NTNU
Norwegian University of Science and Technology
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Department of Marine Technology

Master's thesis

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Probability Study of a Crossing Collision Scenario Involving Hydrogen-Fuelled RoPax Vessels

Master's thesis in Marine Technology
Supervisor: Ingrid Utne
Co-supervisor: Stein Haugen
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Preface

This thesis is written as the final stage in completing my Master of Science degree in Marine Technology with specialization in the field of Marine Systems Design at the Norwegian University of Science and Technology. The thesis corresponded to 30 ECTs and was written in the spring semester of 2022 at the Department of Marine Technology (IMT). The thesis can be seen as a continuation of the work conducted in a preparatory project thesis in the course TMR4560 - Marine Systems Design, Specializartion Project. Some of the material from this project thesis have been revised and included in this Master's thesis. My supervisors assisting me during this semester have been Professor Ingrid Utne at NTNU and Professor Stein Haugen at Safetec AS.

Even F. Stensvand

Even Fjelltun Stensvand

Trondheim, 09.06.2022

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This thesis is dedicated to my dear Turid Fjelltun, who tragically passed away early this year. You are missed greatly by friends and family, and you will always be remembered.

Abstract

The shipping industry is in a transitional phase, and pressure to implement greener fuel solutions for various shipping segments is only increasing. Hydrogen comes forward as an attractive fuel source due to its high energy density per unit weight and zero-emission properties. However, the change in risk by introducing new hydrogen-fuelled vessels should be assessed concerning various different safety aspects at sea. Relevant literature mentions ship collision scenarios involving hydrogen-fuelled vessels as one such aspect that should be further evaluated in relation to safety. RoPax ferries operating on fixed ferry routes along the Norwegian coast come forward as a suitable shipping segment for the implementation of hydrogen as a fuel source. A method based on research related to shipping collision scenarios is adapted to assess the probability of a crossing collision where a ferry operating on a route is struck by a passing vessel. A case study where collision probability is estimated for three different locations along the Norwegian west coast is conducted. The probability of such a scenario varies significantly between the three areas analysed, and the results is found to be challenging to compare with other literature. A methodology to determine the probability of a crossing collision with sufficient impact energy to strike the hydrogen systems on board the ferry directly depending on its location is also developed. However, the assumptions behind this model are coarse, so the results retrieved were associated with high uncertainty. Further work should be conducted to improve the methodology and more accurately estimate the crossing collision probabilities for specific ferry locations.

Sammendrag

Skipsfartsnæringen er i en overgangsfase, og presset fra myndighetene om å iverksette grønne drivstoffløsninger for å redusere utslipp fra skip øker stadig. Hydrogen kommer frem som en attraktiv drivstoffkilde på grunn av sin høye energitetthet per vekt og nullutslippsegenskaper. Endringen i risiko ved innføring av nye hydrogendrevne fartøyer bør imidlertid vurderes i forhold til ulike sikkerhetsaspekter til sjøs. Relevante studier nevner skipskollisjonsscenarier som involverer hydrogendrevne fartøyer som et slikt aspekt som bør vurderes videre i forhold til sikkerhet. RoPax-ferger som opererer på faste fergeruter langs norskekysten fremstår som et egnet skipssegment for implementering av hydrogen som drivstoffkilde. En metode basert på tidligere studier knyttet til skipskollisjonsscenarier er tilpasset for å vurdere sannsynligheten for at en krysningskollisjon hvor en ferge som opererer på en rute blir truffet av et passerende fartøy. En casestudie blir gjennomført, hvor tre ulike ferjelokasjoner langs den norske vestkysten analysers. Sannsynligheten for et slikt scenario varierer betydelig mellom de tre områdene som er analysert. Funnene relatert til sannsynlighet for krysningskollisjon er dessverre vanskelig å sammenligne med annen litteratur, siden ulike scenarioer ofte analyseres. En metodikk for å estimere sannsynligheten for en krysningskollisjon med tilstrekkelig støtenergi til å treffe hydrogensystemene om bord på fergen direkte avhengig av plasseringen blir også utviklet. Antagelsene bak denne modellen er imidlertid grove og upresise, så resultatene som ble beregnet er forbundet med høy usikkerhet. Det bør jobbes videre med å forbedre metodikken for å mer nøyaktig estimere sannsynligheten for krysningskollisjon for spesifikke områder hvor ferjene som seiler bruker hydrogen som kilde til drivstoff.

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Nomenclature

- AIS - Automatic Identification System
- CFD - Computational Fluid Dynamics
- COG - Course Over Ground
- CRI - Collision Risk Index
- DBSCAN - Density-Based Spatial Clustering of Applications with Noise
- EMSA - European Maritime Safety Agency
- ERA - Explosion Risk Analysis
- FEM - Finite Element Method
- FSA - Formal Safety Assessment
- HAZID - Hazard Identification
- IMO - International Maritime Organization
- MGRS - Military Grid Reference System
- nm - Nautical mile
- SOG - Speed Over Ground
- PEM - Proton Exchange Membrane
- QRA - Quantitative Risk Analysis
- SOLAS - Safety of Life at Sea
- TQ - Technology Qualification

1 Introduction

This section serves the purpose of introducing the main background of the master thesis, as well as describing the main objective and limitations. A general overview of how the thesis is structured is also included.

1.1 Background

The need for greener alternatives in the shipping industry is only growing. Hydrogen can be an attractive fuel source for many different shipping applications and is a prominent alternative with a high energy density per unit weight when compared to ships running on only battery electric power. With today's technology, hydrogen as a fuel can be suitable for sailing distances where pure battery-powered vessels are not sufficient enough to operate in an efficient manner. Longer ferry connections appear as a shipping category suitable for hydrogen as a fuel source and have the potential to eliminate CO2 emissions from fuel completely.

The Norwegian government is demanding low or zero-emission vessels on all national ferry connections as a criterion for all new tenders. They are currently working to motivate the industry further to implement low or zero-emission solutions within shipping in the coming years (Norwegian-Government 2019). Hydrogen fuel solutions are one of the leading alternative fuel sources considered for several longer ferry connections along the Norwegian coast. In order to meet the Paris agreement established in 2015, the plan is to reduce the CO2 emissions by 50% compared to emission levels in the nineties and a further 90-95% reduction by the year 2050. To meet these goals, continuous work on developing and implementing new technology is needed to bring the shipping industry into a greener and more sustainable future.

New designs and technologies can also influence the risk picture associated with the vessel and can potentially increase the risk of fatal outcomes in different accident scenarios. One area lacking research and knowledge is how ship collision accident scenarios are affected by introducing hydrogen fuel and handling systems on the vessels. An assessment of the probability of such an event is therefore highly relevant.

1.2 Objective

The overall objective of this master thesis is to investigate the probability of crossing collision scenarios where a hydrogen-fuelled ferry operating on a fixed route along the Norwegian coast is struck by a passing vessel crossing the ferry route. The size of the vessels involved in the collisions is a crucial parameter when assessing the probability related to collisions. Relevant vessel types and sizes will be defined and brought further into the assessment. To establish an overview of collision frequency with different vessel sizes, an analysis of AIS data for the relevant areas is performed. A case study, where three different ferry locations along the Norwegian west coast are analysed, is conducted to illustrate how the methodology for determining crossing collision probability is done. The findings from these three cases will be compared to each other, and similarities and differences will be further commented on in relation to relevant literature on the topic.

A way of influencing the risk of collision scenarios with hydrogen-fueled vessels is to place the fuel cell, hydrogen storage tanks, and handling systems in different locations on the ship. A probability related to a collision with the hydrogen systems is assessed, depending on if it is placed above or below the vehicle deck of the ferry. Classification of potential crossing collisions with a certain level of collision energy is also developed to identify the probability of a high-energy crossing collision where the ferry operating on the route is struck by a passing vessel.

1.3 Scope and limitations

Risk can be defined as a product of probability and consequence. This thesis will only focus on the likelihood of various crossing collision events involving different vessel types. Though penetration length in relation to collision energy is used to classify collision scenarios depending on energy level, this is not an assessment of the severity of a crossing collision event. Information on the height in the bow of the various analysed vessels was unavailable. Coarse assumptions were applied to comment on the probability of a collision scenario with the potential of impacting hydrogen systems depending on their location on the ferry, leading to limited results.

Although many ship-ship collision scenarios are relevant when assessing maritime safety at sea, this thesis will mainly focus on crossing collision scenarios. Collision with rigid structures, grounding, and stranding scenarios may also pose a risk for the hydrogen-fuelled vessel at sea, but these scenarios will not be further assessed in this thesis. A methodology is presented to determine the geometrical probability of a crossing collision event. To estimate the probability of a collision event, a causation probability must also be determined. The methodology developed in this thesis will not present a framework for determining the causation probability. This parameter will be based only on findings from the available literature.

The collision probabilities established are based on assumptions and simplifications that are not necessarily valid for other areas. The methodology presented in this thesis can be applied in other crossing collision analyses for different locations. Still, precautions should be considered since the developed model is not universally applicable to other ship collision analyses. The methodology is mainly based on current knowledge, relevant literature, and current research. Therefore, one should consider updating and improving the methodology with new knowledge if it is applied in future collision risk analyses.

Since AIS data for only one year is analysed, there are uncertainties related to the simplified modeling of traffic in the developed methodology compared to the the actual traffic in the specific areas analysed. Therefore, it is limited how precise the calculated probabilities are compared to a analysis utilizing AIS data for a longer time period. If the methodology is applied to the same area with AIS data from a different time period than the year analysed in this thesis, the collision probabilities may be different in comparison.

1.4 Structure

The thesis is divided into separate sections. The introductory matter will include a literature study of available research and results related to the hydrogen, ship collision scenarios, and AIS data analysis. The main matters consist of a case study, where three different ferry routes along the Norwegian west coast are analysed with respect to collision probability based on available AIS data. The results from applying the methodology are also presented here. Finally, a discussion of the findings and results are presented and a comparison with findings from available research is performed. Uncertainties regarding the results, method, and assumptions are also commented on. Finally, the conclusions are made and areas for further work is commented.

2 Literature Review

To better understand the issue of collision scenarios involving hydrogen-fueled vessels, a review of available literature related to the topic is conducted. The main focus is on existing literature and research on relevant topics such as hydrogen in shipping from a technical and safety aspect, ship-ship collision scenarios, and AIS data analysis for shipping applications. This section is structured by topic, and relevant information from different studies and research are grouped and listed within one of these main topics. Some of the available literature will be able to fit in under several topics. Therefore, these will be placed under the main topic where they are found to be most relevant.

The search for relevant literature is performed using search engines such as Google scholar, NTNU Open, and scientific publishers like Elsevier and Science Direct. Parts of this literature study have already been done in an unpublished project thesis written by the author of this thesis in the autumn of 2021. It will come clearly forward which sections from the project thesis are relevant and also used here in this Master's thesis. The section ends with a summary of the relevant findings from the literature review and a subsection discussing what can be viewed as state-of-the-art models in the industry.

2.1 Hydrogen in Shipping

Hydrogen as a fuel source and fuel cell technologies have gained more and more attention in the last decades and will at least to some degree be a part of the transition from traditional fuel sources to greener alternatives. The technology is still novel in some aspects, and further development is needed to accelerate the implementation of these new systems to contribute to the green transition. The publications included under this topic mainly focus on where the technological development stands today and how the different solutions can be a part of the future shipping industry. Safety aspects related to hydrogen-fuelled vessels are also included here, focusing on new risks introduced, methods and tools used for identification and quantification of risk levels, as well as potential risk-reducing measures.

The Norwegian classification company DNV is active in the development and research related to hydrogen as a fuel source and have conducted several studies in cooperation with other actors on the subject. Safety is one of the main aspects investigated, and among various publications, two studies associated with hydrogen safety are included under the hydrogen in shipping topic. Findings from a third publication on a risk assessment of a high-speed vessel fuelled with hydrogen are also relevant and included.

2.1.1 DNV: Study on the Use of Fuel Cells in Shipping

DNV conducted a study on the use of fuel cells in shipping for The European Maritime Safety Agency (EMSA). The main focus is on a technical overview and risk-based analysis of fuel cell technology in order to evaluate the potential of different fuel cell technologies in maritime shipping applications (Tronstad et al. 2017).

The study is divided into three blocks. The first block focus on fuel cell projects in shipping. Selected projects where fuel cell technology is present are described in detail. Parameters such as type of vessel, fuel cell type, power output, and fuel source are included in the description. Subsequently, a detailed assessment of the different fuel cell technologies is performed. Here, power output, operational temperature, chemical reaction equation within the fuel cell, and various advantages and disadvantages related to the technologies are discussed. Tronstad et al. (2017) ranks the different fuel cell technologies concerning 11 parameters, including relative cost, maturity of technology, safety aspects, efficiency, and more. The three highest-scoring fuel cell technologies are presented and brought further into the study. Table 1 shows the five highest-scoring fuel cell technologies for maritime applications.

Table 1: Ranking of different relevant fuel cell technologies for marine applications by DNV

Fuel Cell technology	Ranking	Score
Proton Exchange Membrane (PEM)	1	75
High Temperature PEM	2	73
Solid Oxide Fuel Cell	3	69
Molten Carbonate Fuel Cell	4	67
Alkaline Fuel Cell	5	66

The second and third blocks focus on the current rules, regulations, and safety concerns relevant to the implementation of fuel cell systems in maritime shipping. Classification societies are working on rules and regulations covering fuel cell technologies and low flashpoint fuels, but more work is needed to establish clear guidelines for use by the industry.

The International Code of Safety for Ships using Gases or other Low-Flash-Point Fuels (IGF Code) covers to some degree specific requirements for low flash point fuels, but only related to LNG and CNG fuels for use in internal combustion engines. New rules and regulations for fuel cells using low flashpoint fuels are under development initiated by IMO and the sub-committee on Carriage of Cargoes and Containers (IMO-CCC7 2021). This will play a significant role in the establishment of regulations and defining the approval process for hydrogen-fueled vessels in the future.

Currently, the way of approving applications of systems and designs using fuel cells and other low flashpoint fuels is to follow the IMO guidelines on alternative designs and arrangements (IMO-MSC.1/Circ.1455 2013). These guidelines state that an alternative design or arrangement must be "*as safe or safer*" than its equivalent traditional design, which must be proven through a safety assessment of the new systems. DNV calls for more research and evaluation of several systems related to hydrogen fuel cells. Some of these systems are related to bunkering, on-board storage of hydrogen, fuel cell systems, and fuel-specific properties of hydrogen for maritime applications.

Concerning safety, Tronstad et al. (2017) especially points out two safety issues related to the use of fuel cell power systems for use on vessels. The first is how different fuel properties and behavior can influence the definition of hazardous zones and safety distances. The second safety issue is related to hydrogen fuel storage on board vessels with respect to different potential collision scenarios and hydrogen storage tanks beneath accommodations.

2.1.2 Concept risk assessment of a hydrogen driven high-speed passenger ferry

The main objective in this publication is to conduct a risk assessment of a concept design high-speed passenger ferry fuelled with liquefied hydrogen (Aarskog et al. 2020) . The main focus is on the risk of fatality related to the hydrogen storage, handling, and fuel cell systems on board during operation and when moored in the harbor. The findings are compared to the level of risk for conventionally fuelled vessels and the requirements stated in the IGF code.

Consequence models developed by Lloyd's Register are used to assess the hydrogen risk. Hydrogen storage systems, low and high-pressure piping, fuel cell systems, and the vent mast are analysed individually using FLACS CFD. Operational fire and explosion scenarios of concern for these systems are evaluated in this study. However, no scenarios related to collision, grounding, or external impact loads are considered.

The authors find that the estimated risk related to the hydrogen systems on board is lower than first anticipated. Less than 0.01 fatalities per 10^9 passenger-kilometer is predicted from accident scenarios associated with hydrogen systems, which is lower than the risk tolerance level of 0.5-1.0 fatalities per 10^9 passenger-kilometer. This means that the risk of fatality linked to high-speed ferries with hydrogen storage, handling, and fuel cell systems is no higher than for conventional high-speed ferries. However, they point out that the maturity of the models used for risk assessment of hydrogen in maritime applications is limited. Many of the assumptions made in this study can be challenged. More research is needed to develop a more accurate model for risk assessment associated with hydrogen systems.

2.1.3 DNV: Handbook for Hydrogen-Fuelled Vessels

DNV collaborated with partners in the industry to develop a handbook for hydrogen-fuelled vessels in a joint development project Maritime Hydrogen Safety (MarHySafe) (DNV 2021). This is the first phase of the project. The main focus is on establishing a basis for a roadmap to hydrogen safety for the shipping industry by utilizing a risk-based approach inspired by the alternative design approval framework from IMO (IMO-MSC.1/Circ.1212 2006). A second phase of the handbook will focus on further developing knowledge related to hydrogen safety for shipping applications and how the technology can be implemented effectively, based on the knowledge and knowledge gaps established in the first phase.

This first phase of the handbook is divided into three parts, much like the DNV study on the use of fuel cells in shipping. Part A introduces where hydrogen is in the maritime industry today, comparing the feasibility, design, operations and maintenance, and safety with other well-known solutions such as natural gas fuel sources. Different arrangements for hydrogen fuel cell systems are presented. Figure 1 below is an example of a below-deck solution for storage tanks, fuel handling systems, and fuel cell power installation.

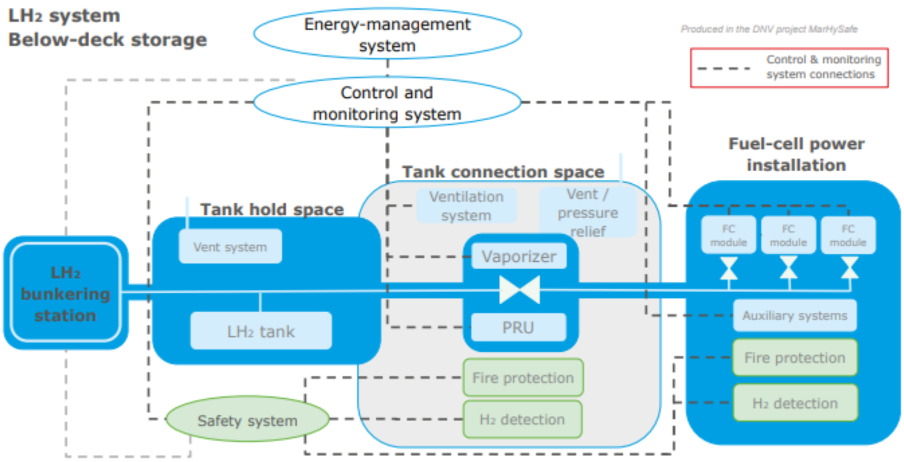

Figure 1: Simplified outline of a LH2 fuel cell propulsion system with below-deck storage of hydrogen created by DNV (DNV 2021)

Part B identifies relevant regulations, codes, and standards for hydrogen as a fuel source for the maritime industry. Here, the IGF Code and IMO's methodology guidelines for the approval process for alternative designs and arrangements are highly relevant. The relationship between the designers and submitters of an alternative design and the regulatory administration is described in detail. IMO's Formal Safety Assessment methodology is brought forward as a suitable tool for guidelines and evaluation of new regulations with respect to safety. The methodology can also be used actively in risk-based decision-making, where there is a call for reducing the level of risk in order to meet requirements. Figure 2 gives an indication of the relationship between the submitters and administrator in the approval process for an alternative design or arrangement, such as a hydrogen fuel cell.

