Final Report

Energy consumption modeling of ships: towards a Door-to-Door (D2D) freight optimization

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Date:
August 2024

Prepared for the Sustainable Mobility and Accessibility Regional Transportation Equity Research Center, Morgan State University, CBEIS 327, 1700 E. Coldspring Lane, Baltimore, MD 21251

ACKNOWLEDGMENT

This research was supported by the Sustainable Mobility and Accessibility Regional Transportation Equity Research Center at Morgan State University and the University Transportation Center(s) Program of the U.S. Department of Transportation.

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1. Report No. SM07

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Energy consumption modeling of ships: towards a Door-to-Door (D2D) freight optimization

5. Report Date
August 29, 2024

6. Performing Organization Code

7. Author(s) *Include ORCID #*
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8. Performing Organization Report No.

9. Performing Organization Name and Address
Virginia Tech Transportation Institute
3500 Transportation Research Plaza, Blacksburg, VA 24061

10. Work Unit No.

11. Contract or Grant No.
69A3552348303

12. Sponsoring Agency Name and Address
US Department of Transportation
Office of the Secretary-Research
UTC Program, RDT-30
1200 New Jersey Ave., SE
Washington, DC 20590

13. Type of Report and Period Covered
Final, September 2023 - September 2024

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract
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Unlike conventional simulators, ShipNetSim integrates key elements such as propulsion, resistance, and ship-to-ship interactions into a single, unified framework. This integration allows for accurate predictions of energy consumption and environmental impact over the entire maritime journey. Additionally, ShipNetSim is designed for computational efficiency, ensuring detailed analyses can be conducted rapidly without sacrificing accuracy. This balance between precision and speed makes ShipNetSim invaluable for researchers and policymakers focused on sustainable maritime practices.

A case study within this report demonstrates the simulator's effectiveness in modeling vessel trajectories, energy consumption, and emissions with high accuracy. The results validate ShipNetSim's potential to enhance understanding of maritime dynamics and inform policy decisions aimed at improving efficiency and reducing environmental impact. ShipNetSim offers a flexible platform suited to the industry's evolving needs. Whether in response to new regulations, emerging technologies, or changing trade patterns, ShipNetSim is poised to play a crucial role in the global effort to create a more sustainable and efficient maritime industry. This report details the simulator's development, key features, and potential applications, paving the way for its broader adoption in future maritime research and policy development.

17. Key Words: ShipNetSim, Ship Large-Scale Simulation, Ship Longitudinal Motion, Energy Consumption, Carbon Footprint.

18. Distribution Statement

19. Security Classif. (of this report) :	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	43	

Abstract

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Introduction

The maritime industry —the cornerstone of global trade and commerce— is undergoing a transformative shift driven by the need to balance economic efficiency with environmental stewardship. As the largest and most energy-intensive mode of transportation, maritime operations are responsible for approximately 2-3% of global CO_2 emissions, a figure that is projected to rise if significant measures are not implemented (*Initial IMO GHG Strategy*, n.d.). The International Maritime Organization (IMO) has set ambitious goals to halve greenhouse gas emissions by 2050 relative to 2008 levels, urging the industry to adopt innovative technologies and practices to meet these goals (Erdem, 2011). In response, the development of advanced simulation tools that can comprehensively model ship operations and their environmental impacts has become increasingly crucial.

Historically, maritime simulation tools have evolved to address specific aspects of ship functionality, such as propulsion systems, hydrodynamic performance, and navigation in confined waters. For example, Computational Fluid Dynamics (CFD) models have been extensively used to simulate the effects of hull design on ship resistance and propulsion efficiency (Sato et al., 2000). Similarly, studies have explored the impact of wave conditions on ship maneuverability and added resistance (Zhang et al., 2017). However, these tools often lack the capacity to integrate these isolated components into a cohesive simulation of the entire maritime journey. This gap limits their utility for evaluating the full scope of energy consumption and emissions over long voyages, which are influenced by a complex interplay of factors including ship interactions, environmental conditions, and operational practices (Calleya et al., 2015).

