other parts of the world, traffic was mentioned as an important factor throughout the interviews.

The interviews showed that dense traffic is a somewhat vague concept, that depends on a lot of other factors. Firstly, not only the number of vessels in the area is important, but also how they are positioned and how they are manoeuvring. Traffic that is organised in a way that encounters are minimized – as for example in a traffic separation scheme – would be considered less dense than traffic that is unorganized. Additionally, navigators described that – when compared to open waters – fewer vessels were required in confined waters for them to feel as though traffic was dense. The types of vessels encountered also influences the perception on the density of traffic – leisure vessels are seen as less predictable and therefore more difficult to collaborate with than vessels with professional crew on board. Finally, traffic is dense or not dense in relation to the vessel you are on yourself. If you experience numerous vessel encounters from different directions, the manoeuvrability of your vessel will determine how constrained you will feel. As a result, traffic density in the same situation might be considered low when steering a highly manoeuvrable vessel, and high when steering a vessel that is hardly manoeuvrable at all. Overall, traffic is not considered to be dense if they feel comfortable in their ability to keep clear from all vessels. The more difficult it gets to understand and react to other traffic, the more navigators feel that traffic is becoming dense.

I feel traffic to become dense when I feel that I cannot steer away from the different vessels with my standard speed in a proper manner.

Interestingly, the issue of traffic was generally not discussed in terms of what to do when you encounter dense traffic, but more in the way of how you can actively avoid getting into situations with dense traffic and numerous close quarters situations.

I will always try to avoid getting into situations where I will experience multiple vessel encounters. Instead, if I notice that I am running into such a situation, I will rather reduce speed ahead of time, wait for the situation to clear, and then continue with normal speed. If I were to continue and then reduce when encountering the dense traffic, my reduction of speed introduces new dangers, such as drift. In an area where there is little space and maybe current this introduces a new danger in itself – and the last thing I want to do in an already difficult situation is to add more distracting factors.

Looking ahead like this means that navigators look at traffic density not only reactively, but proactively. They proactively look out for situations where dense traffic may occur, and try to either not get into that situation, or come prepared. This tendency for proactivity was also highlighted by navigators stating that they will not only consider traffic that they have observed, but also traffic that has not been observed yet.

There are areas where the likelihood of encountering other traffic is just so much higher. In open waters we encounter fewer vessels than when passing ports and cities. And then there are times where we know that more pleasure craft will be on the water – such as the national day.

4.4.4 *Area*

For the area moment, both the proximity to shore or other navigational hazards and available depth of water was combined. The most important aspect of the area is that the navigator must be comfortable navigating in it. Furthermore, the area plays a large role in providing context: The effect of both visibility and other traffic were enhanced when they were taking place in a confined area.

The interviewees working onboard fast ferries basically did not see proximity to shore or other navigational hazards as problematic and stated that they would proceed at full speed even when close to shore.

There are times where we have rocks and shore within 5 metres of the side of the vessel, but we still go with full speed. Tight spaces by themselves do not warrant a reduction in speed.

This is likely due to the generally supreme manoeuvrability of the fast ferries employed in Norway. The maritime pilots who work on many different types of vessels had a more nuanced view. The pilots highlighted the superiority of a U-turn over a stopping manoeuvre when encountering a dangerous situation. As a result, the consensus was that the border between open and confined waters was where the vessel could safely execute a U-turn. A differentiation between open and confined waters therefore depends on the manoeuvrability of the vessel involved. However, from experience, the maritime pilots stated that most vessels below 140 metres in length, having 5 cables of water around them, would be navigating in what they would consider to be open water.

When it comes to the effect the depth of water has on safe speed, the fast ferry navigators stated that the waters off the Norwegian coast are generally so deep that it does not have an effect. While some of the maritime pilots highlighted the increase in turning circle and stopping distance in shallow water, the interviewees indicated that they would reduce speed in shallow areas with the sole intention of reducing the effect of squat and the resulting possibility of touching the bottom.