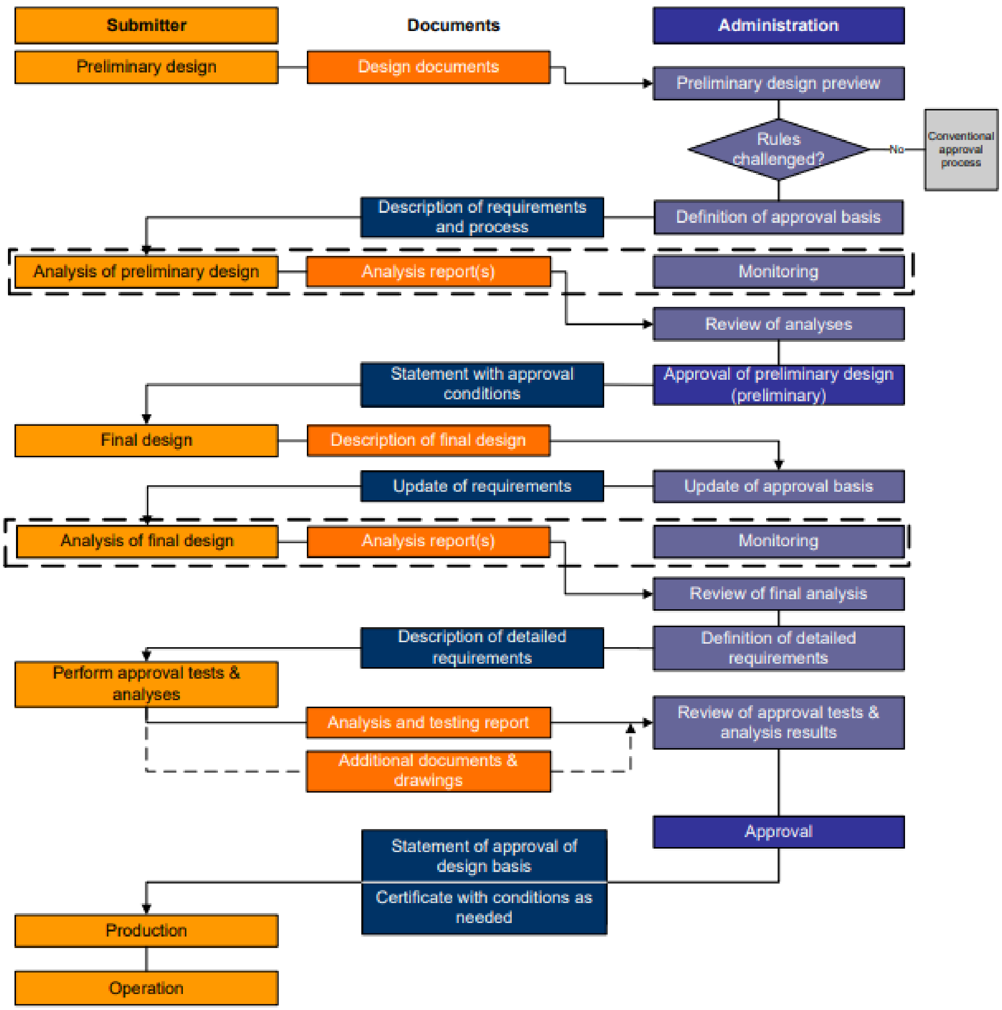

Figure 2: The suggested procedure of approval for alternative designs by IMO (IMO-MSC.1/Circ.1455 2013).

Different risk concepts are further discussed. Concepts such as individual risk, group risk, and risk acceptance criteria are presented. FN curves, which describe the relationship between the frequency of an accident and the number of fatalities, are introduced as a suitable metric for measuring societal risk. Other relevant functional requirements criteria from NORSOK and ISO standards are also discussed.

Finally, Part C focuses on the risk assessment of the new designs and systems. Different qualitative and quantitative risk assessment tools are discussed and evaluated, and a list of recommended methodologies for hydrogen in maritime applications is presented. HAZID, TQ, QRA, and ERA are recommended tools for assessing the risk in different stages of the design process.

The QRA is used to develop a picture of the total risk associated with the hydrogen-powered vessel. Risk contributions from fire and explosions, collisions and grounding, and other impact loads in relation the hydrogen systems on board are evaluated. The results from this assessment are then used to identify areas where explosion and fire scenarios are most relevant. An extensive ERA is conducted for the relevant areas, and CFD models are used to get a detailed understanding of ventilation issues, dispersion, and explosion scenarios. Based on the QRA and ERA findings, measures to reduce risk are presented. These risk-reducing measures are mostly related to fire and explosion risk, while no measures related to collision or grounding scenarios are evaluated.

2.2 Ship-Ship collision scenarios

Tronstad et al. (2017) states that there is lacking knowledge regarding safety when it comes to the storage of hydrogen fuel on board vessels subject to a collision with another vessel. Therefore, it is relevant to look further into available research and publications on ship collision scenarios to identify methodologies and models that can be used to assess risk for hydrogen-fuelled vessels.

A vast amount of accident scenarios are evaluated when vessels are being designed and built, as well as in the planning of voyages and operations at sea. Scenarios such as fire and explosion, stranding and grounding, collisions with rigid structures and other vessels, and operational accidents are some of the most relevant accident scenarios for marine shipping applications. Ship-ship collision scenarios can be divided coarsely into collisions along a route segment, including head-on and overtaking collisions, and collisions involving two routes that cross, merge or intersect (Friis-Hansen 2008).

Digital tools have been used to assess collision risk at sea for a long time. More advanced digital tools utilizing artificial intelligence, machine learning, and heavy computational capacity have been used to improve the accuracy of ship collision models. This subsection includes literature related to models and methods for assessing ship collision scenarios that have been developed in order to improve knowledge and reduce collision risk. Keywords such as "*Ship collision scenarios*", "*ship crossing collision*", "*hydrogen vessel collision*", or similar are entered into the mentioned search engines to identify various relevant scientific literature.

2.2.1 Probabilistic risk analysis for ship-ship collision: State-of-the-art

An extensive study of available literature related to probabilistic risk analysis on ship-ship collisions was performed by Chen et al. (2019). The main activities consist of identifying different stakeholders, relevant models for collision frequency estimation, and causation analysis that stakeholders desire. The methods are classified based on their technical characteristics, and alternatives for different applications are discussed. The authors also propose different ways of improving the present models to assess factors such as vessel collision candidates and how human and organizational factors influence the risk picture more accurately.

Chen et al. (2019) bring forward the importance of probability-based risk analysis of ship-ship collisions and how it gives good quantitative results for risk assessment and mitigation, as well as an estimation of consequence. They comment and discuss the work done by Yahei Fujii and Shiobara (1971), and their model for describing the probability of ship-ship collision $P_{Collision}$, as can be seen in Equation 1 below:

$$P_{Collision} = N_{Candidate} \cdot P_{Causation}, \quad (1)$$

where $N_{Candidate}$ is the number of collision candidates, often referred to as geometric collision probability. $P_{Causation}$ is the causation probability and describes the probability of collision as a result of different factors of failure to avoid collision.

Different models can be used to establish the geometric probability of collision between vessels. Synthetic indicator approach, safe boundary approach, and velocity-based approach are some of the methods being discussed in this study regarding stakeholder interests, applicability, and practicability. Determining the causation probability is a complicated process, and the results are often sensitive to minor adjustments in parameters. Statistical analysis approach, fault tree approach, and Bayesian approach to determine the causation probability are the different methods presented, and they are discussed in relation to results from existing studies and literature.

In their concluding remarks, the authors of the study comment that to improve the accuracy of the geometric probability of ship-ship collisions, methods regarding multiple-ship-encounter scenarios should be further developed. They also point out that the lack of data used for analysis and estimation of the causation probability will makes it difficult to achieve accurate results for the collision probability.

2.2.2 Methods for Navigational Risk Analysis

In chapter 10 of Haugen and Kristiansen (2022)'s yet unpublished book on navigational risk analysis, different ship collision, allision, stranding, and grounding scenarios are assessed and discussed. This book is the second edition of the original book by Kristiansen (2004). General geometric models for ship-ship head-on collisions and crossing collisions from available literature are described. Parts of the following paragraphs on head-on and crossing collisions are extracted from the preparatory project thesis written in the autumn of 2021 by the author of this master's thesis (Stensvand 2021).

To better understand the concept of head-on collisions, a basic geometric approach from Haugen and Kristiansen (2022) is presented. A straight fairway is assumed, with Q_1 as arrival frequency. This traffic will then occupy an area $V_1 \cdot T \cdot W$ of the seaway. For a given time period T, the number of ships that will enter the fairway is $Q_1 \cdot T$. Fairway traffic density ρ can then be defined as:

$$\rho = \frac{Q_1}{V_1 \cdot W} \quad (2)$$

To pass the fairway distance S, a vessel will spend a total time of $T_2 = \frac{S}{V_2}$. But since the model includes two separate vessels in motion, the vessel is exposed to traffic over a distance S'. S' can therefore be calculated as:

$$S' = v \cdot T_2 = \frac{(V_1 + V_2)S}{V_2} \tag{3}$$

The collision cross-section is calculated as the sum of the two vessel breadths $B = B_1 + B_2$. The exposed area for a collision A can then be determined as:

$$A = B \cdot S' = (B_1 + B_2) \cdot S' \tag{4}$$

The amount of meeting situations for vessel 2 can then be estimated with arrival frequency Q_2 as:

$$N_G = \frac{B_1 + B_2}{W} \cdot \frac{V_1 + V_2}{V_1 \cdot V_2} \cdot S \cdot Q_1 Q_2 \tag{5}$$

The downside of using this model is that the traffic is evenly distributed across the breadth of the fairway, which is a weak assumption compared to the real world. Thus, the collision probability is overestimated. Usually, a vessel will tend to follow the starboard side of the fairway depending on its heading, size, and vessel type. Therefore, a more realistic model would assume that the vessels are normally distributed in their fairway section and estimate a geometric probability for collisions based on this. This assumption will generally reduce the collision probability (Haugen and Kristiansen 2022).

Similarly, by using simple geometric assumptions, it is possible to express the number of crossing situations N_G between two vessels in an area. Figure 3 illustrates the crossing collision scenario and outlines relevant parameters used to estimate the expected number of collisions during a given time period.

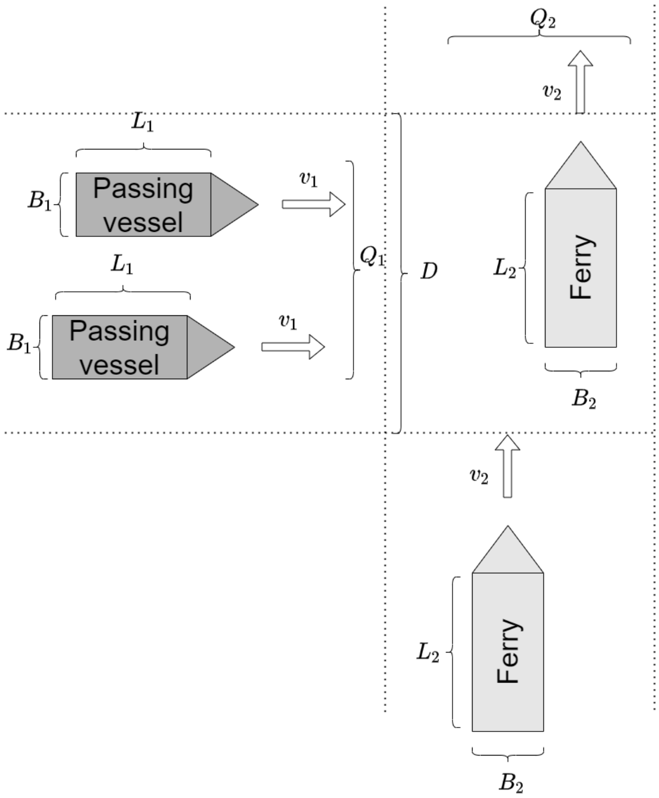

Figure 3: Illustration of cross collision scenario between ferries and a generic ship crossing its fairway based on the model from Haugen and Kristiansen (2022)

The traffic density is the same as Equation 2 for the head-on scenario. The time to cross the exposed section can be expressed as:

$$T_2 = \frac{D}{V_2}, \tag{6}$$

where D is the part of the fairway where the subject vessel is exposed. The critical sailing distance D_1 of crossing ships while the subject ship is exposed is then:

$$D_1 = V_1 T_2 = V_1 \cdot \frac{D}{V_2} = D \cdot \frac{V_1}{V_2} \tag{7}$$

In a crossing scenario where crossing ships hit the subject ship, the impact diameter will be the length of the subject ship and the breadth of the crossing vessels:

$$D_i = B_1 + L_2, \tag{8}$$

so the area subject to collision hazards can be written as:

$$A_1 = D_i \cdot D_1 = (B_1 + L_2) D \cdot \frac{V_1}{V_2} \tag{9}$$

Combining Equation 2 with Equation 9 where $D = W$, the expected number of collisions per passage of the fairway is expressed as the product of the exposed area and the traffic density:

$$P_{i1} = A_1\rho = (B_1 + L_2)D \cdot \frac{V_1}{V_2} \cdot \frac{Q_1}{V_1 \cdot W} = (B_1 + L_2) \cdot \frac{Q_1}{V_2} \tag{10}$$

Using the same approach, the expected number of collisions per passage where the subject vessel hits the passing vessels can be written as:

$$P_{i2} = A_2\rho = (B_2 + L_1) \cdot \frac{Q_2}{V_1} \tag{11}$$

Hence, the total expected number of crossing collisions is:

$$N_G = P_{i1} + P_{i2} = \frac{Q_1 Q_2}{V_1 V_2}[(B_1 + L_2)V_1 + (B_2 + L_1)V_2] \tag{12}$$

It is also possible to include different collision angles for passing vessels θ, as proposed by Friis-Hansen (2008). The number of crossing situations can then be expressed as:

$$N_G = \sum_{i,j} \frac{Q_i^{(1)} Q_j^{(2)}}{V_i^{(1)} V_j^{(2)}} \cdot D_{ij} V_{ij} \frac{1}{sin\theta}, \theta \in [10°, 170°], \tag{13}$$

where D_{ij} and V_{ij} are defined as collision diameter and relative speed for the two vessels involved in the scenario. However, Haugen and Kristiansen (2022) argue that the difference in the result using the more advanced modeling will only slightly improve the accuracy of the estimated collision probability.

A simple method for estimating impact energy is also adapted from the first edition of the book on methods for navigational risk analysis by Kristiansen (2004). Assuming a collision angle of 90°, this can be calculated as:

$$E_{impact} = \frac{m_1 \cdot m_2 \cdot (1 + C_h)}{2 \cdot (m_1 + m_2 \cdot (1 + C_h))} \cdot (v_1 \cdot sin(\alpha))^2, \tag{14}$$

where m_1, m_2 represents the vessel weights of the passing vessel and the ferry respectively, C_h is the added mass coefficient, which is estimated to 0.75 in sway for a 90° crossing collision, v_1 is the speed of the striking vessel, and α is the collision angle. The absorbed energy of the ferry is then estimated as:

$$E_{absorbed} = E_I \cdot \frac{1}{1 + \frac{m_2}{m_1}} \tag{15}$$

The absorbed collision energy is an important parameter and can be combined with models to determine hull penetration length in a collision scenario. An empirical method for estimating the hull penetration length was also presented by Kristiansen (2004). However, as commented in the preparatory project thesis written in 2021 by the author of this Master's thesis, the penetration length seems to be over-estimated for larger absorbed collision energies (Stensvand 2021). An alternative method for quantifying the penetration length is therefore investigated further.

2.2.3 Analysis of structural crashworthiness of double-hull ships in collision and grounding

A conceptual framework for collision and grounding analysis involving double-hull structures is presented in this article. The focus is on simplifying the input parameters utilized in the structural analysis and provide a design-oriented probabilistic procedure that can be used when assessing collision and grounding scenarios for vessels at sea (Bin Liu et al. 2021). Four different scenarios are examined further, including collisions with a bulbous bow, a straight bow, bottom raking, and bottom stranding. A case study involving a 4200 TEU double-hull container ship is carried out. The finite element method (FEM) is used to analyse how a collision with another vessel will affect the hull structure and penetration length in the different collision scenarios.

In the structural damage analysis, both large and small likelihood accidents are considered. Figure 4 illustrates the relationship between absorbed collision energy and penetration length for bulbous bow collision based on a less likely 90-percentile value, where the different curves represent hull materials with a tensile strength of 560 MPa (1), 490 MPa (2), and 630 MPa (3). 90-percentile means that 90% of collision scenarios will statistically be less severe than the values represented in the figure.

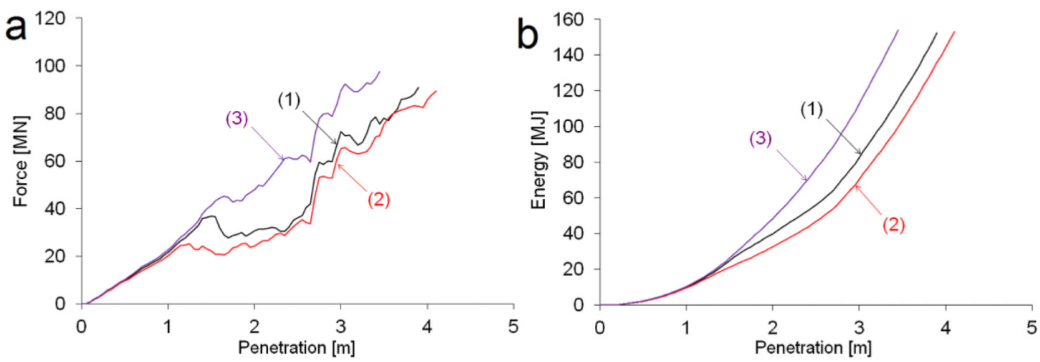

Figure 4: Curves representing the relation between force (a), absorbed energy (b), and hull penetration length.

The results indicate how a crossing collision can affect a double-hull structure and, through simulation, predict how the penetration length will vary with absorbed collision energy. Although the case analysed involves a large container ship with a double-hull structure, the findings related to the consequences of various collision and grounding scenarios and the framework itself can be helpful in the design phase of other types of vessels. The findings can also indicate how the penetration length varies with absorbed collision energy. This can be used to make an estimation of how low- and high-energy collisions involving other types of vessels will affect the structural integrity of the hull early on in the design process, and they can be compared to relevant standards required from the authorities and class societies.

2.2.4 A molecular dynamics approach for modeling the geographical distribution of ship collision risk

In this paper, Z. Liu et al. (2020) proposes a model based on a radial distribution function in molecular dynamics to assess the geographical distribution of collision risk in a specified area. The vessel traffic is assumed to be a "molecule" in two dimensions, where each vessel represents an "atom" in the "molecule". Figure 5 shows a simplified illustration of the model. Collision risk between each vessel pair is determined using analytical models estimating the distance between them in the radial distribution function. The collision risk for the specific area is then determined by using space interpolation to develop a detailed picture of the geographical distribution of collision risk based on the traffic density. Real AIS data from the Bohai Strait of China is used to validate the method.

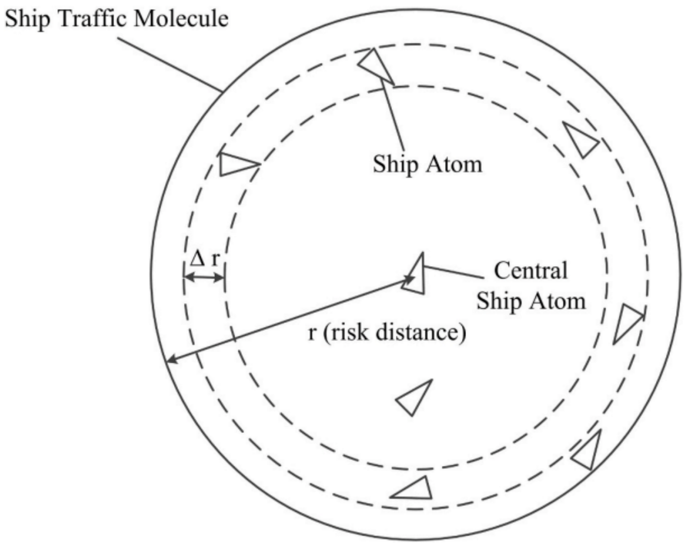

Figure 5: Simplified model description of the ship traffic "molecule" and corresponding ship "atoms" proposed by Z. Liu et al. (2020).

The results show that the proposed model successfully identifies and maps the geographical distribution of ship collision risk using AIS data from the specified area. Compared to traditional methods, the proposed model shows some advantages in identifying the collision risk distribution instantaneously. This dynamic collision risk mapping can be used by vessel operators and other stakeholders to monitor relevant water areas for sailing and ultimately increase the navigational safety at sea.

However, the proposed model shows limited results in situations where few vessels are localized within the area analysed. This increases uncertainty for the geographical distribution of the collision risk compared to collision risk models used for more specific localized situations. Parameters such as the maneuverability of the vessels and weather conditions were also not included in the model. It is sensible to assume that these parameters will directly influence the collision risk, and they should be included in future models to improve the accuracy of the results.