ShipNetSim, the open-source simulator presented in this report, addresses this critical gap by offering a comprehensive platform that simulates the full range of interactions between multiple vessels on a large-scale, open-sea environment. Unlike traditional simulators, which may focus on either propulsion or resistance in isolation, ShipNetSim integrates these factors within a dynamic framework that also accounts for ship-to-ship interactions, path planning, and real-time energy consumption. This holistic approach is essential for accurately estimating the carbon footprint of maritime operations, as it considers the cumulative effects of various operational and environmental variables over the entire course of a voyage (Işıklı et al., 2020; Thiaucourt et al., 2023).

One of the primary innovations of ShipNetSim is its emphasis on computational efficiency without compromising the accuracy of the simulations. Traditional ship simulators often involve high computational costs due to the detailed modeling of multiple degrees of freedom (DOF) in ship movements, which can significantly slow down simulation times, especially in large-scale studies (Ueng et al., 2008). In contrast, ShipNetSim employs a streamlined modeling approach, focusing on a single degree of freedom in the current release, which simplifies the computational process while still delivering precise estimates of energy consumption and emissions. This makes the simulator particularly suitable for extensive studies that require rapid data processing and analysis, such as those assessing the impact of different fuel types similar to what was done in A. Aredah, Du, et al. (2024), operational strategies similar to what was done in A. Aredah, Fadhloun, et al. (2024) or A. Aredah & Rakha (2024), or environmental regulations on maritime sustainability (Chen et al., 2019; Liu & Duru, 2020).

Furthermore, ShipNetSim's open-source framework fosters continuous innovation and collaboration within the maritime research community. The ability to modify and extend the simulator's underlying models allows researchers to adapt it to a wide range of study scenarios, from simulating the effects of alternative propulsion systems to exploring the impact of emerging environmental policies. This adaptability is crucial as the maritime industry continues to evolve, driven by both technological advancements and increasingly stringent environmental regulations (Mocerino et al., 2021). For instance, future versions of ShipNetSim could incorporate additional degrees of freedom, such as lateral and rotational movements, to more accurately simulate the complexities of ship behavior in varying sea conditions. Additionally, the integration of real-time weather data and predictive models could enhance the simulator's ability to forecast and mitigate the impacts of adverse weather on ship operations (Wu et al., 2021).

Another key feature of ShipNetSim is its focus on real-time energy consumption and emissions calculations. By providing instantaneous feedback on these metrics, the simulator allows for a detailed assessment of the environmental impact of different operational scenarios. This capability is particularly important for evaluating the effectiveness of emissions reduction strategies, such as route optimization, and the use of cleaner fuels (Jensen et al., 2018). Moreover, ShipNetSim's ability to model the interactions between multiple vessels makes it a valuable tool for studying the cumulative effects of fleet operations on energy use and emissions. This is critical for understanding the broader implications of individual ship behaviors on the global maritime system and for developing coordinated strategies to improve overall fleet efficiency (Luo & Wang, 2017).

The modular structure of ShipNetSim also supports the incorporation of alternative fuels and propulsion systems, enabling researchers to explore the potential impacts of new technologies on maritime sustainability. For example, the simulator could be used to model the use of hydrogen fuel cells or battery-electric propulsion in different ship types, assessing their effects on energy efficiency, emissions, and operational costs (Park et al., 2020). This functionality is increasingly relevant as the industry explores a range of low-carbon technologies in response to global emissions targets (Yun et al., 2018). By simulating the integration of these technologies within a realistic operational framework, ShipNetSim can provide valuable insights into their viability and guide future investments in sustainable maritime technologies.

In addition to its technical capabilities, ShipNetSim has significant potential for informing policy development in the maritime sector. The detailed simulations it provides can support the creation of more effective regulations and standards, particularly in areas such as emissions control, fuel efficiency, and the adoption of alternative propulsion systems (Erdem, 2011). For example, by simulating the impact of different emissions regulations on ship operations, ShipNetSim can help policymakers identify the most effective measures for reducing the maritime industry's environmental footprint while maintaining economic viability. This is particularly important as the industry moves towards more stringent environmental controls under frameworks like the IMO's Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII) (*Initial IMO GHG Strategy*, n.d.).