4.4.5 *Wind, Waves and Current*

Interviewees stated that wind is a factor of great importance, that needs be taken into account during nearly all operations. This includes not only the wind speed, but also the wind direction. Wind is seen as more problematic when blowing perpendicular to the vessels course, and less problematic when blowing parallel to the vessels course. The effect of wind speed on safe vessel speed is generally seen to be inverted, i.e. high wind speeds require high vessel speeds. This is because the drift inducing effect wind has on a vessel is larger at lower speeds, and less at higher speeds.

It is wind that we struggle with the most. Wind causes you to drift, and if you then reduce speed you drift even more. That is why you need high speed in high winds.

Reduction of drift is important for several reasons. If you are in a tight space, the introduction of drift makes the space even tighter as the required leeway angle to keep the vessel on course means that the vessel takes more space in the waterway. The leeway angle increases with increased drift or reduced vessel speed, up to a point where the vessel will not be able to keep on track and risks being pushed aground. Finally, large drift may lead other traffic to become uncertain about your intentions, as illustrated by the AIQ below:

Our own leeway angle can, in some places, create uncertainty with regards to my intentions. So that if I compensate for drift with adjusting my course, it can look like I'm steering straight towards someone – even though I'm not. I want to avoid creating wrong signals - or signals that can be misunderstood – at all times.

The effect of waves on safe speed was generally not connected to collision avoidance, but rather to the reduction of forces that may cause damage to the vessel. Interviewees therefore mentioned that high waves would cause a reduction in speed to reduce the chance of damages to the own vessel.

Interviewees did not mention current as a factor that induces drift but were more focused on current that sets either in the same, or opposite direction to the vessels course. In this regard the navigators highlighted that current that sets opposite to the vessels course is generally seen as having a positive influence on control over the vessel, while current that sets with the vessel has a negative influence on control over the vessel. Vessels that proceed against the current might be able to reduce their speed over ground to zero, while maintaining enough speed through water to maintain manoeuvrability. On the other hand, it is virtually impossible to come to a stop when the current sets in the same direction as the vessel, as the vessel will loose steering due to low speed through the water before ever coming to zero speed over ground. With this being said, navigators still stated that in practice current only has an impact on their alertness, and not on their selection of speed.

4.4.6 *Background Light*

Background light had two meanings for the interviewees – it could come from both inside and outside the navigational bridge. In any case, it is seen as a disturbance and – where possible – steps were being taken to reduce their occurrence. This includes asking others on the bridge to switch off any background light on the bridge, as well as a case where navigators took contact with a quay to ask them to modify a newly installed floodlight in a way that it becomes less interfering.

Navigators stated that the disturbing effect of background light is largest when navigating in unknown areas, and is significantly reduced by both modern support technology such as radar and AIS and when a navigators knows the area so well that he is able to quickly filter out background light and focus on the lights that are important for safe navigation.

In practice this means that background light influences safe speed only when the navigator does not feel comfortable with the situation.

In a normal setting when experiencing background light, the radar image gives me such a good picture of where I am, where I am going, where I am going to turn, and which boats are around that it does not affect my set speed.

5 DISCUSSION

The results presented above show that the real-world problem of determining safe speed is too complex to be adequately captured by overly simplistic descriptions. The interviews show that the different factors affecting safe speed cannot be looked at in isolation, but within the context in which they occur on the water. Navigators therefore do not determine safe speed by following rule 6 of the COLREGs word for word, taking into account each factor in order, but instead interpret it as a goal-based rule. Navigators equate the requirement of proceeding at a speed where they can take proper and effective action to a speed where they feel in control and adjust their speed accordingly. Importantly, navigators do not only focus on being in control in the current situation, but also in the foreseeable future. This understanding is exemplified by navigators mentioning reducing speed in open waters and good conditions to avoid meeting other vessels in confined waters with possibly less favourable conditions.