2.2.5 Probability modeling of vessel collision

Montewka et al. (2010) assesses the probability of vessel collisions and presents a new approach for estimating the geometrical probability of various collision scenarios that considers vessel dynamics. In other words, the maneuverability of the vessels once they get within a critical distance of the other vessel. They aim to develop a method for a more detailed analysis of overtaking, head-on, and crossing scenarios involving two vessels.

The method is based on a 2-D molecular model, and vessels are modeled as particles with a disc of a given radius representing a no-go area for other vessels. By combining the discs for two vessels, one can define the critical distance for collision. In this study, the critical distance is called the minimum distance to collision (MDTC). Figure 6 presents the general idea of the molecular model and how MDTC is calculated.

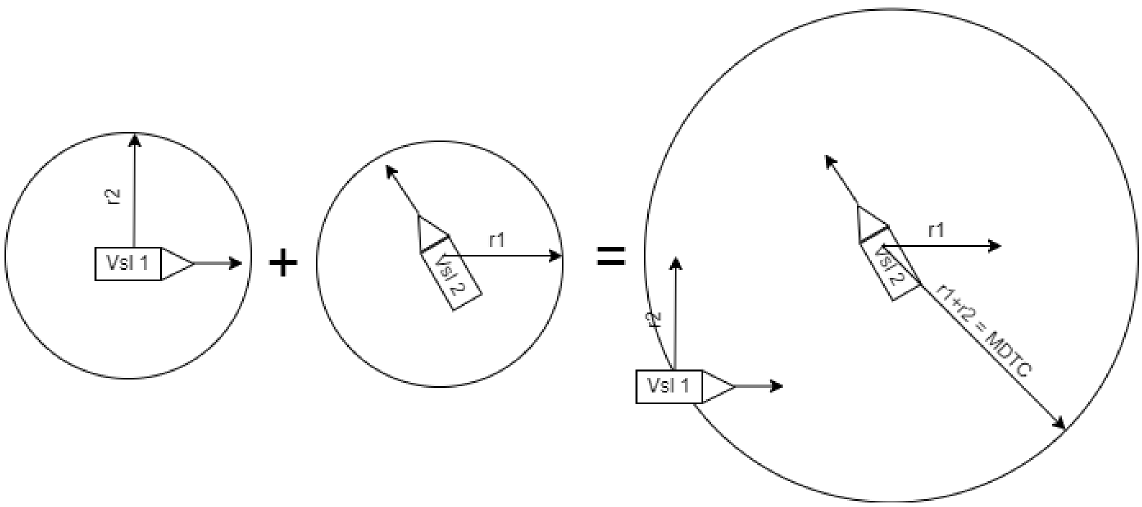

Figure 6: Illustration of 2-D molecular model and MDTC based on figure from Montewka et al. (2010)

The authors propose a model for estimating the number of crossing collision candidates based on a given vessel velocity and a constant arrival intensity when entering the waterway. The number of crossing collision candidates $N_{Crossing}$ is determined by using Equation 16 below:

$$N_{Crossing} = \sum_{i,j} \frac{RE'[V_{ij}]\lambda_i\lambda_j}{V_iV_jsin(\alpha)}, \tag{16}$$

where R is equal to MDTC as seen in Figure 6, $E'[V_{ij}]$ describes the expected relative velocity between the vessels i and j, λ describes the arrival frequency of the vessels into the waterway, V is the vessel speed, and α is the angle of intersection of the waterway. To quantify the risk, a causation probability is adapted from earlier research on the topic.

When comparing reported near-miss encounters from vessels sailing in the waterways between Helsinki and Tallin in the Baltic Sea with estimated collision values from the novel model presented in this article combined with AIS data, the estimated amount of collisions is shown to be close to the reported encounters. However, the results were only for the summer traffic, and the difference between observed values and modeled periods between collisions is notable. The authors claim that the reason why is that the causation factor used in the study is not compatible with the proposed MDTC-based model. The causation probability is also extracted from available literature and does not account for area-specific considerations. Factors such as surveillance of the area and Traffic Separation Schemes will affect the causation probability and should be incorporated into the model in further development.

Related to further research, the authors also call for including variations associated with the time of the day within the model. The assumed constant rate of arrival intensity in the proposed model is not realistic compared to the actual vessel traffic in the specific area. The proposed model should also be applied to other sea areas of interest, where near-miss data for vessel collisions are available for further validation of the model and generated results.

2.2.6 Basic modeling principles for prediction of collision and grounding frequencies

Friis-Hansen (2008) proposes a procedure for analysing grounding and ship-ship collision scenarios, focusing on event frequency and the associated damage caused by the event. In relation to the risk of such events, a framework for estimating the causation probability for various grounding and ship collision scenarios is presented. A review of earlier published collision studies were also conducted. It was discovered that the causation probabilities for crossing collision scenarios used in these studies varied between $2.8 \cdot 10^{-4}$ and $5.9 \cdot 10^{-5}$. In this study, a Bayesian Network model is used as the foundation to estimate the causation probabilities for ship-ship encounters and includes factors related to weather, technical equipment, vessel speed, alarm systems, human errors, and more.

The total causation probability for meetings between conventional vessels is found to be $9.00 \cdot 10^{-5}$. The causation probabilities retrieved from the Bayesian Network model are compared to earlier conducted studies worldwide. The results show that the framework gives comparable results in agreement with various earlier published literature.

2.2.7 Estimation of vessel collision frequency in the Yangtze River estuary considering dynamic ship domains

By analysis of AIS data from the Yangtze River estuary, an assessment of vessel collision frequency was performed for this specific area north of Shanghai, China (Chai et al. 2019). Influence of vessel type, time of the day, and other factors were included in the model and used to estimate the number of vessel conflicts N. The causation probability p_c used to quantify the collision risk between vessels is adapted from earlier research related to the topic. As proposed by Macduff (1974), the vessel collision frequency f can be estimated as:

$$f = N \cdot p_c \tag{17}$$

The specific fairways used for sailing into the port in Shanghai are also divided into geographical zones from A to K to more accurately assess the collision risk at different stages of the voyage to and from the port. The authors use p_c values depending on the type of collision (i.e. head-on, overtaking, small angle, and large-angle crossing), and the time of the day, distinguishing between daytime and nighttime.

To quantify the risk of collision scenarios, a causation probability is extracted from previous studies on ship collision scenarios. Different values are used for the four collision scenarios analysed, and there is also a distinction between scenarios in daytime and nighttime. These values can be seen in Table 2 below.

Table 2: Different values for causation probability

Collision type	Time of the day	Causation probability
Head-on	Daytime	$4.9 \cdot 10^{-5}$
	Nighttime	$4.9 \cdot 10^{-5}$
Large-angle crossing	Daytime	$5.87 \cdot 10^{-5}$
	Nighttime	$6.69 \cdot 10^{-5}$
Small-angle crossing	Daytime	$6.83 \cdot 10^{-5}$
	Nighttime	$8.48 \cdot 10^{-5}$
Overtaking	Daytime	$4.9 \cdot 10^{-5}$
	Nighttime	$4.9 \cdot 10^{-5}$

The results from the analysis show that head-on collisions involving container ships, cargo ships, and oil tankers are the most frequent in the area. It is also demonstrated that vessel conflicts are more frequent in the areas leading into and away from the port. The collision frequency is also found to be higher in the daytime compared to nighttime, which is somewhat sensible considering the higher traffic density during the day.

The authors also point out that the causation probability used in the analysis is not necessarily suitable and verified for use in the specific area included in this study. They also point out that a future study should include the effects of wind and visibility from the vessels when assessing collision risk. AIS data from the vessels in the specific area was only transmitted every five minutes, which will reduce the accuracy related to position and speed compared to a higher transmission rate. It is therefore proposed that a future study should investigate how the estimated collision frequency is affected by a higher transmission rate of AIS data.

2.3 AIS data analysis of maritime traffic

To get better insight into analysis of maritime traffic, a review of relevant publications involving marine vessel AIS data analysis is explored. AIS data is an essential source of marine traffic data and can be used to improve both navigational efficiency and safety at sea. There has been an increase in the use of AIS data in research and publications related to vessel traffic at sea in the last decades. More researchers are looking into how this available data can be used to improve knowledge and technology in different fields related to activity at sea.

Relevant publications focusing on AIS data analysis in relation to identifying marine traffic patterns, collisions with rigid structures and other vessels at sea, and factors influencing collisions are reviewed in this subsection. Keywords such as "*AIS data collision*", "*AIS data marine traffic*" and similar are used to find relevant information on various search engines.

2.3.1 Predicting Motion Patterns Using Optimal Paths

Fromreide and Hansen (2021) are proposing a dynamic grid-based technique for learning motion patterns by mapping them onto the optimal paths in a problem with a disordered landscape. An example of a disordered landscape problem can be marine traffic around ports and in fairways at sea. This grid-based technique models the maritime landscape as a grid, and transition probabilities between grid cells are calculated using training data. The training, validation, and testing data sets are based on available AIS data. The authors describe the method in the following way:

> *Imagine a plane and that* $\vec{x}$ is a point on this plane. There is a stochastic field $e(\vec{x})$ associated with the plane. We then choose a path P through the plane starting at point $\vec{x_A}$ and ending point $\vec{x_B}$. We then integrate the field $e(\vec{x})$ along the path P

$$E_P = \int_{\vec{x} \in P} e(\vec{x}) d\vec{x} \tag{18}$$

> *The optimal path is found by the minimization*

$$E_O = min_P E_P = min_P \int_{\vec{x} \in P} e(\vec{x}) d\vec{x}, \tag{19}$$

where E_O is the optimal solution to the problem (Fromreide and Hansen 2021).

Different iterative algorithms can be implemented to find the optimal path through the space. The paper's authors do not try to present a fully implementable algorithm for marine applications but instead provide the central idea of finding the optimal solution for paths. The work indicates that the proposed method can identify paths that optimize the relationship between the path length and frequency of use. The authors also state that more work must be performed to make the method more practical to use by others. Areas of work include cluster identification, grid construction, types of vessels sailing in the area, and more.

2.3.2 Knowledge-based Clustering of Ship Trajectories Using Density-based Approach

This paper presents a method for density-based clustering of real-world trajectories from ships transmitting AIS data in order to compare them to IMO rules for ship traffic (Bo Liu et al. 2014). Here, the clustering method used is the Density-based spatial clustering of applications with noise (DBSCAN) method. One interesting advantage of the method is that the speed and direction of the vessels, which are non-spatial attributes, are evaluated in the clustering method. The method is applied to two different actual data sets extracted from two areas along the North American west coast.

When the generated results from the analysis are compared to the rules defined by IMO, it shows that the mapping between results and IMO rules and regulations works. The method also successfully identifies clear moving and stopping areas for vessels. It identifies the gravity vector and sampled stopping point for stopping clusters, which can be defined as the representative center for moving and stopping clusters.

The downside of this method is that it is sensitive to changes in parameters, which means that if the same parameters are applied when analysing other areas, the results may be imprecise. Fine-tuning of the parameters used for clustering is therefore needed when a new area is analysed to achieve a good clustering result. The authors also suggest that further work should be conducted to improve the efficiency of the algorithm used in the presented method. This would make the method more applicable to other areas, as well as make it perform better on larger data sets reducing the total processing time.

2.3.3 A novel framework for regional collision risk identification based on AIS data

The authors of this paper present a novel framework for identifying regional collision risk for vessels based on AIS data (Z. Liu et al. 2019). In order to cluster the sailing vessels in the water area, the DBSCAN method is applied. The framework is divided into two steps. In the first step, collision risk and risk contribution from each vessel within the cluster are used to measure the collision risk within the cluster.

Different analytical models are used to identify the collision risk of each vessel, and its contribution to the cluster collision risk is determined by the use of methods from game theory.

Z. Liu et al. (2019) state that the calculations of collision risk for heavily trafficked areas can be computationally demanding, such as the area analysed in the case study. The risk of collision between each vessel within the area should be calculated to determine the total collision risk. Therefore, the application of clustering is suitable only to calculate collision risk for vessels in close proximity to each other. The general formula used to calculate the Regional collision risk for the specific area (RCR) is defined as:

$$RCR = \sum_{i=1}^{n} CR_i \cdot S_i, f \tag{20}$$

where CR_i is the collision risk for each vessel i and S_i is the contribution to the risk of each vessel summed over the total number of vessels n. Z. Liu et al. (2019) proposes to instead cluster the vessels within the specific area by using DBSCAN. When the clusters have been classified, collision risk is calculated for each individual cluster as in Equation 20. Then, each cluster's collision risk is combined to obtain a total regional collision risk for the specific area. The equation for determining the regional collision risk can therefore be written as:

$$RCR = \sum_{j=1}^{m} CCR_i \cdot S_j, \tag{21}$$

where CCR_j is the collision risk of each cluster, S_j is the collision risk contribution of each cluster j summed over the total number of clusters m

The framework is implemented in a case study based on AIS data from an area in the Northern Yellow Sea in China to test its validity. The results from this case study show that the output from the framework can reflect the real collision risk of specific areas at sea. The authors state that the framework can be used by marine surveillance operators to improve knowledge about the particular water area and improve the accuracy of estimated collision risk to increase safety.

2.3.4 A Study of Satellite AIS Data and the Global Ship Traffic Through the Singapore Strait

This Master's thesis from 2015, written by Bjørnar Brende Smestad, investigates Satellite AIS data (S-AIS) and questions the quality of the information and whether this is a reliable source of vessel information or not (Smestad 2015). Smestad outlines how heuristics can be used to determine different ship types using S-AIS, which removes the need to use commercial ship databases to gain this knowledge.

The suggested heuristics are applied for use on vessel traffic in the Singapore Strait to illustrate how the method works. The results from this case study show that the proposed heuristics can identify specific ship types with high accuracy, solely based on S-AIS data. Another aim of the thesis is to investigate if S-AIS data could be used to track ships entering the Singapore Strait. This could be used to track vessels on their complete journey from the endpoint and back to their port of origin. The complete voyage data could then be used to analyse emissions or collision risk for the vessels. The results show that most vessels could be tracked back to their port of origin. However, local traffic was hard to follow due to them not leaving the Strait and surrounding highly trafficked regions.

Smestad points out that the S-AIS data available in 2015 contained erroneous data, such as vessel dimensions, ship ID, geographical position, and vessel speed over ground (SOG). Therefore, sorting of data, removal of erroneous data, and good knowledge of the data set are essential steps before conducting any analyses of marine traffic based on AIS data.

2.3.5 AIS data For Increased Insight Into Navigational Impacts Post Installation of Man-made Structures at Sea

In this Master's thesis, the author Amalie Bu investigates how marine traffic and navigation are affected by the installation of man-made structures at sea. AIS data is used to compare how vessel traffic in the area surrounding the new structures is now compared to how traffic was before installation (Bu 2019). Several relevant locations along the Norwegian coast are analysed in a case study to address differences in traffic before and after the installation of the structures at sea. The AIS data is used to visualize parameters such as traffic density, geospatial traffic distribution, vessel speed, and more.

The results were somewhat limited, and the only area surrounding oceanographic buoys was investigated due to a lack of AIS data for other man-made structures. However, the results indicate that vessels post-installation keep a reasonable distance to the installed buoys. Therefore, the alterations in course cause denser traffic further away from the buoy and could potentially increase the probability of ship-ship collisions. In some cases, higher activity near installed objects is observed. This is not discussed further in the thesis, but Bu suggests it is an interesting subject for further work.

2.3.6 Allision risk analysis of offshore petroleum installations on the Norwegian Continental Shelf—an empirical study of vessel traffic patterns

The main objective of this article is to investigate how local vessel traffic patterns change as a result of new offshore petroleum installations (Hassel et al. 2016). The Norwegian Petroleum Safety Authority (PSA) requires that operators of offshore installations perform a risk assessment of impacts between passing vessels and offshore installations. The risk model used to calculate impact risk (COLLIDE) is based on AIS data from vessels sailing in the area before the offshore installation is in place and does not consider future changes to the traffic pattern due to the new installation.

The results from analysing the AIS data for each of the seven locations investigated in this article show an apparent increase in vessel installation passing distance. Vessel operators adjust their sailing tracks to pass the new offshore installation with at least 1 nm, and most vessels alter their course to achieve a 1-3 nm passing distance. Figure 7 shows how the change in ship passing distance is affected by the new offshore installation. As a result, the COLLIDE risk model based on pre-installation AIS data will lead to an overly conservative estimation of allision risk.

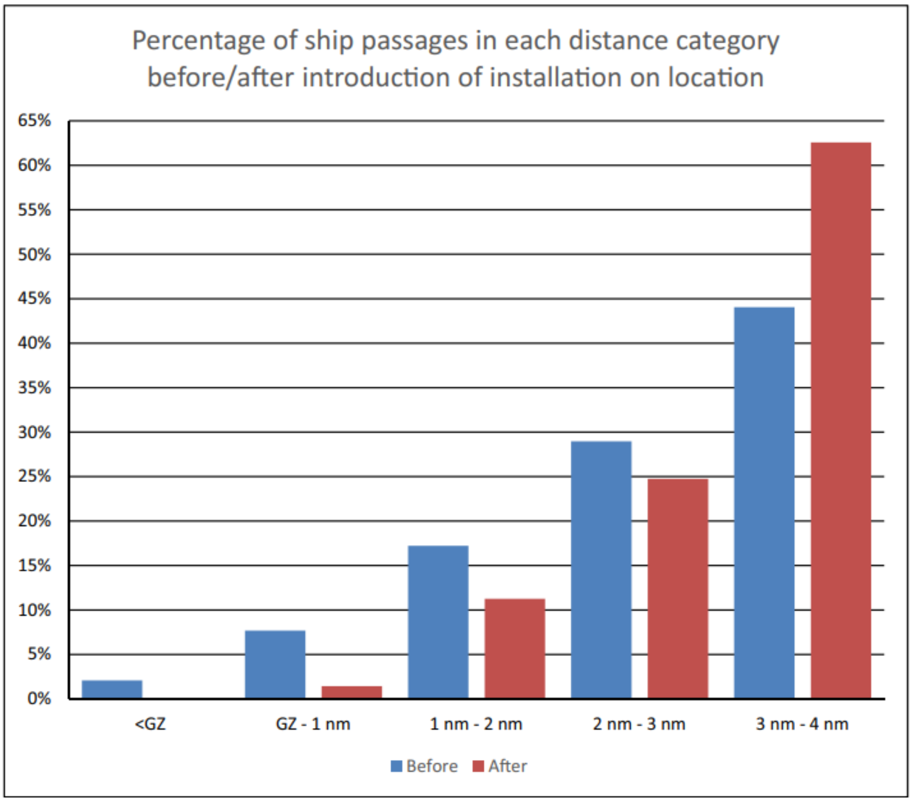

Figure 7: Normalized result of the categorized vessel installation passing distance for vessels before and after installation (Hassel et al. 2016)

The authors call for improving the then-current industry standard for calculating allision risk COLLIDE. The results and new knowledge discovered through analysis of vessel AIS data pre and post-installation should be incorporated to improve the accuracy of future allision risk assessment models.

2.3.7 A Big Data Analytics Method for the Evaluation of Ship-Ship Collision Risk reflecting Hydrometeorological Conditions

The authors behind this paper are introducing a method utilizing big data analytics to evaluate ship-ship collision risk. A RoPax vessel is defined as the struck ship in the analyses (Zhang et al. 2021). The method consists of three steps:

- (1) - A model for clustering ship trajectories of ships that have struck using unsupervised machine learning algorithms such as K-means and DBSCAN
- (2) - Identify time-dependent traffic situations and meteorological conditions at the time of potential collisions in the identified clusters
- (3) - Utilizing a risk model based on a Collision Risk Index (CRI) for ship collision risk assessment

The results show that a combination of K-means and DBSCAN for clustering of ship trajectories gives a more detailed and useful result compared to only using one clustering method. It also shows that now-cast data and AIS data can be beneficial in developing a picture of how time-dependent traffic situations and hydro-meteorological conditions influenced the vessels during unwanted events.