Furthermore, the simulator's ability to model interactions between multiple vessels and their cumulative effects on energy use and emissions is crucial for developing coordinated strategies to improve fleet-wide efficiency. This is particularly relevant in the context of integrated transportation systems, where maritime operations must be aligned with other modes of transport, such as rail (using the open-source NeTrainSim[1]) and road (using the freeware INTEGRATION[2]), to optimize overall energy efficiency and reduce carbon footprints (Chen et al., 2019). ShipNetSim's ability to simulate these complex interactions and provide real-time feedback on energy consumption and emissions makes it a valuable tool for both researchers and policymakers.

ShipNetSim represents a significant advancement in maritime simulation technology, offering a comprehensive platform that integrates ship propulsion, resistance, and interaction dynamics within a single framework. Its emphasis on computational efficiency, adaptability, and real-time energy consumption modeling makes it an essential tool for advancing maritime research and informing policy development. As the industry continues to evolve in response to environmental and economic pressures, ShipNetSim will play a crucial role in guiding the transition toward more sustainable and efficient maritime operations.

The following sections of this report will delve deeper into the existing literature on maritime simulation tools, highlighting the specific gaps that ShipNetSim addresses. We will then present the mathematical models and simulation framework that underpin ShipNetSim, followed by a detailed description of its architecture and operational capabilities. Case studies will be used to validate the performance of the simulator, demonstrating its applicability to real-world maritime challenges. The report will conclude with a discussion of future enhancements to ShipNetSim, as well as its broader implications for maritime research and policy development.

[1] NeTrainSim is an open-source simulator developed by researchers at Virginia Tech (VT) with experties from Deutsch Bahn (DB) and North Carolina State University (NCSU) (A. S. Aredah et al., 2024). Interested readers can access the simulator and its source code from https://github.com/VTTI-CSM/NeTrainSim

[2] INTEGRATION is a freeware developed by researchers at Virginia Tech (VT). Interested readers can get a free copy from https://github.com/VTTI-CSM/INTEGRATION

Literature Review

The development of maritime simulation tools has seen substantial progress over the past few decades, driven by the need to enhance the safety, efficiency, and environmental sustainability of maritime operations. This literature review synthesizes key research advancements in maritime simulation, focusing on the evolution of ship simulators, the integration of energy consumption and emissions modeling, and the application of these tools in route optimization and policy development. The review highlights the gaps in existing technologies and the need for comprehensive simulators like ShipNetSim.

Evolution of Ship Simulators

The evolution of ship simulators has closely followed advancements in computational technology and the increasing complexity of maritime operations. Historically, early ship simulations were rudimentary, often relying on physical scale models tested in wave tanks. These physical models were instrumental in understanding basic hydrodynamic behavior, but they were limited by scale effects, the inability to simulate a wide range of environmental conditions, and the high costs associated with physical testing. These limitations pushed the maritime industry towards more sophisticated computational methods, leading to significant developments in digital simulation.

Early Computational Simulations

The mid-20th century marked a significant turning point with the advent of digital computers, which allowed for the development of early computational models in maritime simulation. These initial models focused primarily on ship stability and resistance, utilizing two-dimensional analyses that, while groundbreaking at the time, were computationally intensive and limited in scope. A key milestone was the development of linear seakeeping models in the 1960s, which laid the foundation for predicting a ship's response to waves, albeit in a simplified manner (Salvesen et al., 1970).

As computational power grew, so did the complexity of simulations. The introduction of Computational Fluid Dynamics (CFD) in the 1970s and 1980s revolutionized the field, allowing for the three-dimensional (3D) simulation of fluid flows around ship hulls. This was a major leap forward, enabling detailed analyses of hydrodynamic performance, including aspects such as resistance, propulsion, and maneuverability. However, CFD simulations were—and still are—computationally expensive, often requiring significant time and resources to produce results (Jasak et al., 1999).

To address the challenge of computational intensity in resistance analysis, ShipNetSim leverages faster resistance calculation methods such as the Holtrop method, a well-established empirical approach that offers a faster alternative to CFD for resistance calculations. By incorporating this method, ShipNetSim enables quicker simulations without sacrificing the required accuracy necessary for operational decision-making, making it particularly useful in scenarios where time is a critical factor.

Integration of Seakeeping and Maneuvering Simulations

During the 1980s and 1990s, there was a growing recognition of the need to integrate seakeeping and maneuvering simulations. Earlier models had treated these aspects separately due to computational constraints, but advances in technology made it possible to develop more holistic simulations that could capture a ship's behavior across a broader range of conditions. This integration allowed for a more realistic representation of maritime operations, encompassing both calm water and rough sea conditions, as well as complex maneuvers such as turning or emergency stops (Edition et al., 2001).