5.1 *The Gap Between Work-as-Done and Work-as-Imagined*

This way of determining safe speed is in contrast with the way legal scholars approached this problem, taking each factor for itself and interpreting its effect on the safe speed in isolation. This indicates a difference between the work-as-done by the navigators and the work-as-imagined by theorists and legal scholars and is in line with the findings of a study, where the speeds of vessels in different visibility conditions was analysed [19]. That study found that contrary to the legal understanding of "safe speed", vessels did not significantly reduce their speed in poor visibility. A large distance between how work is imagined, and how work actually is done indicates an ill-calibration at the blunt end to the challenges and risks encountered at the sharp end of real operations [20]. This distance might be attributed to legal scholars having a worldview where safety and compliance with rules are the only factors that affects speed. In reality, it is widely known that "human behavior in any work system is shaped by objectives and constraints which must be respected by the actors for work performance to be successful" [21]. These objectives and constraints can often be contradictory. In practice, the interviewees have shared how the objective to proceed at a safe speed may clash with the objective to follow the rules (as with the case where some speed restrictions in place in Norway would require navigators to proceed at unsafe slow speeds), or with the economic objectives of the shipping company (as with the case where navigators are pressured to proceed at high speeds in order to stay on schedule).

With collision avoidance being a game of coordination, where navigators on different vessels have to independently choose mutually compatible strategies [5], it is feasible to predict that MASS designed according to how work is imagined and not how work is done will have trouble coordinating with conventional vessels. Furthermore, as informal work-systems and adaptations often develop when humans come into contact with systems designed according to work-as-imagined [22], one can expect seafarers on other vessels to develop new ways of interacting with MASS that are designed according to work-as-imagined. These new habits may be degrading safety and causing new types of hazardous situations in the shipping routes and fairways [23].

As the ability to elicit and represent the knowledge of experts is a growing concern in systems design [24, 25], the results of this paper can be seen as an exchange of knowledge between navigators and the designers of MASS, hopefully contributing to bridging the gap between work-as-imagined and work-as-done.

5.2 *Limitations*

The findings and generalisability of this study must be seen considering some limitations. The informant group is made up of a limited number of navigators that were selected as part of a convenience sample. Only Norwegian navigators were included in the study, leaving the possibility that navigators of other countries interpret the rules in a different way. Exploring the possibility of different interpretation of the COLREGs by navigators educated in different countries is something that could be looked at in future research. However, considering the international nature of the maritime industry, where navigators work with international colleagues and are subject to international regulation, the conclusions drawn may still have broad relevance and should be further investigated to find whether they resonate with the navigators in general.

6 CONCLUSION

The objective of this study was to extend the knowledge of how navigators interpret the rules, with a specific focus on how they interpret the rule covering the requirement to proceed at a safe speed. Although a small-scale qualitative study, valuable insight into the tacit knowledge of navigators and how they interpret the requirement to proceed at a safe speed was obtained.

It was found that the most important aspect for navigators with regards to safe speed was the feeling of being in control. The major factors impacting this feeling was the navigator's comfortableness with both the vessel and the area they are navigating in.

The navigators' interpretation of the factors mentioned in COLREGs rule 6 shows how navigators must determine the safe speed in a real world that is complex, and where each factor must be seen in relation to the context of the overall situation. This breaks with the view of how legal scholars approach this problem, where each factor is analysed in isolation. While legal scholars conclude that it is unsafe to proceed at high speeds in low visibility, navigators have no problem with proceeding through fog at high speeds, given that they are in open waters with no other traffic around.

Interesting take-aways include the fact that a slower vessel speed is not safer by default. Indeed, a too low speed can also be an unsafe speed. Another interesting take-away is that navigators include future situations in their determination of safe speed in the present. Navigators are aware of situations where a change in speed does not affect the safety of navigation in the present but has an impact of the safety of navigation in the future. An example here would be navigators reducing their vessels speed in open waters ahead of a confined waterway, with the intention of letting another vessel leave the waterway before entering the waterway themselves.

The conclusion of this paper is that determining a safe vessel speed is more complicated than made out in the literature. As the MASS of the future will have to collaborate with conventional vessels, it is important to ensure that MASS are not programmed with only work-as-imagined in mind, but also by considering the work-as-done in practice.

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