The authors point out that the vessel voyage may be the key influential factor and significantly influence the collision risk. Traditional models usually ignore this. The results show that for $CRI > 0.45$, 97.5% of scenarios account for evasive actions for vessel operators, implying that a CRI criteria could provide critical input for vessel operators as a part of a more extensive intelligent decision support system used for collision avoidance.

2.3.8 Risk factors and navigation accidents: A historical analysis comparing accident-free and accident-prone vessels using indicators from AIS data and vessel databases

In this publication, the authors provide an empirical basis for how risk factors and indicators for maritime navigation accidents can be identified Aalberg et al. (2022). The research provides knowledge for ship collision scenarios and aims to improve the development of generalized risk model for use in risk assessment related to maritime activity along the Norwegian coastline. Stakeholders can also use this knowledge to get a better insight into risk indicators that can be used to monitor collision risk in specified areas at sea before sailing.

Accidents in the Norwegian waters in the ten years from 2010 to 2019 involving different cargo vessels were analysed, and AIS data from the same area and period was extracted. The long period of sampled data is one of the main novelties of the study, and most other studies in the field only sample data for a few months or years in comparison. The results from the logistic regression analysis show that parameters such as vessel type, lower gross tonnage, older ships, and higher average speed increases the probability of the vessel having reported being involved in a grounding or collision accident.

2.4 Concluding remarks - Literature review

Although the technological advance for hydrogen solutions in maritime applications has been significant over the last years, the available publications and literature associated with the topic reveal that more research and knowledge is needed to accelerate the development. DNV points out in their study on the use of fuel cells in shipping that knowledge related to the use of fuel cells on vessels exposed to various collision and impact scenarios is lacking (Tronstad et al. 2017). Damage to the hydrogen storage, handling, and fuel cell systems has the potential to be disastrous, and knowledge related to the probability of hazardous events and the consequences is sought after by the industry.

A review of available literature on collision scenarios involving hydrogen systems on board marine vessels gave poor results. However, ship-ship collision scenarios have been an area of interest since the first major assessments by Yahei Fujii and Shiobara (1971), and still is a concern for the safety of life, assets, and the environment at sea. The general ideas from Yahei Fujii and Shiobara (1971) and Macduff (1974), seen in Equation 1 and 17, have been used and improved by various means over the last decades, and the use of digital tools has made the models more precise when analysing collision risk in specific areas.

AIS data provides valuable insight into vessel traffic at sea, and can through analysis give a detailed picture of different collision scenarios involving both rigid structures (Hassel et al. 2016, Bu (2019)), and with other vessels (Zhang et al. 2021, Z. Liu et al. (2019), Chai et al. (2019), Montewka et al. (2010)). Several of the findings in this literature review will be used to develop a model for assessing the crossing collision risk for hydrogen-fuelled vessels. Initially, the idea was to use different clustering methods to analyse the traffic in a specific area, such as methods presented by Fromreide and Hansen (2021) and Bo Liu et al. (2014). However, machine learning clustering methods to identify patterns in traffic, and detect areas and fairways with dense traffic, will not be used and developed further in this thesis.

The framework presented by Bin Liu et al. (2021) can be used to make a simple classification of the energy level of the collision scenarios with respect to penetration length. The impact and absorbed energy in a crossing collision scenario can be estimated based on the model presented by Kristiansen (2004). This can be useful to determine the probability of higher and lower energy collisions for the specific areas surrounding various ferry routes, which will vary depending on the local traffic composition.

2.5 State-of-the-Art methodology for establishing ship-ship collision probability

To assess ship-ship collision risk at sea, the general models describing the collision probability as a product of a geometric probability and causation probability (Equation 1 and 17) developed early on by Yahei Fujii and Shiobara (1971) and Macduff (1974) are also used in today's state-of-the-art models. More recent research related to the topic has further developed these models by introducing more advanced methods for determining the geometric probability and the causation probability.

To establish the geometric probability of collisions, various advanced methods can be applied. Chen et al. (2019) address some of these models in their study. These models include methods for determining parameters such as relative speed and collision diameter in more detail based on transmitted AIS data for the vessels in the area. These models also take all collision angles into account. To determine the collision diameter, a molecular model such as the ones formulated by Montewka et al. (2010) and Z. Liu et al. (2020) can be also be utilized. These models are more comparable to real-world scenarios, where vessel paths cross in various manners and can be considered more chaotic.

The causation probability is a complicated parameter, and various methods can be used to estimate it. Chen et al. (2019) bring forward three approaches that can be used to determine this value. A statistical analysis approach of historical accidents in the area has been widely used in many studies since it was first introduced by Yahei Fujii and Shiobara (1971). However, historical ship-ship collision data can be limited for the specific area of interest and would increase the uncertainty of the estimated value of the causation probability. The fault tree approach has also been widely used in various ship collision models. These will consider factors related to various human, technical, and organizational factors and the relationship between them to derive a causation probability. Another alternative can be to introduce a Bayesian approach. Friis-Hansen (2008) applies a Bayesian Network model to estimate the causation probability of various ship-ship encounters.

3 Methodology for Determining the Probability of Crossing Collision Scenarios

A methodology is developed to estimate the probability of a crossing collision per annum, where a passing vessel collides with a hydrogen-fuelled vessel. Vessel types are defined to establish the crossing collision frequency involving the different types. Geometrical assumptions for the vessel dimensions are also made to determine the mass and energy involved in a potential collision scenario. This will also be used to comment on the collision probability in relation to the placement of hydrogen storage, handling and fuel cell systems on board the ferry. Several steps are needed to quantify the probability associated with a crossing collision between passing vessels and a ferry operating on a fixed route at a specific location. The methodology will address how relevant areas for hydrogen-fuelled ferries are determined and the type of data that should be acquired for further analysis.

A review of the extracted data is conducted, and relevant methods are applied to remove erroneous and irrelevant data in the set to improve the quality of the analysis. The data set is divided into two categories: ferries operating on the route and passing vessels. This is done to get a better overview of the traffic patterns, density, and speed of the ferries and the vessels passing by. Different Python libraries and the geographical information system QGIS are utilized to prepare the data, analyse the number of crossings between ferries and passing vessels, and vessel speeds, and retrieve the results needed to determine the geometrical probability.

Figure 8 outlines the general steps to determine the number of crossings and the transformation of the raw AIS data file to the final data frame to fulfill these steps. These steps will be described in detail later in this section.

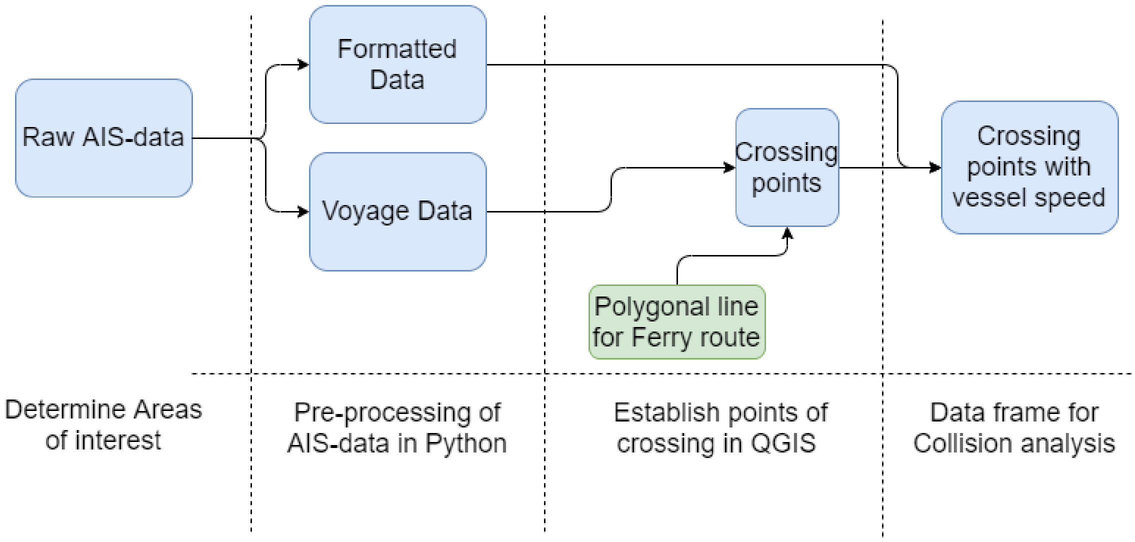

Figure 8: Flow diagram illustrating the process for determining the number of crossings and vessel speeds

Geographical and geometrical assumptions related to the specific area and vessel types are made to determine the geometrical probability of a crossing collision.

Combined with a causation probability obtained from available literature, a crossing collision probability can be quantified, distinguishing between potential low, medium, and high energy collision scenarios involving different vessel types. The product of vessel dimensions and an assumed block coefficient from available literature is used to determine the total weight of the vessels and is used to calculate the energy level in a potential crossing collision to establish the frequency of such a scenario. Relevant findings are visualized with different plots and figures.

To assess the situation where hydrogen-related systems are placed below and above deck, assumptions about the height in bow for the various vessel types are made. The collision energy and height in the bow for the various vessel types are also assessed when the probability of crossing collision scenarios is established. Methods for determining the absorbed energy in a crossing collision provided by Kristiansen (2004) are combined with the findings in Bin Liu et al. (2021) on the relationship between absorbed collision energy and hull penetration length to determine the probability of a passing vessel penetrating far enough into the hull of a ferry to impact the hydrogen systems directly.

Figure 9 illustrates how the various data sets from the pre-processing of the raw AIS data are used to determine the probability of different collision scenarios where the ferry operating on the route is struck by a passing vessel. All the python code used in the methodology can be seen in the Appendix Section A.

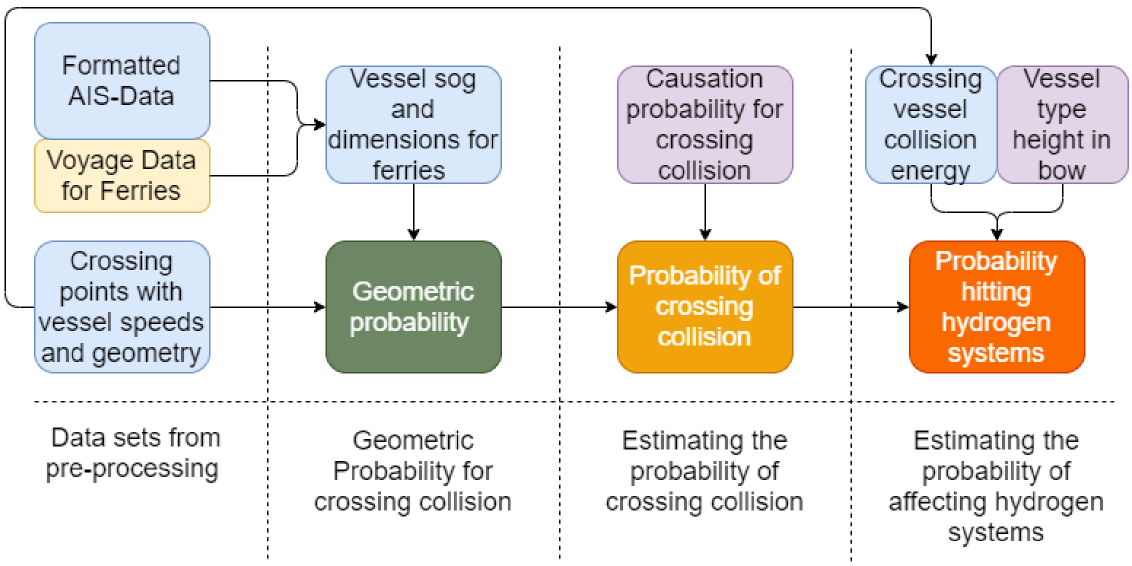

Figure 9: Flow diagram illustrating the process for estimating the probability for a crossing collision scenario and affecting hydrogen systems

3.1 Establishing areas of interest and required data for analysis

The length of the ferry route is relevant when choosing the locations for the case study, and longer routes are the most relevant. Ferries sailing on shorter routes can potentially utilize fully battery-electric propulsion systems more effectively. Therefore, hydrogen as a fuel source may not be the best alternative for short ferry routes. Areas with higher traffic density are also of interest since the probability of collision most likely will increase with more traffic. To get better insight into the chosen areas of analysis, specific details are needed. Parameters such as the number of ferries operating on the location, the length of the ferry route, the dimensions of the operating ferries, speed, and timetables for departures and arrivals are relevant information gathered for the analysis.

The specific area is defined based on the ferry route, and a sufficient area surrounding the route is included. This is done to capture a sufficient amount of AIS data messages transmitted by passing vessels in the area. Four geographical coordinates representing a rectangular shape surrounding the ferry route are defined, and all transmitted AIS messages within the area are extracted. An example illustrating how the area around a ferry route is defined can be seen in Figure 10.

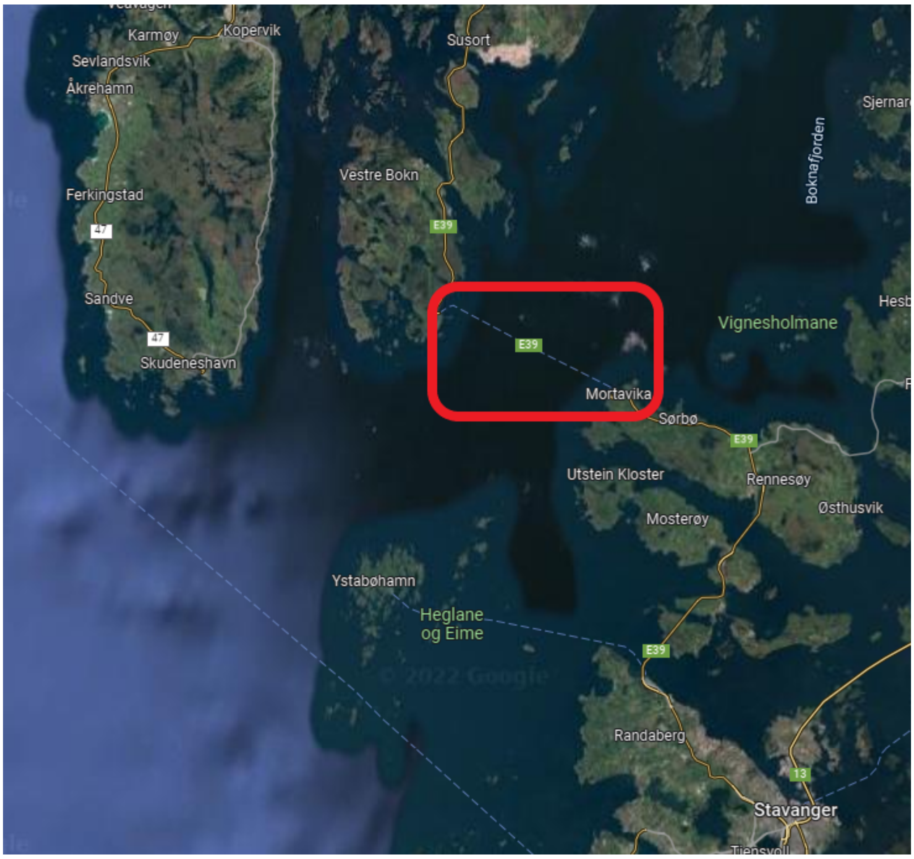

Figure 10: Example of how the area of interest is determined for extraction of AIS data for further analysis.

AIS data availability and reliability can vary depending on where the data is transmitted and received, as commented by (Smestad 2015). For this analysis, both static and dynamic historical AIS data from 2019 are extracted from Kystverket's land-based stations. The IMO/MMSI number, as well as these dynamic and static AIS data parameters, are most relevant for the analysis:

- Time and date transmitted

- Longitude
- Latitude
- Speed over ground (sog)
- Heading (cog)
- Vessel type level 1 (Work vessel/cargo vessel etc.)
- Vessel type level 2 (Dry cargo/Fishing/Tanker/Offshore vessel etc.)
- Vessel length (Lpp)
- Vessel breadth (B)
- Vessel draught (D)
- Deadweight (dwt)

A large data set consisting of AIS messages with these static and dynamic parameters can be used for various analyses related to maritime traffic and safety and will provide a good foundation for an assessment of crossing collision probability. It is important to sample data for a longer period to account for seasonal variations in traffic. Therefore the data set should at least contain data for an entire year, in this case, the year 2019. Data from 2020 and 2021 could also be a relevant time period for the analysis. However, due to the reduction in maritime traffic as a consequence of the global COVID pandemic, the year 2019 is considered a more representative time period for a more normal shipping activity level.

3.2 Vessel traffic classification

A part of the objective of this thesis is to investigate the scenario where hydrogen systems are placed below deck and a scenario where the systems are located above deck. Therefore it is also useful to identify the different vessel types and associated geometrical properties. Information about the bow height for the vessels is not an available parameter in the extracted AIS data. The block coefficient for the vessels C_b is also not available. Information in the AIS data related to "*Vessel Type Level 2*" is used to define the different vessel types. The following vessel types and a corresponding value of the block coefficient C_b are defined:

- Bulk Carriers - 0.80
- Dry Cargo/Passenger Vessels - 0.80
- Fishing Vessels - 0.45
- Offshore Vessels - 0.70
- Tanker Vessels - 0.83

- Miscellaneous - 0.70

where the block coefficients are based on values as per British Standard presented by Shah and M (2016). C_b is combined with the vessel's main dimensions length, breadth, and draught to determine the total mass of the passing vessels. Non-ship structures can be a vessel category present in the data set. Non-ship structures consist of larger buoys, semi-submersible platforms, and other man-made marine structures being moved around at sea. This category will not be included in the analysis, and data related to these are removed from the data set. Missing values related to vessel type are often present in extracted AIS data as well and will be removed in this analysis.

3.3 AIS data analysis

Performing analysis on large data sets can, in many cases, be a time-consuming process. It is therefore essential to plan and prepare a framework of steps to reach the main objective of the assessment in an effective manner. Relevant Python libraries such as Pandas, GeoPandas, NumPy, MatplotLib, and more are utilized in the Jupyter Notebook environment to pre-process, analyse, and present relevant findings from the analyses. QGIS is also used to find information about the number of crossing situations and vessel speeds at specific locations for both passing vessels and the ferries operating on the route. The following Python libraries and what they are used for are presented below:

- **NumPy** - Numerical calculations and computing
- **Pandas** - Reading and manipulating data sets
- **GeoPandas** - Extension of Pandas for easier handling of Geo-spatial data in Python
- **Matplotlib** - Plotting and visualization of data
- **Seaborn** - Plotting and visualization of data
- **Mgrs** - Converting to and from coordinates and mgrs-values
- **Datetime** - Manipulating values for date and time

3.3.1 Pre-processing of AIS data

Before conducting any analysis involving the AIS data, a review and pre-processing of the extracted data set is performed. The Jupyter Notebook environment is used with the presented Python libraries to read in, process data, and represent relevant findings. It is essential to become familiar with the data set to understand how it is structured and to detect erroneous and missing values in the transmitted AIS messages. Erroneous data may include message duplicates, messages lacking necessary data, messages registered outside the relevant area or on land, and messages reporting unrealistic values for important parameters such as speed over ground. These are removed to improve the quality of the data set.

To pose a risk in relation to a crossing collision scenario with a larger RoRo-passenger ferry, a certain vessel size and speed are required. Vessels with an average speed of less than 3 knots and a length over all of less than 25 meters are therefore removed to reduce the computational time since they most likely would not cause additional risk in a crossing collision scenario.

The data set is split into one data set for the ferries operating on the route and one data set for the passing vessels. This will make it easier to distinguish between the two later in the process. The arrival frequency of ferries operating on the location is established using AIS data and available tables and schedules from the operators online. Speed over ground for the voyage is also determined by using AIS data.

When analysing AIS data from a larger specific area for an entire year, the number of transmitted messages can be enormous. Depending on the vessel category and speed over ground, AIS messages can be transmitted almost every second (Smestad 2015). To reduce the size of the data set and streamline the analysis, the Military Grid Reference System (MGRS) is introduced. MGRS is a Geo-coordinate system developed by NATO where the earth's surface is divided into a grid with a given precision level used to identify points anywhere on the Earth's surface (Wikipedia 2022). Depending on what application the system is used for, the level of positional accuracy can be determined by using different precision levels. Here, a MGRS precision level of 2 is used, which means that each MGRS square is $1km^2$. Data is then grouped per MMSI number, date, and MGRS square. This means that all AIS messages transmitted per day from one vessel within a MGRS square are formatted to a single line of data. The average value for hours sailed within the MGRS square, and the distance sailed is also converted from the original AIS messages. The structure of the formatted data frame can be seen in Table 3.