While ShipNetSim offers basic functionality for seakeeping and maneuvering simulations, its primary strength lies in providing a straightforward and efficient tool for simulating the longitudinal motion of vessels. By focusing on the essentials, ShipNetSim ensures that even with basic seakeeping and maneuvering capabilities, users can achieve meaningful insights into ship behavior without the need for excessively complex or resource-intensive simulations.

Advances in Multi-Ship Simulation

The rise in maritime traffic and the need for coordinated operations in congested waters led to the development of multi-ship simulators in the late 1990s and early 2000s. Early simulators focused on single vessels, which was sufficient for studies of basic hydrodynamics or individual ship handling. However, as maritime operations became more complex, the need to simulate interactions between multiple vessels became increasingly apparent. Developed mathematical models allowed for the modeling of scenarios such as collision avoidance, formation sailing, and coordinated maneuvers in confined waterways, providing valuable insights into the dynamics of ship-to-ship interactions (Miao et al., 2021; Shi et al., 2024; Szlapczynski & Szlapczynska, 2021).

A key feature of ShipNetSim is its ability to enforce a minimum distance between ships, which is crucial for preventing collisions and ensuring safe operations in crowded maritime environments. This capability makes ShipNetSim an effective tool for simulating complex multi-ship interactions.

Integration of Environmental and Energy Efficiency Factors

As the 21st century progressed, the maritime industry faced increasing pressure to reduce its environmental impact, particularly in terms of fuel consumption and emissions. This led to the integration of environmental and energy efficiency factors into ship simulators. Early models focused on the design stage, assessing the potential for fuel savings and emissions reductions through technological innovations. For example, the Ship Impact Model (SIM) developed by (Calleya et al., 2015) was one of the first to assess carbon dioxide reduction technologies at the design stage, highlighting the potential for significant environmental benefits (Calleya et al., 2015).

More operationally focused models soon followed, incorporating real-time data and dynamic environmental conditions to provide more accurate predictions of energy use and emissions. These advancements were driven by the growing demand for tools that could support not just the design of more efficient ships but also the optimization of their operations in real-time (Jensen et al., 2018).

ShipNetSim contributes to this area by incorporating real-time calculations of energy consumption based on fuel use at the engine level. By simulating the fuel consumed by different engines under various operational scenarios, ShipNetSim provides users with valuable insights into the energy efficiency of their operations. This feature is particularly important for evaluating the environmental impact of different operational strategies and making informed decisions that balance efficiency with sustainability.

Current Trends and Future Directions

Today, the field of ship simulation is rapidly advancing with trends such as artificial intelligence (AI), machine learning, and cloud computing poised to revolutionize the industry. These technologies offer the potential to enhance the predictive accuracy of simulators, enabling more adaptive models that can respond to real-time data and changing environmental conditions. Additionally, the use of cloud-based platforms and distributed simulation environments allows for the modeling of large-scale, complex maritime scenarios, supporting global shipping networks and the assessment of new technologies on a global scale (Gammelgaard & Nowicka, 2024).

While ShipNetSim currently focuses on providing a robust and efficient platform for traditional simulations, there are plans to incorporate these cutting-edge technologies in future updates. The integration of AI, machine learning, and cloud computing will enable ShipNetSim to handle even more complex simulations, offering the ability to conduct large-scale, distributed simulations. These enhancements will further solidify ShipNetSim's role as a leading tool in the evolution of maritime simulation technology.

Integration of Energy Consumption and Emissions Modeling

The integration of energy consumption and emissions modeling into ship simulators has become increasingly critical as the maritime industry strives to meet stringent environmental regulations and improve operational efficiency. The International Maritime Organization (IMO) has played a significant role in driving these efforts, particularly through the introduction of the Energy Efficiency Design Index (EEDI) and the Carbon Intensity Indicator (CII), which mandate reductions in carbon emissions and improvements in fuel efficiency across the global fleet.