Table 3: Caption

mgrs	dateID	shipID	Hours sailed	nm sailed	Lat	Lon
32VKN8048	20190101	375681	0.104	0.0723	60.80633	4.95522
32VKN8051	20190109	277797	0.073	0.3302	60.80633	4.95522

The AIS data points from each vessel are also used to generate data set with a polygonal line representing the voyage. These voyages are based on the MMSI number and date-time. Additionally, if a voyage duration is more than six hours, a new voyage is generated. An example of a set of voyages can be seen in Figure 11. The average speed per voyage is also generated. This value is more inaccurate than the vessel speed calculated per MGRS square since it is sensible to assume that the vessels will change their speed over ground at some point during the voyage. The method of calculating the vessel speed in the MGRS squares close to the ferry route is more precise and will be used to determine the speed close to the crossing point.

By merging the two data sets consisting of the original AIS data formatted per MGRS square and the data set representing the voyages for each vessel, relevant information for each vessel can be established close to the point of crossing. This can be used to identify the speed of passing vessels close to the point of crossing later in the analysis and will provide a more accurate value compared to the average value for the entire voyage.

3.3.2 Identifying the number of crossing situations

The pre-processed data is now ready for further analysis in QGIS to determine the number of vessels crossings the ferry per annum. The file containing the vessel voyages is imported and represented with a line of color depending on the type of vessel. To find the number of crossings, a new layer with a polygonal chain representing the ferry route is defined, as can be seen in Figure 11. The function "*Line Intersections*" in QGIS is then used to determine where the passing vessels intersect the polygonal chain representing the ferry route. The intersection points are then exported and added to each voyages data frame.

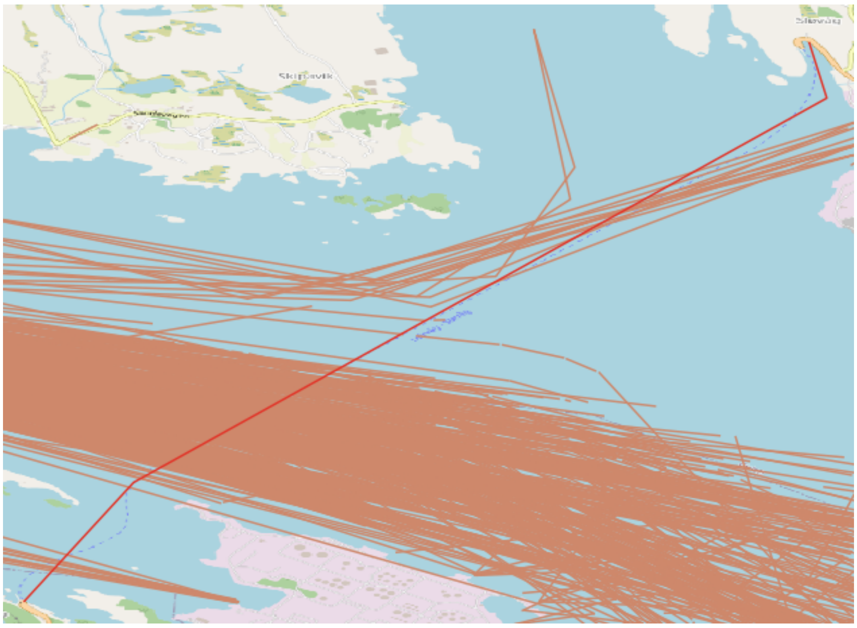

Figure 11: Example of polygonal chain representing the fixed ferry route between two locations (red), and crossing paths of a certain vessel type (brown)

As discussed, the average speed for each voyage available in the AIS data can be inaccurate and misleading because most vessels will alter the speed and course during the voyage. The function "*Points along Geometry*" is used to generate points along the ferry route, and the generated points are imported back into Jupyter Notebook. Based on the coordinates of the points along the ferry route, a MGRS reference with precision level 2 is generated. This "chain" of MGRS points is then merged with the data frame containing the formatted AIS data per MGRS square in the specific area to determine the vessel speeds close to the ferry route. This new data frame is then merged on vessel ID and date ID with the voyage data containing the crossing points for each voyage. This now means that a more accurate value for the vessel speed close to the crossing point is established for all the voyages that crossed the ferry route in 2019.

3.4 Quantification of geometric probability for crossing collision

The annual number of crossing situations where passing vessels cross the ferry route is now determined, depending on vessel type and size. An average value for vessel speed, total weight, and breadth is also calculated based on the data for the crossing vessels and will be used to determine the geometrical probability and collision energy. Missing data related to vessel length, breadth, and draught will most likely be present in the data set. These AIS messages will be removed when calculating the mentioned average values. The length, breadth, draught, and the assumed block coefficient depending on vessel type, are combined to determine the total weight $M_{tot}$of each vessel:

$$M_{tot} = L \cdot B \cdot D \cdot C_b, \tag{22}$$

where L is the length over all (LOA), B is the moulded breadth, D is the reported current draught, and C_b is the block coefficient. Ideally, the vessel length between perpendiculars is used to estimate the total weight displacement of a floating vessel. If this is not available in the extracted AIS data, the use of LOA will only slightly over-estimate the weight displacement of the vessels.

The main focus is establishing the number of crossing collisions where the subject ship (the ferry) is struck by crossing vessels per annum. The crossing collision models presented by Haugen and Kristiansen (2022) is adapted. P_i1 represents the expected number of crossing collisions where the passing vessel is crossing the ferry route, and the ferry is the subject ship potentially being struck. The expected number of these crossing collisions per ferry passage per vessel type can be expressed as:

$$P_{i,passage} = (B_1 + L_i2) \cdot \frac{Q_1}{V_2}, \tag{23}$$

where B_1 is the breadth of the crossing vessels, where i is the vessel type, L_2 is the length of the ferry operating on the route, Q_i is the arrival frequency of the crossing vessels type per annum, and V_2 is the velocity of the ferry. $B_1 + L_2$ is in this model considered the collision diameter. By multiplying with the arrival frequency of the ferries operating on the route Q_2, the annual number of expected crossing collisions where a specific vessel type strikes the ferry is:

$$P_{i,total} = (B_i + L_2) \cdot \frac{Q_i Q_2}{V_2} \tag{24}$$

By summing over all the vessel types i, the total number of crossing collisions where the ferry is struck by a passing vessel is:

$$P_{Total} = \sum_i (B_i + L_2) \cdot \frac{Q_i Q_2}{V_2} \tag{25}$$

The breadth of the crossing vessels B_i is based on an average of the value moulded breadth per vessel type from the AIS data. Moulded breadth is defined as the maximum breadth of the vessel, excluding the thickness of the outer shell plating. The length of the ferry L_2 is based on the LOA reported in the AIS data. If multiple ferries are operating on the route, an average value is used. The speed of the ferry V_2 is assumed to be constant when sailing across the area of the route where passing vessels are crossing the route. Basing the speed on the average value only is not sufficient. Therefore, the sailing speed of the ferry is based on the mode of the vessel speed found in the AIS data. Figure 12 show a histogram of the registered vessel speed over ground, with a clear indication that 11 knots is close to the operational speed on the route. With the method described here, a geometrical probability of a crossing collision where crossing vessels strike the subject ferry vessel is established.

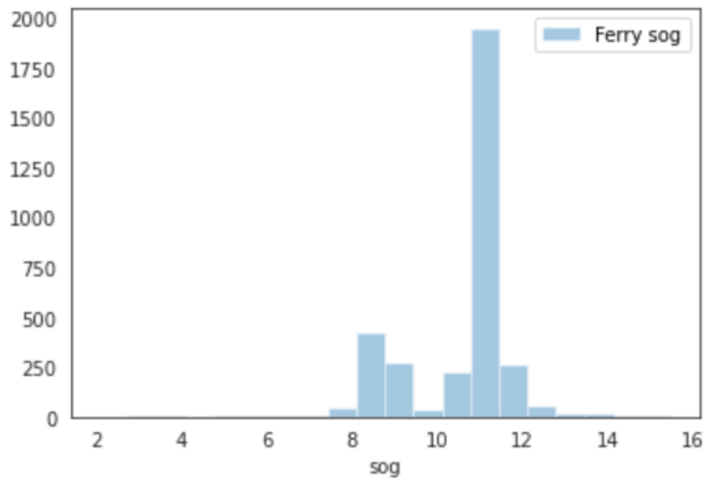

Figure 12: Example histogram of ferry speed over ground extracted from AIS data

3.5 Causation probability for crossing collision

In order to quantify the probability of crossing collisions, the causal probability P_C must be determined. The causal probability represents the probability that both the operator of the ferry and the passing vessel lack control over their respective vessel and can not initiate an emergency maneuver to avoid a collision. Determining the causation probability can be a complicated process (Chen et al. 2019), and it is difficult to know if the chosen value is the right one for the specific area. Since this Master's thesis does not focus on developing a framework to determine the causation probability for each specific location, the value is based on findings from the research and studies accounted for in the literature study.

Y. Fujii n.d. found that the causation probability in various Japanese waterways gave a value ranging between $0.8 \cdot 10^{-4}$ to $3.3 \cdot 10^{-4}$, which is also close to the value found by Friis-Hansen (2008). Therefore the conservative value of P_C stated below in Equation 26 is chosen. This value will be applied to all the three areas investigated in the case study and to all vessel categories.

$$P_C = 2 \cdot 10^{-4} \tag{26}$$

3.6 Probability of crossing collision

The general definition of the probability of a ship-ship collision from Yahei Fujii and Shiobara (1971) is utilized in this methodology and is defined as:

$$P_{collision} = P_G \cdot P_C \tag{27}$$

To only include collision scenarios where the ferry is struck by a crossing vessel, the total geometrical probability P_G is replaced with P_{Total} as expressed in Equation 25:

$$P_{collision} = P_1 \cdot P_C = (B_{vessel} + L_{ferry}) \cdot \frac{Q_{vessel} Q_{ferry}}{V_{ferry}} \cdot 2 \cdot 10^{-4} \tag{28}$$

3.7 Probability depending on the placement of hydrogen systems

To get better insight into what type of crossing collision scenarios pose a risk for a hydrogen-fuelled ferry, a classification of scenarios involving the various vessel types and potential collision energy is performed. Table 4 illustrates an evaluation of how different vessel types and speeds of passing vessels affect the risk of crossing collision with a hydrogen-fuelled ferry. The values are found by using the equation for impact energy and absorbed energy presented Kristiansen (2004), and combining them with the findings related to hull penetration length presented by Bin Liu et al. (2021). To determine the impact energy and absorbed collision energy for a scenario where the ferry is struck by a passing vessel, and assuming a collision angle of 90°, the following equations is used:

$$E_{impact} = \frac{m_{passing} \cdot m_{ferry} \cdot (1 + C_h)}{2 \cdot (m_{passing} + m_{ferry} \cdot (1 + C_h))} \cdot v_{passing}^2 \tag{29}$$

$$E_{absorbed} = E_{impact} \cdot \frac{1}{1 + \frac{m_{ferry}}{m_{passing}}}, \tag{30}$$

where $m_{passing}, m_{ferry}$ represents the total vessel weights of the passing vessel and the ferry respectively, C_h is the added mass, which is assumed to be 0.75 in sway for a 90° crossing collision, and $v_{passing}$ is the speed of the passing vessel.

The values related to absorbed energy associated with the level of risk in Table 4 is based on an assessment of the severity of a crossing collision scenario in relation to penetration length. A scenario where the absorbed energy is less than 10 MJ will most likely only cause minor damage to the hull structure of the ferry but can potentially damage equipment if placed very close to the hull. A collision scenario with absorbed energy level between 10 and 60 MJ absorbed energy will be more damaging, and the striking ship can potentially penetrate through the ferry's hull. The results from Figure 4 indicate that a 60 MJ collision can result in extensive damage to a double hull structure and penetrate up to three meters into the hull structure. The consequences associated with such a scenario is high. Detailed analysis of the consequences of a crossing collision with a hydrogen-fuelled vessel is not carried out further. This classification is only defined to determine the frequency of crossing scenarios per year involving vessels potentially causing these levels of absorbed energy and associated hull penetration length.

Table 4: Classification of crossing collision scenarios with the potential of striking hydrogen systems on board the ferry.

Vessel type	Total absorbed collision energy		
	<10 MJ	10-60 MJ	>60 MJ
Bulk Carrier	Low Risk	Medium Risk	High Risk
Dry Cargo/Passenger	Low Risk	Medium Risk	High Risk
Fishing Vessel	Low Risk	Medium Risk	High Risk
Offshore	Low Risk	Medium Risk	High Risk
Tanker Vessel	Low Risk	Medium Risk	High Risk
Miscellaneous	Low Risk	Medium Risk	High Risk

Assumptions related to the height in the bow are made to establish the vessels capable of impacting the hydrogen storage, handling, and fuel cell systems placed above the deck on the ferry. Information related to this topic is lacking, and assumptions are made based on a general idea of the design of the various vessels. Figure 13, provided by Norled, show the placement of the hydrogen systems on the 82.4 meters long and 17.5-meter wide ferry MF Hydra operating in the Hjelmeland area on the Norwegian west coast. When the ferry operates under normal conditions, the distance between the waterline and the systems is close to 9.6 meters. It is therefore assumed that larger ferries with similar configurations will have the hydrogen systems placed at least 9 meters above the operational waterline.

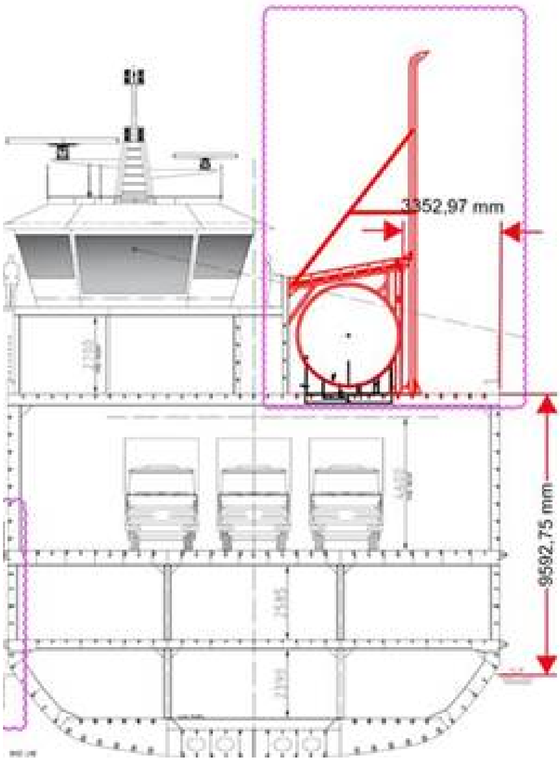

Figure 13: Cross-section illustrating the placement of the hydrogen systems on MF Hydra. Figure provided by Norled.

Figure 14 shows the vessel MF Hydra from above. It is observed that the systems are placed on the starboard side next to the bridge and that they are placed in the middle of the vessel longitudinally. Norled stated that the hydrogen storage tanks are placed 3.3 meters from the vessel's starboard side, according to the IGF Code demanding that storage tanks be placed at least B/5 inwards from both sides.

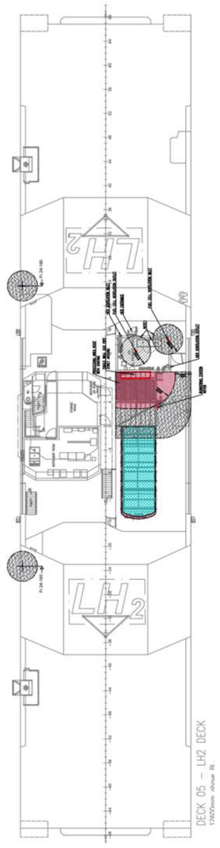

Figure 14: Cross-section illustrating the placement of the hydrogen systems on MF Hydra provided by Norled.

Based on the findings related to the design of MF hydra, it is assumed that ferries operating on the route in the case study of this exercise have one of the two alternatives for placement of hydrogen systems:

- **Above the car deck** - The systems are placed above the deck, 9 meters above the water line. They are also at least placed 3.0 meters from the starboard or port side.
- **Under the car deck** - The systems are placed below the car deck, near the water line. They are also at least placed 3.0 meters from the starboard or port side.

Information about the dimensions of the height and geometry of the bow for the various passing vessels is lacking. Therefore a distribution of the vessels capable of directly impacting the systems placed below deck and above the deck is established as seen in Table 5. It is assumed that vessels capable of striking the systems above deck also can strike the systems if located below the car deck. Additionally, since the systems are placed more towards one side of the ferry, it is reasonable to assume that it is possible to strike the systems in a collision from one side. Therefore, it is assumed that only half of the potential collision scenarios are capable of striking the systems.

Table 5: Overview of vessels that can strike hydrogen systems placed above the vehicle deck, and below the deck.

Vessel type	Potential of striking systems above and deck
Bulk Carriers	Yes
Dry Cargo/Passenger	No
Fishing Vessels	No
Offshore Vessels	Yes
Tanker Vessels	Yes
Miscellaneous	No

Combining the values from Table 5 with Table 4 and the probability of a crossing collision per vessel type, the likelihood of a collision where both alternatives for placement of hydrogen systems are determined. This value is then divided by 2 to account for the fact that the systems can only be struck from one side of the vessel. Findings from Bin Liu et al. (2021) indicate that, depending on the material properties used in the hull of the subject vessel, a crossing collision where the absorbed energy is more than 60 MJ is capable of penetrating around three meters into the subject vessel. 60 MJ is therefore used as a critical parameter to determine if the collision scenario causes damage to the hydrogen systems or not.

4 Case Study

In this section, the methodology is applied to identify and further analyse vessel traffic around three ferry locations along the Norwegian west coast. The purpose is to identify relevant parameters to establish a crossing collision probability for each specific location, which will be discussed in detail later in the thesis. Results from each area are presented in individual subsections, where relevant information about the area and the ferries operating on the route, as well as the probabilities retrieved by applying the methodology.

4.1 Mortavika - Arsvågen

The ferry route between Mortavika and Arsvågen is located north of Stavanger in Boknafjorden in Rogaland, close to the open North Sea. An illustration of the relevant area can be seen in Figure 15. Currently four ferries are operating at the location, and there are approximately 47 500 departures every year based on online information from the operators (Fjord1 2022). More details about the ferries and the ferry route can be seen in Table 6 and Figure 15.

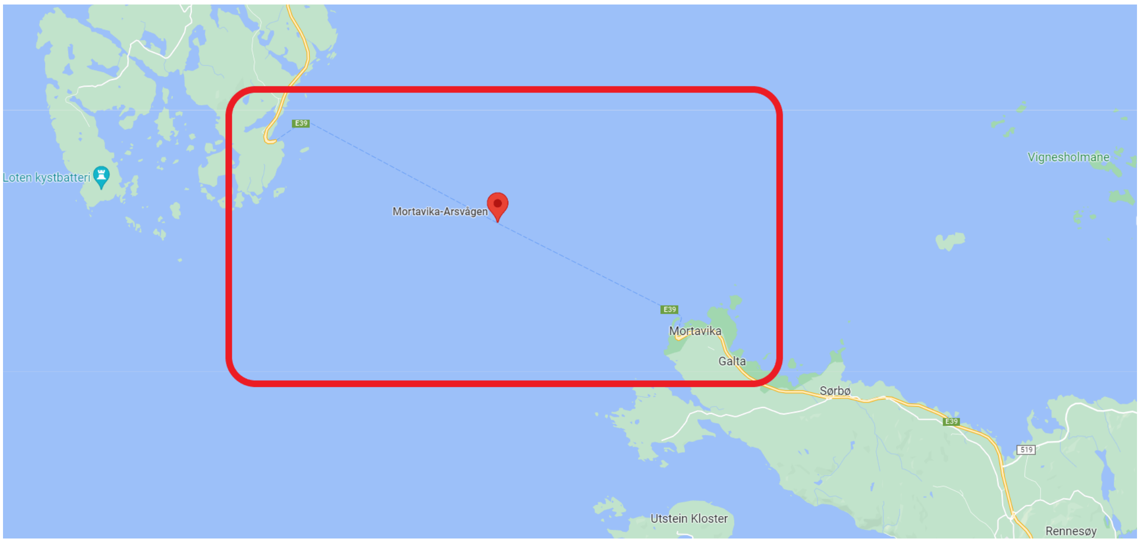

Figure 15: The area surrounding the ferry route between E39 Mortavika - Arsvågen

The ferry route between Mortavika and Arsvågen will eventually be replaced by an underwater tunnel as a part of the project E39 Rogfast, which will connect the coastal road between Kristiansand and Trondheim. However, the tunnel project is not estimated to be finished before 2031 (Statens-Vegvesen 2021). The route of 9.1 km crosses a heavily trafficked area with larger offshore vessels, cargo vessels, and tanker vessels frequently passing by. Due to the long sailing distance, a vessel only powered by batteries will not be able to operate effectively with today's technology on this route. Therefore, hydrogen-fuelled vessels could potentially be a suitable, greener alternative.

Table 6: Parameters for the ferries operating on the ferry route E39 Arsvågen - Mortavika

Vessel name	MMSI	B [m]	L [m]	D[m]	Dwt [t]
Bergensfjord	258271000	19	130	4.5	1025
Mastrafjord	259216000	19	129	4.5	1025
Stavangerfjord	259386000	19	129	4.5	1025
Raunefjord	258223000	19	130	4.5	1025
Generic Value		19	130	4.5	1025

An average value for the ferry's dimensions is calculated and used as the vessel parameters in the subsequent calculations in this section. Assuming a C_b of 0.5, the total weight of the ferry operating on the route is estimated to be 5500 tons. The speed over ground for the ferries is established from the extracted AIS data. From Figure 16, the registered ferry speeds can be observed. The mode in this data is 15 knots, with over 12 000 registered messages. Therefore, it is assumed that the ferries operating on the route hold a constant speed of 15 knots when crossing Boknafjorden.

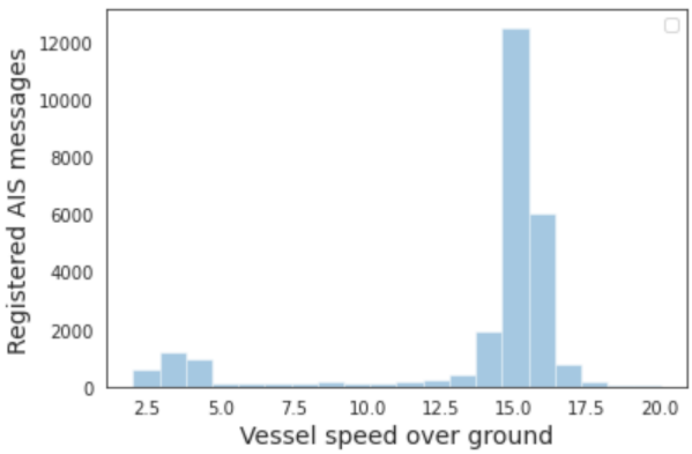

Figure 16: Ferry speed over ground for Mortavika - Arsvågen 2019

The analysis shows that there crossing vessel traffic in the area consists mainly of dry cargo/passenger vessels, tanker vessels, and bulk carrier vessels, with more than 80% of the total number of crossings. Figure 17 shows a bar plot of the number of crossings in the area per vessel type. Although the area often is associated with traffic related to the offshore supply industry, offshore vessels were the least frequent crossing the ferry route, with less than 157 crossings in 2019.

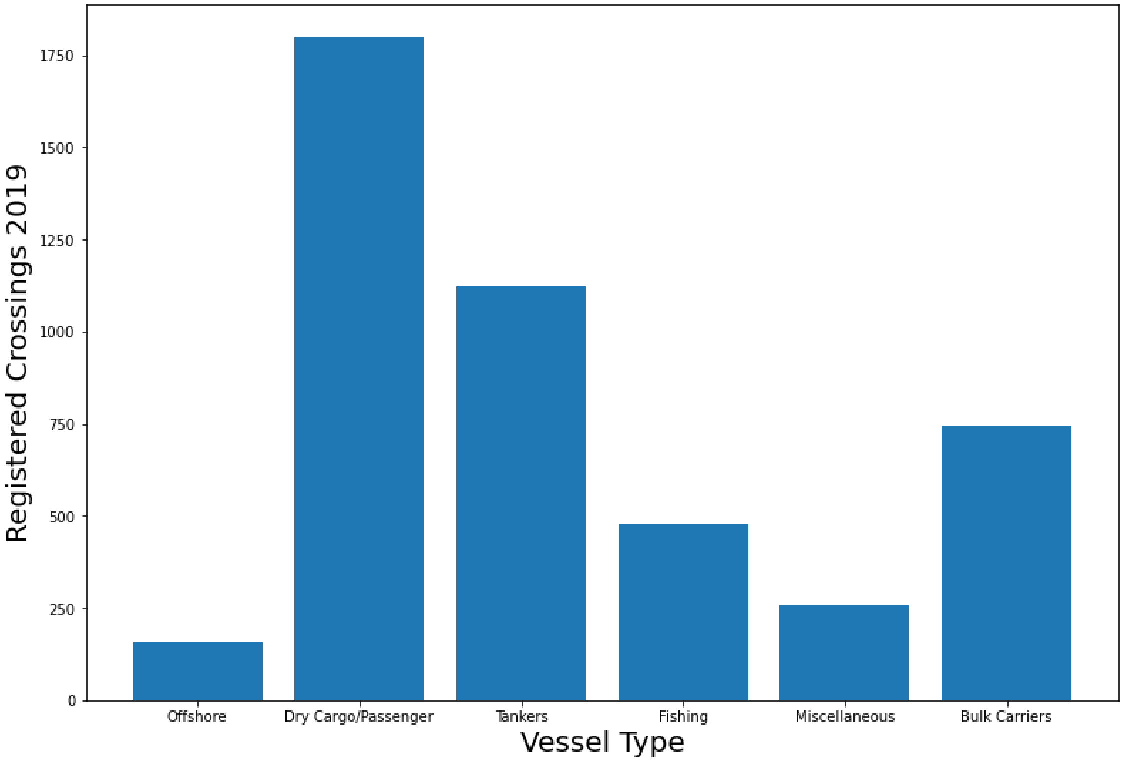

Figure 17: Amount of vessels crossing the ferry route between Mortavika - Arsvågen in 2019

Table 7 also shows the total number of crossings in 2019, as well as the average values for speed over ground, total weight, and breadth for the different vessel types. Tanker, bulk, and offshore vessels are significantly larger regarding total vessel weight and breadth compared to the other vessel types.

Table 7: Average values for speed over ground, weight, and breadth for Mortavika - Arsvågen 2019

Vessel type	**Crossings**	**Sog [kn]**	**Total Weight [t]**	**Breadth [m]**
Tankers	1124	12.0	28 000	22.1
Bulk	744	12.4	36 000	24.9
Offshore	157	11.8	24 000	25.3
Fishing	479	9.9	2 700	13.8
Cargo / Passenger	1799	10.9	5 700	13.7
Miscellaneous	256	9.6	2 600	12.8
Total	4559	11.3	16 800	18.1

By inserting the values from Table 7 into Equation 23 and multiplying with the chosen causation probability of $2 \cdot 10^{-4}$, the probability of a crossing collision per passage per vessel type, where the passing vessel type strikes the ferry operating on the route, is established. By multiplying with the number of ferries crossing the fjord in 2019 and summing over all vessel types as in Equation 25, the total probability of a crossing collision where the ferry is struck is found to be $2.6 \cdot 10^{-2}$, or once every 38.5 years. When it comes to specific vessel types, a crossing collision scenario involving a cargo/passenger vessel is most probable, while a scenario with an offshore vessel is least likely to occur.

Table 8: Probability of crossing collision Mortavika - Arsvågen

Vessel type	**Probability per passage**	**Probability per annum**
Tankers	$1.4 \cdot 10^{-7}$	$6.7 \cdot 10^{-3}$
Bulk	$9.5 \cdot 10^{-8}$	$4.5 \cdot 10^{-3}$
Offshore	$2.0 \cdot 10^{-8}$	$9.5 \cdot 10^{-4}$
Fishing	$5.7 \cdot 10^{-8}$	$2.7 \cdot 10^{-3}$
Cargo / Passenger	$2.1 \cdot 10^{-7}$	$1.0 \cdot 10^{-2}$
Miscellaneous	$3.0 \cdot 10^{-8}$	$1.4 \cdot 10^{-3}$
Total	$5.5 \cdot 10^{-7}$	$2.6 \cdot 10^{-2}$

A mapping of the absorbed collision energy is established by using Equation 29 and Equation 30. The results show that 1637 of the crossing vessels annually have the potential to strike the ferry, causing absorbed collision energy of more than 60 MJ. Tanker and bulk vessels constitute more than 85% of these high-energy crossings. Most of the cargo/passenger vessel crossings are less than 60 MJ scenarios, and only 7% exceed this limit.

Table 9: Number of crossing situations per vessel type distributed on absorbed collision energy in a collision scenario where the ferry is struck

Vessel type	**$<$ 10MJ**	**10MJ-60MJ**	**$>$ 60MJ**
Tankers	22	393	695
Bulk	1	40	703
Offshore	21	24	112
Fishing	192	139	0
Cargo/Passenger	377	1256	125
Miscellaneous	183	68	2
Total	791	1920	1637

Using the assumptions from the method section related to the vessel geometries in Table 5, placement towards one side of the vessel, and the relationship between absorbed energy and penetration length, the probability of striking the hydrogen systems depending on their placement per annum is established. The results can be seen in Table 10. A 60 MJ collision is needed to penetrate far enough into the hull to impact the hydrogen systems directly. This means that the total annual probability of a high energy collision scenario directly hitting the systems placed below deck for all vessel types is $5.0 \cdot 10^{-3}$, or once every 200 years. Given that only tanker, bulk, and offshore vessels have the geometry to directly hit the systems placed above the car deck, the annual probability is slightly lower with $4.6 \cdot 10^{-3}$, or once every 217 years.

Table 10: Annual probability of impacting the hydrogen systems on board the ferry for Sløvåg - Leirvåg

	Probability of striking systems per annum Mortavika - Arsvågen	
Vessel type	**Systems below deck**	**Systems above deck**
Tankers	$2.1 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$
Bulk	$2.3 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$
Offshore	$3.4 \cdot 10^{-4}$	$3.4 \cdot 10^{-4}$
Fishing	0	0
Cargo/Passenger	$3.5 \cdot 10^{-4}$	0
Miscellaneous	$5.5 \cdot 10^{-6}$	0
Total	$5.0 \cdot 10^{-3}$	$4.6 \cdot 10^{-3}$

4.2 Leirvåg - Sløvåg

Next to the Mongstad processing plant in western Norway, the ferry route between Leirvåg and Sløvåg is located. The voyage takes about 20 minutes along the 6.1-kilometer route crossing Fensfjorden. An illustration of the route can be seen in Figure 18. There are around 13 000 departures on the route every year (Fjord-1 2022).

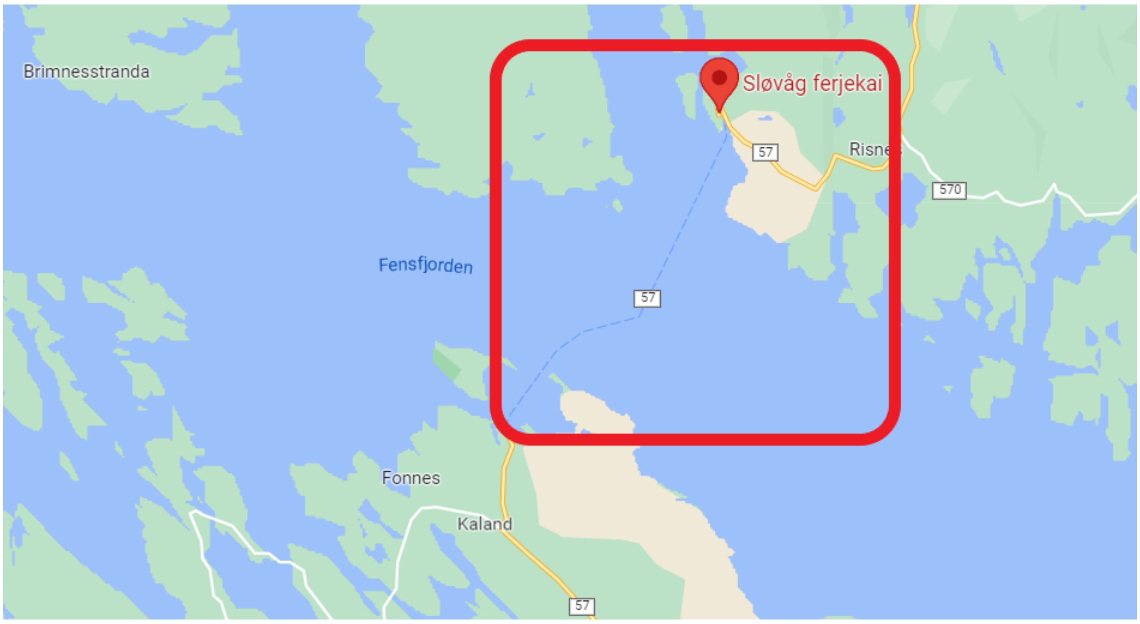

Figure 18: The area surrounding the ferry route between Sløvåg - Leirvåg

The vessel traffic around the ferry location is influenced by being right next to Equinor's processing plant at Mongstad, and large tank ships and offshore vessels frequently pass by. Therefore, a collision between ferries crossing the fjord and passing vessels is a relevant scenario. MF Storfjord, with a length of 110 meters, breadth of 17 meters, and an operational draught of 4.5 meters, is the only vessel operating on the route. Due to the long sailing distance and only one vessel operating on the route, a fully battery-electric propulsion system may be insufficient since charging batteries can be too time-consuming. A hydrogen-fuelled vessel may therefore be a better alternative for the ferry route.

Based on the vessel dimensions of MF Storfjord and an assumed C_b of 0.5, a total vessel weight of 3270 tons is determined. These values will be used further when estimating the geometric probability of the crossing collision scenario and the associated collision energy of such a scenario. Figure 19 show the registered speed over ground for the passenger ferry operating on the route. Based on these values, it is assumed that the ferry is sailing with a speed of 11 knots when crossing the fjord.

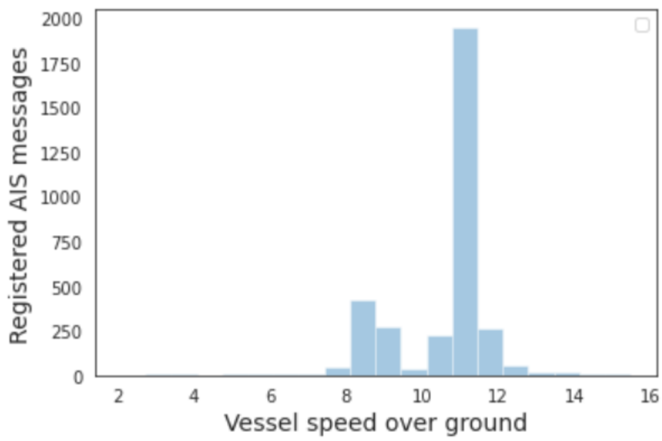

Figure 19: Ferry speed over ground for Leirvåg - Sløvåg 2019

The total amount of registered crossings for 2019 was 5 260, where offshore, dry cargo/passenger and tanker vessels were the most frequent. Of the registered crossings, 80% were either offshore or dry cargo/passenger vessels. Figure 20 shows the registered crossings for all the various vessel types, and it can be seen that bulk carrier crossings were the least frequent in 2019.

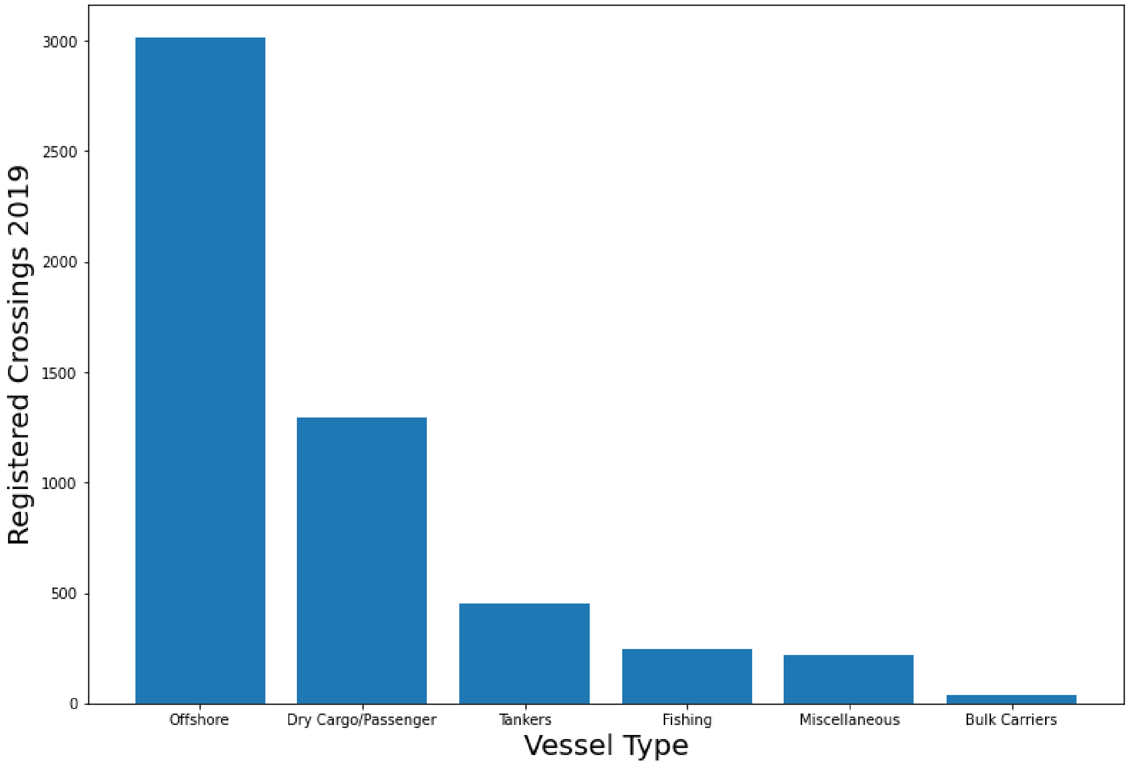

Figure 20: Amount of crossings per vessel type for Leirvåg - Sløvåg 2019

The tanker vessels crossing the ferry route here are significantly larger than the other vessel types. This is most likely due to the large oil tankers arriving at and departing from Equinor Mongstad. The fishing and miscellaneous vessel have the lowest total weight with 2 100 and 1 600 tons, respectively. There is not much difference in the speed over ground for the various vessel types, but the miscellaneous vessels stand out with an average speed of 6.9 knots. Tanker and offshore vessels have the largest breadth with an average of 27.3 and 20.3 meters, respectively.

Table 11: Average values for speed over ground, weight, and breadth for Sløvåg - Leirvåg 2019

Vessel type	**N crossings**	**Sog [kn]**	**Total Weight [t]**	**Breadth [m]**
Tankers	452	8.9	59 000	27.3
Bulk	37	9.7	12 000	15.3
Offshore	3014	10.3	9 600	20.3
Fishing	245	9.6	2 100	12.1
Cargo / Passenger	1290	10.2	5 300	13.3
Miscellaneous	218	6.9	1 600	12.3
Total	5256	10	12 300	18.6

Using Equation 23 with the parameters given in Table 11, the probability of a crossing collision where the ferry is struck by the various vessel types is determined. The results indicate that the probability of a crossing collision with an offshore vessel is the most likely with $5.7 \cdot 10^{-3}$ per year or once every 175 years. The total probability for all vessel types is $9.8 \cdot 10^{-3}$, or slightly less than once every 100 years.