Early Approaches to Energy and Emissions Modeling

Initially, efforts to model energy consumption and emissions in maritime operations were largely focused on statistical and empirical methods that could predict fuel usage under specific conditions. These models typically employed multiple linear regression techniques based on historical data, enabling ship operators to estimate fuel consumption and CO_2 emissions with reasonable accuracy. For instance, a study by Bocchetti et al. (2015) developed a statistical approach for monitoring ship fuel consumption, which could alert management to potential inefficiencies by comparing predicted and actual fuel usage. This model was particularly effective in accounting for factors like hull and propeller fouling, which can significantly impact fuel efficiency (Bocchetti et al., 2015).

Advancements in Real-Time Modeling

As technology advanced, there was a growing need to incorporate real-time data into energy consumption models to provide more accurate and dynamic assessments of a ship's environmental impact. Luo and Wang (2017) explored the integration of solvent-based carbon capture systems with marine diesel engines, demonstrating the potential for reducing CO_2 emissions by up to 90% when additional energy utilities were incorporated. Their research highlighted the importance of considering the entire ship energy system, including the interactions between propulsion and emissions reduction technologies, to achieve meaningful reductions in greenhouse gases (Luo & Wang, 2017).

Similarly, Erto et al. (2015) developed a procedure for predicting and controlling ship fuel consumption using real-time navigation data. This model moved beyond traditional Speed-Power curves by incorporating multiple regression analyses based on dynamic operational data, allowing for more precise adjustments to improve energy efficiency and reduce emissions in real time (Erto et al., 2015).

Innovative Techniques and Optimization Models

Recent studies have further refined these models by incorporating advanced simulation and optimization techniques. For example, a study by Yang et al. (2019) introduced a genetic algorithm-based grey-box model (GA-GBM) for predicting ship fuel consumption, which combined principles of ship propulsion with advanced optimization algorithms to achieve higher accuracy, particularly in varying weather conditions. This model was validated using real-world operational data, demonstrating its potential to significantly improve fuel efficiency and reduce greenhouse gas emissions (Yang et al., 2019).

Additionally, Thiaucourt et al. (2022) investigated the effectiveness of alternative engine control strategies in head wave conditions. By coupling engine models with ship simulators, they were able to demonstrate that innovative control approaches, such as constant fuel rack strategies, could reduce fuel consumption by up to 1.6%, offering a promising avenue for further reductions in maritime greenhouse gas emissions (Thiaucourt et al., 2022).

ShipNetSim's Contribution

ShipNetSim builds on these advancements by providing a comprehensive platform that integrates real-time energy consumption and emissions modeling into its simulation framework. By leveraging established methods such as the Holtrop resistance analysis and incorporating dynamic environmental inputs, ShipNetSim offers users the ability to assess the environmental impact of their operations in real-time. This capability is particularly valuable for evaluating the effectiveness of different operational strategies, such as route optimization and speed adjustments, in reducing fuel consumption and emissions.

Moreover, ShipNetSim's modular design allows for continuous updates and enhancements, ensuring that it can incorporate the latest developments in energy efficiency and emissions reduction technologies. This makes it an indispensable tool for both researchers and policymakers seeking to develop and implement more sustainable maritime practices.

Route Optimization and Real-Time Simulation

The integration of route optimization and real-time simulation has become increasingly critical in maritime operations, particularly for improving energy efficiency and reducing emissions. These technologies have evolved significantly, driven by the need to optimize fuel consumption and minimize the environmental impact of shipping activities. This section explores the historical context, advancements in optimization techniques, real-time data integration, and the contributions of ShipNetSim in this domain.

Historical Context and Early Developments

Historically, route optimization in maritime transport was primarily focused on finding the shortest or most economical route, with little consideration given to real-time environmental factors. This approach, while beneficial for basic navigation, often led to suboptimal performance in terms of energy efficiency and emissions reduction. Early models did not account for dynamic changes in weather conditions or the impact of external forces such as wind, waves, and currents.

Advancements in Real-Time Data Integration

The integration of real-time data into route optimization models marked a significant advancement, allowing for continuous adjustment of a vessel's route based on current environmental conditions. This has proven to be a game-changer in maritime operations. Cammin et al. (2020) emphasized the importance of real-time data in reducing emissions in maritime ports by enhancing operational efficiency. Their study demonstrated how real-time data could be used to improve both landside and seaside operations, significantly reducing fuel consumption and emissions (Cammin et al., 2020).