Table 12: Probability of crossing collision Sløvåg - Leirvåg

Vessel type	**Probability per passage**	**Probability per annum**
Tankers	$6.7 \cdot 10^{-8}$	$8.7 \cdot 10^{-4}$
Bulk	$5.2 \cdot 10^{-9}$	$6.8 \cdot 10^{-5}$
Offshore	$4.4 \cdot 10^{-7}$	$5.7 \cdot 10^{-3}$
Fishing	$3.4 \cdot 10^{-8}$	$4.4 \cdot 10^{-4}$
Cargo / Passenger	$1.8 \cdot 10^{-7}$	$2.3 \cdot 10^{-3}$
Miscellaneous	$2.3 \cdot 10^{-8}$	$3.0 \cdot 10^{-4}$
Total	$7.5 \cdot 10^{-7}$	$9.8 \cdot 10^{-3}$

When assessing the absorbed collision energy by the ferry, the results show that most scenarios involve energy levels between 10 and 60 MJ with more than 75% of the total number of crossings. Fishing and miscellaneous vessels have 0 crossing scenarios with energy levels higher than 60 MJ, and only 369 of the registered crossings can be classified as high-energy crossings. Tanker, offshore, and cargo/passenger vessels are over-represented in this category.

Table 13: Number of crossing situations per vessel type with distributed on absorbed collision energy in a collision scenario where the ferry is struck

Vessel type	**$<$ 10MJ**	**10MJ-60MJ**	**$>$ 60MJ**
Tankers	42	290	115
Bulk	15	16	6
Offshore	19	2874	118
Fishing	114	29	0
Cargo/Passenger	377	764	130
Miscellaneous	200	14	0
Total	767	3987	369

The same methodology is applied to this case as for Mortavika - Arsvågen and the probability per annum of striking the hydrogen systems on the ferry depending on their placement on board is determined. These values can be seen in Table 14. Given the 60 MJ requirement to directly impact these systems, the annual probability of impacting the systems below and above deck is $3.4 \cdot 10^{-4}$ and $2.3 \cdot 10^{-4}$, respectively.

Table 14: Annual probability of impacting the hydrogen systems on board the ferry for Sløvåg - Leirvåg

	Probability of striking systems	
Vessel type	**Systems below deck**	**Systems above deck**
Tankers	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
Bulk	$5.5 \cdot 10^{-6}$	$5.5 \cdot 10^{-6}$
Offshore	$1.1 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
Fishing	0	0
Cargo/Passenger	$1.2 \cdot 10^{-4}$	0
Miscellaneous	0	0
Total	$3.4 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$

4.3 Molde - Vestnes

Further north on the western coast of Norway, four vessels operate on the ferry route between Vestnes and Molde, the main connection between the two major cities, Ålesund and Molde, along E39. Figure 21 illustrates the ferry route crossing Midfjorden. The route length is 11.5 kilometers, and the voyage takes around 33 minutes, making it the longest in this case study (Boreal 2022).

Figure 21: The area surrounding the ferry route between Molde - Vestnes

The four ferries operate every day of the year and have totally around 100 departures during weekdays and 72 on the weekends, making it around 33500 each year. The vessels are powered by a battery hybrid system, but to meet the Norwegian government's plans for hydrocarbon-free emissions in public transport by 2025, an alternative technological solution is needed (Norwegian-Government 2019). The long sailing distance of 11.5 kilometers rules out fully battery-electric propulsion with today's technology. Therefore, a hydrogen fuel solution replacing the hydrocarbon fuel source may be suitable for this ferry route.

Table 15: Parameters for the ferries operating on the ferry route E39 Molde - Vestnes

Vessel name	MMSI	B [m]	L [m]	D[m]	Dwt [t]
Malmefjord	258004980	17	109	3	700
Tomrefjord	258007730	18	110	3.5	700
Harøyfjord	258841000	18	123	5.8	750
Vestrefjord	258007760	18	109	3.8	700
Generic Value		17.8	113	4.0	700

Based on the vessel dimensions of the four ferries in Table 15, a set of generic vessel dimensions is determined based on the average values. These are used to set parameters for a generic ferry operating on the route. Assuming a C_b of 0.5, the total weight of this generic ferry is estimated to be 4000 tons.

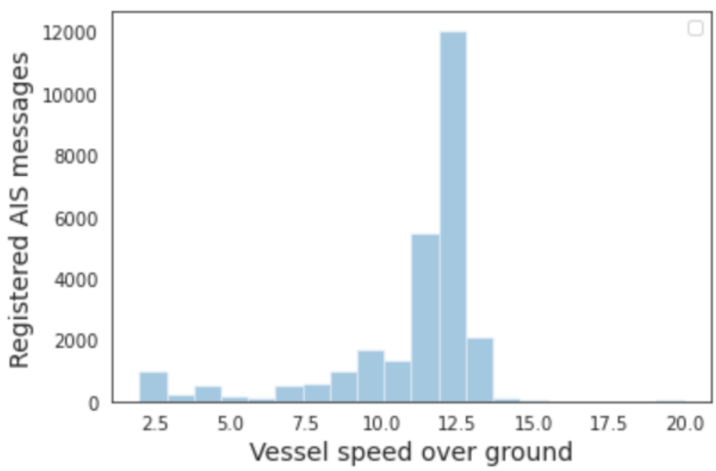

Figure 22: Ferry speed over ground for Molde - Vestnes 2019

From Figure 22, the speed over ground of the generic ferry sailing on the route is determined. The results show that the mode of the registered speeds is 12.5 knots. This speed is assumed to be the operating speed for the ferry when crossing the fjord between Molde and Vestnes.

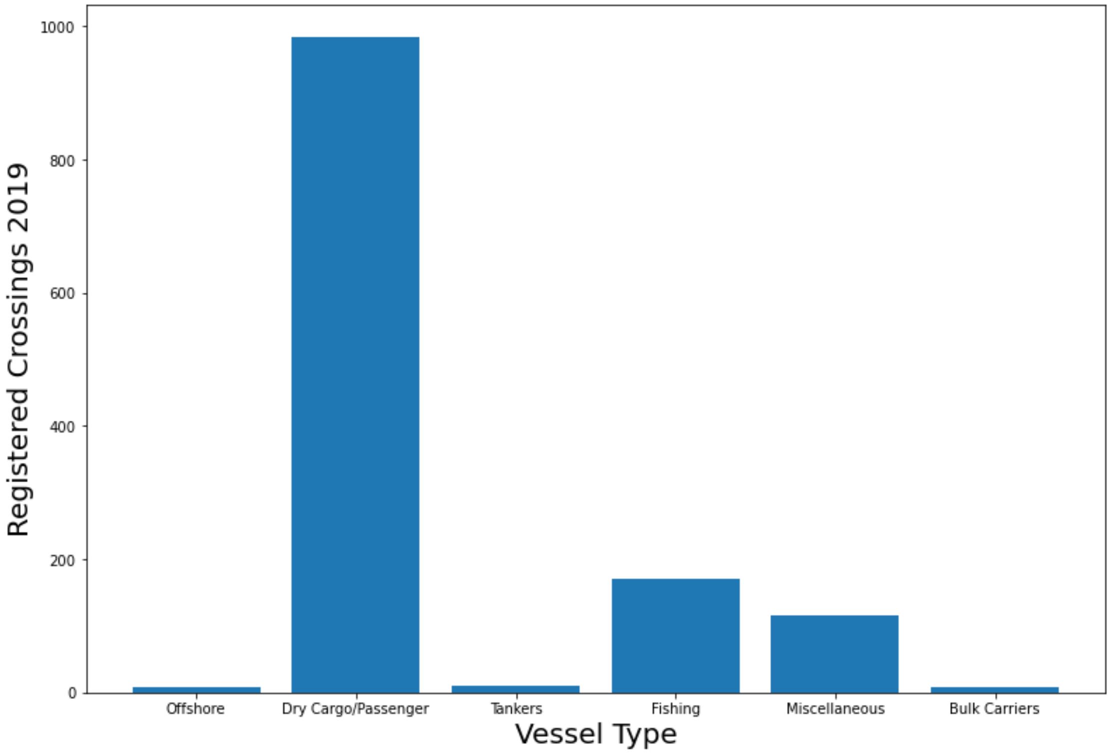

Figure 23: Amount of crossings per vessel type for Molde - Vestnes 2019

The results show that dry cargo/passenger vessels are by far the most frequent vessel type crossing the ferry route, with more than 75% of the registered crossings in 2019. There were only 28 registered crossings for tanker, bulk, and offshore vessels, which is less than 2% of the total crossings. The average total vessel weight is less than 10 000 for all vessel types, where offshore, bulk, and dry cargo/passenger vessels are the largest, with total weights in the 7 000 ton range.

Table 16: Results Molde Vestnes. Average values for sog, weight and breadth

Vessel type	**N crossings**	**Sog [kn]**	**Total Weight [t]**	**Breadth [m]**
Tankers	11	10.6	4 800	12.7
Bulk	8	10.2	7 300	15.1
Offshore	9	11.2	7 600	17.5
Fishing	171	9.5	2 100	12.5
Cargo / Passenger	984	10.5	7 300	13.7
Miscellaneous	116	8.4	800	8.6
Total	1299	10.3	6 300	13.2

Following the presented methodology, the probability of a crossing collision where the ferry is struck by a passing vessel is calculated per passage and year. The total probability per annum is estimated to be $4.5 \cdot 10^{-3}$, or once every 222 years. A collision scenario involving a dry cargo/passenger vessel is most likely of the vessel types. The low crossing rate per annum of the tanker, bulk, and offshore vessels causes the probability of a crossing collision involving them to be $9.8 \cdot 10^{-5}$.

Table 17: Probability of crossing collision Molde - Vestnes

Vessel type	**Probability per passage**	**Probability per annum**
Tankers	$1.1 \cdot 10^{-9}$	$3.8 \cdot 10^{-5}$
Bulk	$8.4 \cdot 10^{-10}$	$2.8 \cdot 10^{-5}$
Offshore	$9.7 \cdot 10^{-10}$	$3.2 \cdot 10^{-5}$
Fishing	$1.8 \cdot 10^{-8}$	$5.9 \cdot 10^{-4}$
Cargo / Passenger	$1.0 \cdot 10^{-7}$	$3.4 \cdot 10^{-3}$
Miscellaneous	$1.2 \cdot 10^{-8}$	$3.88 \cdot 10^{-4}$
Total	$1.3 \cdot 10^{-7}$	$4.5 \cdot 10^{-3}$

Only two offshore vessels and 165 dry cargo/passenger vessels are classified as high-energy crossing scenarios, potentially causing absorbed collision energy in the ferry of more than 60 MJ. The results also show that dry cargo/passenger vessels are over-represented in the other two energy categories. Most of the crossing scenarios, with more than 56%, are less than 10 MJ.

Table 18: Number of crossing situations per vessel type with distributed on absorbed collision energy in a collision scenario where the ferry is struck

Vessel type	**< 10MJ**	**10MJ-60MJ**	**> 60MJ**
Tankers	3	8	0
Bulk	4	4	0
Offshore	3	2	2
Fishing	64	33	0
Cargo/Passenger	497	314	165
Miscellaneous	110	2	0
Total	681	363	167

As a consequence of the assumptions, there are only two crossing scenarios by offshore vessels that have the energy level and geometry for striking the systems placed above the deck. The probability of such a scenario is $3.6 \cdot 10^{-6}$ per year. Cargo/passenger vessels only have the capability of striking the systems placed below deck, and by adding the probability from offshore vessels, the total probability of directly striking the systems placed below deck is $2.9 \cdot 10^{-4}$.

Table 19: Annual probability of impacting the hydrogen systems on board the ferry for Molde - Vestnes

	Probability of striking storage tanks per annum	
Vessel type	**Systems below deck**	**Systems above deck**
Tankers	0	0
Bulk	0	0
Offshore	$3.6 \cdot 10^{-6}$	$3.6 \cdot 10^{-6}$
Fishing	0	0
Cargo/Passenger	$2.9 \cdot 10^{-4}$	0
Miscellaneous	0	0
Total	$2.9 \cdot 10^{-4}$	$3.6 \cdot 10^{-6}$

5 Discussion

The purpose of this section is to discuss the findings and results from the case studies performed. The results are also compared to findings in relevant literature. Assumptions and simplifications made in the model are discussed in relation to their accuracy and impact on the final results. The model and results are also compared to the state-of-the-art methodology established in the literature review.

5.1 Comparison of results

When comparing the number of crossings situations in the three different areas in the case study, it is clear that the traffic picture varies a lot. The results show that most vessels cross the ferry route between Leirvåg and Sløvåg, with 5 256 crossings in 2019. This is four times as many compared crossings for Molde-Vestnes. There is also significant variation in the number of crossings per vessel type, illustrated by Figure 24. The largest variation in the number of crossings is for the offshore vessel type. The ferry route between Sløvåg and Leirvåg had more than 3 000 offshore vessel crossings in 2019, while there were only 166 crossings at the two other locations combined.

The most likely reason for the lower number of crossings at the ferry route between Molde and Vestnes is that there is far less activity associated with the Norwegian oil and gas industry in the area. The close proximity between Sløvåg-Leirvåg and the Mongstad processing plant leads to more traffic of larger tanker vessels transporting oil and other offshore vessels involved in various activities. The case is the same for Mortavika-Arsvågen, with numerous larger ports, the Kårstø processing plant, and other sites associated with traffic of larger vessel types. Another factor could be that Molde-Vestnes is located further into the fjord compared to the other two locations. It is sensible that also vessel traffic would be lower compared to further out in the fjord.

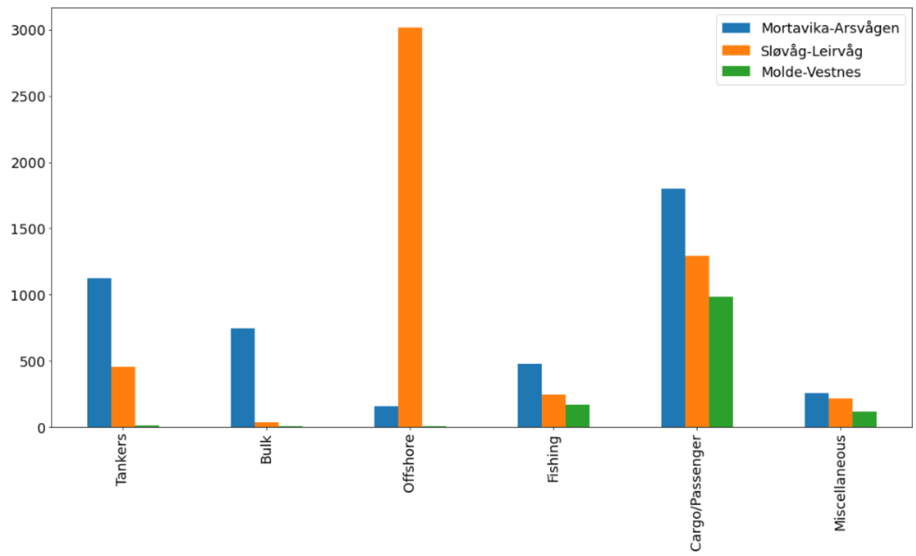

Figure 24: Comparison of the total number of crossings for the three specific areas in 2019

Comparing the values in Table 8, 12, and 17, it is observed that the annual probability of a crossing collision where a ferry is struck by the passing vessel varies notably. Although more vessels were crossing the ferry route between Sløvåg and Leirvåg, the probability of a crossing collision is over 2.5 times higher at Mortavika-Arsvågen. This is due to the higher vessel traffic for the ferries operating on the route. At Sløvåg-Leirvåg, there is only one vessel operating at the time with only 13 000 departures every year, while at Mortavika-Arsvågen, there are around 47 500 departures every year. The traffic of passing vessels around Molde-Vestnes leads to the probability of the crossing collision scenario also being the lowest. The three annual crossing collision probabilities where the ferry is struck by a passing vessel can also be seen in Figure 25.

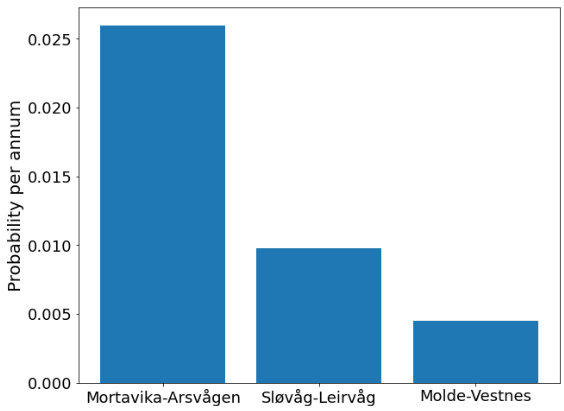

Figure 25: Comparison of the probability of a crossing collision where the ferry is struck by a passing vessel per location

Chai et al. (2019) estimated the collision frequency per year for the Yangtze River and found the combined frequency of various crossing collision scenarios to be $5.5 \cdot$

10^{-4}. This is significantly lower than the values found in the case study of this thesis. One of the reasons for this may be the causation probability ranging between $5.87 \cdot 10^{-5}$ and $8.48 \cdot 10^{-5}$, which was used. Another influencing factor can be the difference in the geometry and vessel traffic of the specific area. A narrow river with vessels sailing to and from a port is quite different concerning traffic patterns, vessel speeds, and points of crossing compared to the examples used in this thesis.

Montewka et al. (2010) applied various marine traffic modeling methods in the Gulf of Finland to map vessel traffic and estimate the probability of crossing, overtaking, and head-on collision scenarios. The total probability of a crossing collision per year was found to be 0.263, where a causation probability of $1.3 \cdot 10^{-4}$ was used. This probability is close to ten times higher compared to the values from Mortavika-Arsvågen. However, it is not accurate to compare these values directly. The collision probabilities from Montewka et al. (2010) account for the crossing collision probability for all vessels in the area, while the values from Mortavika-Arsvågen only represent the probability of a crossing collision scenario where a ferry operating on the route is struck by a passing vessel. It is also reasonable to assume that the traffic in the Gulf of Finland is quite different from the traffic in Boknafjorden, making it difficult to compare the probabilities directly.

The energy level associated with the crossing scenarios is shown to vary greatly depending on the specific location. Only 167 vessels were estimated to have a potential high-level absorbed energy collision with a ferry operating on the route between Molde and Vestnes, and 165 of these vessels were Dry cargo/passenger vessels. The high amount of potential high-energy collisions at Mortavika-Arsvågen is most likely due to a higher passing rate of the larger tanker, bulk, and offshore vessels and a higher associated sailing speed. Comparing Table 7, 11, and 16, it is clear that these larger vessel types sail at a higher speed than in the two other analysed locations. Equation 29 used to calculate the impact energy for the various passing vessels is proportional to the square of the crossing speed. Therefore, it is sensible that there is a larger amount of a high-energy collisions involving the ferries operating at Mortavika-Arsvågen.

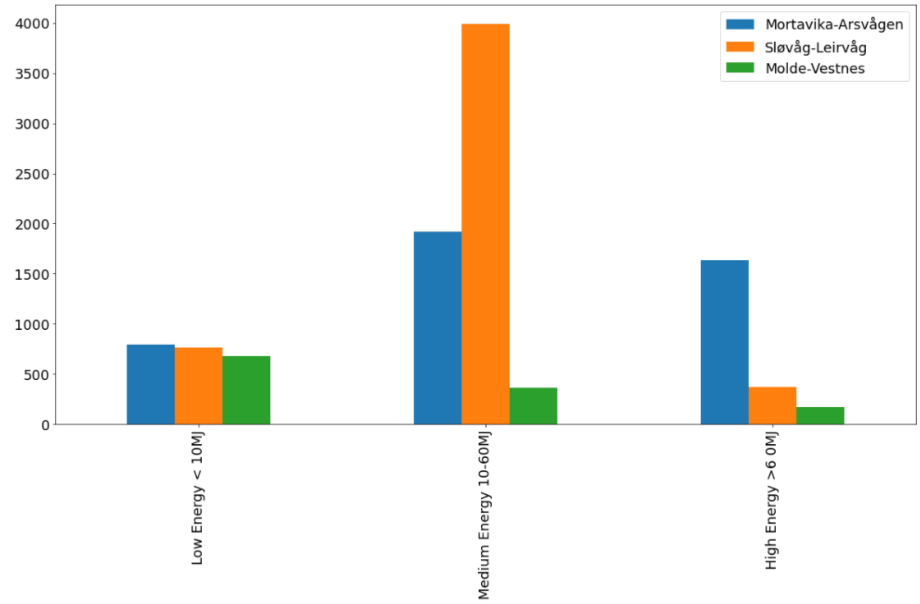

Figure 26: Comparison of the absorbed energy level of the crossings for the three specific areas in 2019

The quantitative estimation of the annual probability of striking the hydrogen systems depending on their placement in the three cases shows the most deviating results. The rough geometrical and energy-level assumptions in the methodology suggest that the probability of a scenario where the hydrogen systems are directly impacted is very low. The assumptions indicate that the impact probability is slightly higher when the systems are placed below the ferry's deck. This is because it is assumed that all vessels have the capability of striking the systems located below deck if the associated absorbed energy of the collision is more than 60 MJ. Table 10, 14, and 19 show the results related to the probability of striking the systems. The highest probability per year is again for Mortavika-Arsvågen. This is due to the higher annual probability of a crossing collision where the ferry is struck, and a larger amount of high-energy vessel crossings compared to the other two locations.

The annual probabilities associated with impacting the hydrogen systems are far lower than the probability of a crossing collision for the three locations. For Mortavika-Arsvågen, the probability of striking the systems below deck is $5 \cdot 10^{-4}$, or once every 200 years. The probability of striking the systems placed above the deck is slightly lower with $4.6 \cdot 10^{-4}$, or once every 217 years. The results from the other two locations show that the probability is far less likely, and can be assumed to be almost negligible compared to the values from Mortavika-Arsvågen.

5.2 Assumptions, simplifications, and uncertainty

To produce the final results presented in the case study, many assumptions and simplifications which can influence the results were made. Though assumptions and simplifications are needed in a model, they always lead to a more inaccurate result compared to the real world.

Assuming a collision angle of 90° is a substantial simplification compared with how the crossing scenarios are in the real world. Although it can be argued that many vessels crossed the ferry routes in the three case studies with an angle close to 90°, it is not accurate to assume that all vessels do, as can be seen in Figure 27. Haugen and Kristiansen (2022) argue that the more advanced model proposed by Friis-Hansen (2008) in Equation 13, where all collision angles are included to estimate the geometric probability of a crossing collision, only slightly improves the results. However, in order to develop a more realistic model, all collision angles should be included.

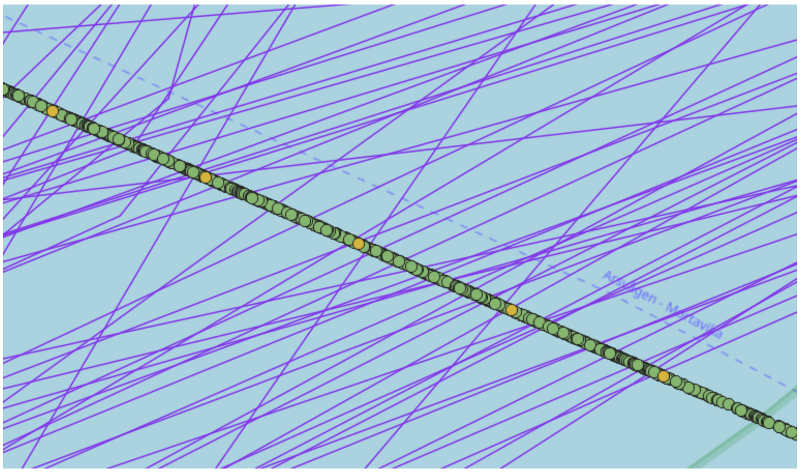

Figure 27: Sample of some voyages for bulk vessels crossing the ferry route at Mortavika-Arsvågen in 2019

In the model presented in this thesis, the collision diameter used to estimate the geometric probability of a crossing collision is the sum of the length of the ferry and the breadth of the passing vessel. This can be an inaccurate assumption, especially if all collision angles are incorporated into the model. A more detailed model for estimating the collision diameter for a ship-ship collision scenario will most likely give a more precise estimation of the geometrical probability.

To estimate the mass and impact energy of the passing vessels, some assumptions related to the dimensions of the vessels and added mass were made. The parameters "length over all", "moulded breadth", "draught", as well as the block coefficient values based on general values from Shah and M (2016) were used. Ideally, the "length between perpendiculars", "max breadth", and "operational waterline draught" should be combined with the actual block coefficient of the vessel to more accurately estimate the total mass of the vessel. However,these values were not as available as "length over all" and "moulded breadth". The "length over all" and "moulded breadth" is very similar to the actual "length between perpendiculars" and "max breadth" and were used since there were many cases of missing data for the two latter parameters. A added mass coefficient for the ferry in sway motion of 0.75 was also used to calculate the impact energy. The added mass coefficient varies a lot with the vessel geometry under the water line and should be estimated more accurately to improve the estimation of the impact energy further.

The causation probability used to determine the probability of crossing collision scenarios in this thesis was set to $2 \cdot 10^{-4}$, which can be regarded as a conservative value. The causation probability for crossing collision used in the reviewed literature is ranging between $2.8 \cdot 10^{-4}$ from Friis-Hansen (2008) to as low as $5.9 \cdot 10^{-5}$ from Chai et al. (2019). Though the causation probability is difficult to establish accurately for a specific collision scenario and area, a more detailed assessment of this value is beneficial for the accuracy of the collision probability.

The ferries operating on the route and passing vessels are assumed to cross the fjord with a constant arrival frequency independent of the time of the day. Since there usually is more traffic of passing vessels during the day, and ferries do not operate during a period at night, the assumption made in this thesis may give a more inaccurate estimation of the collision probability. If a more precise model for the various vessel arrival frequency concerning the time of the day and seasonal variations is implemented, the final result may be more accurate. A polygonal line was created to represent the route the ferries use when crossing the fjords. To assume that all ferries sail along a narrow line is inaccurate, and ferries often sail in two corridors when operating on a fixed route between two locations.

The presented methodology uses coarse assumptions of the geometry of the height in the bow for the various vessel types to assess the potential of impacting hydrogen systems on board the subject ferry in a crossing collision scenario. These assumptions are inaccurate, and it is not sensible to only assume the vessel geometry based solely on vessel type. It would be more accurate to develop a model where the vessel size and general geometry of the different vessel types are incorporated. No literature was discovered related to this topic. A more detailed framework for the consequences of various levels of absorbed energy should also be included in the model. Though indications of penetration length in a collision scenario can be retrieved from research such as the models presented by Bin Liu et al. (2021), more detailed methods should be developed. These could then be used to set design requirements and limits for hydrogen storage, handling, and fuel cell systems to reduce the consequences in a crossing collision scenario.

When estimating the probabilities associated with impacting the hydrogen systems, it is assumed that the collision diameter is the same as when the probability of a crossing collision was estimated. Observing Figure 14, the hydrogen systems seem only to be located around the middle part of the vessel. A more detailed assessment of the size of hydrogen systems and where they are located should be performed to establish a more precise value for the collision diameter when determining the probability of impacting the hydrogen systems on board the subject vessel. This will most likely reduce the probability of such a scenario further since the collision diameter is reduced compared to the total length of the vessel.

The assumption that hydrogen systems may only be reached in a collision scenario from one side is sensible for the areas studied in this thesis. This was accounted for by dividing the probability of a crossing collision with a high enough energy level to directly impact the systems by 2. However, this may be an inaccurate assumption if the vessel traffic is not equal from both directions when crossing the ferry route. Therefore, an individual assessment of this issue should be conducted when applying the model to other areas of interest.

There is also uncertainty associated with the AIS data for the vessels sailing in the area. This is the case both for AIS messages reporting wrong values and when different values are missing. Erroneous data were removed from the analysis, but a framework for identifying inaccurate data reporting was not implemented. Inaccurate reporting of vessel type is in some cases present in the analysed AIS data and can be hard to detect. A framework, such as the one developed by Smestad (2015), can be used to validate if the reported vessel type is correct based on vessel behavior.

Vessels sailing with an average speed of less than 3 knots and reported length over all of less than 25 meters were removed from the data set. This assumption was made because they were assumed not to pose a risk in a collision scenario. The removal of these vessels was done to reduce the computation time when processing the data. This limit is only set based on advice from expert people with experience on the topic. The same applies to the limits regarding reported vessel speeds of more than 50 knots, which is assumed to be erroneous because it is unrealistic for the vessels sailing in the area. Therefore, it is essential to be critical when setting limits for what data should be considered accurate.

5.3 Method Comparison with State-of-the-Art

When comparing the presented methodology with the state-of-the-art models presented in the reviewed literature, it is clear that there is room for more improvement. The method used to determine the geometrical probability of crossing collisions per annum for the three ferry locations in the case study is a simplified methodology. A more advanced model incorporating a more accurate collision diameter, relative motion, and speed between vessels should be developed to more accurately determine the geometrical probability. Some of the models presented by Chen et al. (2019) may be suitable to improve the quality of the geometric probability estimation.

A more detailed methodology for establishing a causation probability for each specific area of interest is desired. The methodology presented in this thesis defined the causation probability to be $2 \cdot 10^{-4}$ for all the three analysed areas. Implementing a model based on a statistical analysis of historical accident data such as proposed by Yahei Fujii and Shiobara (1971), a fault tree approach, a Bayesian network approach such as proposed by Friis-Hansen (2008), or a combination of them to establish a causation probability for the area of interest will give a much more precise estimation of the value. Since the likelihood of a collision scenario is directly proportional to the causation probability, it is essential to establish an accurate value when assessing collision risk.

A state-of-the-art model for assessing the placement of hydrogen systems on board a hydrogen-fuelled vessel in relation to a collision scenario was not found. Although the model presented in this thesis provides a simplified procedure for classifying the level of energy in a crossing collision scenario, a more detailed framework is sought after. This can be used to find the return period for a collision scenario with a certain level of collision energy in a specific location.

6 Conclusion

A review of literature related to hydrogen in shipping revealed that there is a need for more knowledge in the field. This is needed to accelerate the development to offer greener alternatives for fuel in the shipping industry. One of the areas of interest pointed out is the use of fuel cells and hydrogen fuel systems on a vessel subjected to various collision and impact scenarios. Appropriate methods from research on ship-ship collision scenarios are adapted. A model for estimating the probability of a collision scenario between a hydrogen-fuelled ferry operating on a route and a passing vessel crossing this route is established. AIS data for the area surrounding the ferry route was extracted and used to determine the crossing collision probability.

The methodology developed in this thesis was applied to three different ferry locations along the Norwegian west coast. An estimation of a crossing collision probability, where the ferry operating on the route is struck by various vessel types, was successfully established for the three locations. The results show that the collision probability varies significantly between the three locations. There is also great variation in the vessel types and sizes crossing the different ferry routes. As a result, the ferry route between Mortavika and Arsvågen is identified to have the highest probability of the crossing collision scenario, with 0.026 collisions per annum.

There is a lack of similar models in the published literature. Therefore, comparing the crossing collision probabilities quantified in this thesis with other results from collision studies is difficult. Some other studies found the collision probability higher for a specific area, and some found it to be almost negligible. The methodology developed to calculate the probability of a crossing collision with sufficient impact energy to strike the hydrogen systems on board the ferry directly was not able to produce results with adequate accuracy. Though a very low probability of this scenario occurring was calculated, the assumptions behind the method were coarse. No comparable studies have been conducted for such a scenario, so the results presented in this thesis on this scenario are difficult to validate.

6.1 Recommendation for Further work

Further work should be conducted to improve several aspects of the model to estimate the probability of the crossing collision scenarios more precisely. A more detailed framework for establishing a geometric probability and causation probability of crossing collision scenarios for the specific area should be developed. This framework should incorporate advanced models for calculating the relative velocity and position between vessels to determine the collision diameter. All collision angles should also be included. Statistical analysis of historical accidents, fault tree analysis, or Bayesian Belief Networks can be adapted to establish the causation probability for each area of analysis more precisely. Values for what can be considered high-energy impacts and penetration length with the potential of hitting hydrogen systems on board the struck vessel should also be established and can be useful in the design process of new hydrogen-fuelled vessels. A method for determining the height and geometry in the bow depending on vessel type and size is also desired.

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Appendix

A Codes

A.1 Pre-processing of data

```python
# Importing relevant libraries

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import geopandas as gpd
import seaborn as sns

# Reading the original data set for vessel voyages

gdf0 = gpd.read_file('MyVoyages/Voyages.tab')

# Introducing a counter to each row to more easily
# count different values in the data set

gdf0['counter'] = 1

# Separating the data for the ferry operating on the route

ferry = gdf0.loc[gdf0['shipname'].isin \
                  (['STORFJORD' , 'MELDERSKIN', 'BJORNEFJORD', 'SULAFJORD'])]

# Save file for the ferry data

ferry.to_csv('ferry.csv')

# Passing vessels

NotF = gdf0.loc[~gdf0['shipname'].isin \
                 (['STORFJORD' , 'MELDERSKIN', 'BJORNEFJORD', 'SULAFJORD'])]

# Removing Non ship structures and vessels not with
# missing value for vessel type

NotF = NotF.loc[~gdf0['shiptypelevel2'].isin(['Non Ship Structures' , 'NN'])]

# Remove vessels with an average speed below 3kn and above 50

NotF = NotF[NotF.avg_speed_over_ground > 3]
NotF = NotF[NotF.avg_speed_over_ground < 50]
```

```

# Remove vessels with a Length over all less than 25 meters

NotF = NotF[NotF.lenthoverallloa > 25]

# Saving pre-processed file for furhter analysis in QGIS

with open('NotF.gpkg', 'wb') as ofile:
    NotF.to_file(ofile, driver='GPKG', layer = 'vessels')
```

A.2 Generating data frame with crossing points

```
# Importing relevant libraries

import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import geopandas as gpd
import seaborn as sns
import mgrs
import datetime as dt

# Import formated AIS-data messages
df0 = gpd.read_file('facts_formatted.csv')

# Import data base with tracks for passing vessels and point of crossing

df1 = gpd.read_file('krysninger.gpkg')

# Calculate speed over ground [kn]
df0['sog'] = df0['nautical_miles_sailed'].astype(float) / df0['hours_in_operation'].astype(float)

# Setting data format for the columns for shipid to float
# in both data frames
df1['shipid']= df1['shipid'].astype(float).astype(int)
df0['shipid']= df0['shipid'].astype(float).astype(int)

df1['geometry']= df1['geometry'].astype(str)

# Import interpolated points along the line representing the ferry strait
df2 = gpd.read_file('intpunkter.gpkg')

# Transform from coordinates to mgrs format
m = mgrs.MGRS()
df2['mgrs'] = df2['geometry'].apply(lambda g: m.toMGRS(g.y, g.x, MGRSPrecision=2))

```

```
# Remove duplicate mgrs points
df2 = df2.drop_duplicates(subset =['mgrs'], keep = 'first')

# Make format on time the same for both data frames
df1.starttime = [dt.datetime.strptime(timestamp, "%Y-%m-%d %H:%M:%S").strftime("%Y%m%d") for times

# Change to the same column name for date in both data sets
df1 = df1.rename(columns = {'starttime':'date_id'})

# Same data message appears twice, so remove duplicate
df1 = df1.drop_duplicates(subset =['geometry'], keep = 'first')

# Merge formatted AIS-data with set of  mgrs-points to find messages close to the point of crossin
df = df0.merge(df2, on = 'mgrs', how = 'inner')
# Drop duplicates of same date and ship
df = df.drop_duplicates(subset =['shipid','date_id'], keep = 'first')

# Merge this with data set with data for the crossing points
df_final = df1.merge(df, on = ['date_id', 'shipid'], how = 'inner')

# Save data frame with information of crossing vessels
df_final.to_csv('Crossings.csv')
```

A.3 Estimation of collision energy

```
# import pandas as pd
import numpy as np
import matplotlib.pyplot as plt
import geopandas as gpd
import seaborn as sns

# Read in data frame with informatin
# about crossing vessels

df = pd.read_csv('Crossings.csv')

# Defining relevant columns for the analysis
# and removing non-relevant columns
df1 = df[['date_id','shipname','mmsi','imo','shiptypelevel2','lenthoveralllloa',\
'breadthmoulded','draught','deadweight','shipid','counter', 'geometry', 'sog']]

# Define table with values for Cb
# for the various vessel types
cb = pd.DataFrame({"shiptypelevel2":\
['Bulk Carriers','Dry Cargo/Passenger','Fishing','Miscellaneous',\
'NN','Non Ship Structures','Offshore','Tankers'],\
```

```
"Cb":[0.8,0.8,0.45,0.7,0.65,0.65,0.7,0.83]})

# Merge the crossing vessels with Cb
# values depending on vessel type
df_final = df1.merge(cb, on = ['shiptypelevel2'], how = 'inner')

# Estimate the total weight of vessels
df_final['TotalWeight'] = df_final['lenthoveralllo a']\
*df_final['breadthmoulded']*df_final['draught']*df_final['Cb']

# Removing vessels with missing values
# for dimensions
dfc = df_final.loc[df_final['TotalWeight'] != 0]

# Creating tables with vessel categories
# depending on ship type

tankers = dfc.loc[dfc.shiptypelevel2 == 'Tankers']
bulk = dfc.loc[dfc.shiptypelevel2 == 'Bulk Carriers']
offshore = dfc.loc[dfc.shiptypelevel2 == 'Offshore']
fishing = dfc.loc[dfc.shiptypelevel2 == 'Fishing']
cargo = dfc.loc[dfc.shiptypelevel2 == 'Dry Cargo/Passenger']
miscellaneous = dfc.loc[dfc.shiptypelevel2 == 'Miscellaneous']

# Number of Crossings per vessel type

Ncrossings = df_final.groupby(['shiptypelevel2']).count()['counter']
Ncrossings = Ncrossings.sort_values(ascending = False)
Ncrossings

# Extracting mean values to establish
# geometric probability for the vessel types
print('tankers', tankers.sog.mean(), tankers.TotalWeight.mean(), tankers.breadthmoulded.mean())
print('bulk', bulk.sog.mean(), bulk.TotalWeight.mean(), bulk.breadthmoulded.mean())
print('offshore', offshore.sog.mean(),\
offshore.TotalWeight.mean(), offshore.breadthmoulded.mean())
print('fishing', fishing.sog.mean(), fishing.TotalWeight.mean(), fishing.breadthmoulded.mean())
print('cargo', cargo.sog.mean(), cargo.TotalWeight.mean(), cargo.breadthmoulded.mean())
print('miscellaneous', miscellaneous.sog.mean(),\
miscellaneous.TotalWeight.mean(), miscellaneous.breadthmoulded.mean())

# Defining parameters for the ferries based on AIS-data
# NOTE - Different values for each location studied
l_ferry = 110
b_ferry = 17
d_ferry = 3.5
Cb_ferry = 0.5
A_sway = 0.75
```

```
m_ferry = l_ferry * b_ferry * d_ferry * Cb_ferry

# Calculating the impact energy in a crossing
# collision scenario with the different vessels
dfc['ImpactEnergy'] = (dfc['TotalWeight'].astype(float)\
* m_ferry*(1+A_sway)) \
/(2*(dfc['TotalWeight'].astype(float) + m_ferry *\
(1+A_sway)))* (dfc['sog']*0.5144*np.sin(np.pi/2))**2

# Calculating the absorbed energy in the ferry
# in the potential collision scenario
dfc['Absorbed'] = dfc['ImpactEnergy'].astype(float)\
* (1)/(1+(m_ferry)/(dfc['TotalWeight'].astype(float)))

# Defining energy-level categories
highC = dfc.loc[dfc.Absorbed > 60000]
mediumC = dfc.loc[dfc.Absorbed < 60000]
mediumC = mediumC.loc[mediumC.Absorbed > 10000]
smallC = dfc.loc[dfc.Absorbed < 10000]

# Count number of crossings with
# high, medium, and low absorbed energy level
high = highC.groupby(['shiptypelevel2']).count()['counter']
high = high.sort_values(ascending = False)
medium = mediumC.groupby(['shiptypelevel2']).count()['counter']
medium = medium.sort_values(ascending = False)
small = smallC.groupby(['shiptypelevel2']).count()['counter']
small = small.sort_values(ascending = False)
print('High', high)
print('Medium', medium)
print('Small', small)
```

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