Further advancements were seen in the work by Wang et al. (2016), who developed a real-time optimization model for ship energy efficiency. Their model predicts the optimal navigation speed under varying environmental conditions, enabling real-time adjustments that optimize fuel consumption and reduce emissions. This model, based on wavelet neural networks, allows ships to adjust their engine speed in response to real-time predictions of environmental changes, ensuring optimal energy efficiency throughout the voyage (Wang et al., 2016).

Optimization Techniques and Algorithms

As route optimization has become more sophisticated, so too have the algorithms and techniques used to achieve it. A notable example is the Dynamic Programming (DP) approach, which has been employed to create optimal speed adjustment plans for ships navigating specific routes. Kim and Lee (2018) introduced a DP-based method that utilizes big data from ship status, marine environmental conditions, and speed changes to build optimal speed adjustment plans. This approach allows ships to exploit external forces such as tidal currents and wind to reduce fuel consumption and emissions (Kim & Lee, 2018).

Another significant development is the use of Model Predictive Control (MPC) for dynamic optimization. Wang et al. (2018) demonstrated how MPC could be used to optimize ship energy efficiency by dynamically adjusting sailing speeds in response to time-varying environmental factors. This method significantly improves energy efficiency and reduces CO_2 emissions, particularly in situations where weather conditions change frequently over the length of a ship's route (Wang et al., 2018).

Real-Time Simulation and Dynamic Optimization

Real-time simulation, when combined with dynamic optimization techniques, provides a powerful tool for managing energy consumption and emissions in maritime operations. For example, Kobayashi et al. (2015) proposed a weather-routing optimization technology that focuses on minimizing fuel consumption and the Energy Efficiency Operational Indicator (EEOI) during voyages. By performing a full maneuvering simulation that accounts for wind, wave, and current conditions, this method provides an optimized route that significantly reduces fuel consumption compared to traditional great circle routes (Kobayashi et al., 2015).

Similarly, Li et al. (2022) proposed a route segmentation and weather loading-speed optimization algorithm that improves the reliability of speed optimization results. This approach effectively reduces the difference between optimized fuel consumption and actual fuel consumption, achieving a fuel-saving rate between 2.1% and 5.2%. By integrating real-time weather data, the model allows ships to adjust their speed and route dynamically, optimizing fuel efficiency (X. Li et al., 2022).

ShipNetSim's Contribution

ShipNetSim builds on these advancements by offering real-time simulations that incorporate dynamic environmental conditions such as wind, waves, and currents. By simulating the entire journey of a ship and providing real-time feedback on energy consumption and emissions, ShipNetSim enables more effective route planning and operational decision-making. This capability is particularly valuable for large-scale maritime operations, where the efficiency of individual vessels can significantly impact the overall performance of a fleet.

Policy Development and Environmental Impact

The intersection of maritime policy development and environmental impact has become a focal point in the shipping industry, driven by the urgent need to reduce greenhouse gas (GHG) emissions and improve energy efficiency. The International Maritime Organization (IMO) and other regulatory bodies have introduced a range of policies aimed at mitigating the environmental impact of shipping activities. This section delves into the evolution of these policies, the effectiveness of various emission reduction strategies, and the role of ShipNetSim in supporting these initiatives.

Evolution of Maritime Environmental Policies

The IMO has been at the forefront of maritime environmental regulation, with a particular focus on reducing GHG emissions. The Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI) are two key instruments introduced by the IMO to regulate the environmental performance of ships. The EEDI, established in 2013, mandates a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types and sizes. The EEOI, on the other hand, provides a mechanism for assessing the operational energy efficiency of a ship over a specific period, thereby encouraging continuous improvement in ship operations.

According to Wada et al. (2021), while these regulations have been effective in setting benchmarks for energy efficiency, their impact on overall GHG reduction has been mixed. The study highlights that while EEDI has prompted some innovation in ship design, its impact is limited by the slow adoption of new technologies. The EEOI has proven more effective in driving operational improvements, but its success largely depends on the commitment of shipping companies to implement energy-saving measures during voyages (Wada et al., 2021).

Effectiveness of Emission Reduction Strategies

Various strategies have been employed to reduce emissions from shipping, with slow steaming and fuel switching being among the most widely adopted. Slow steaming, the practice of operating ships at lower speeds, has been particularly effective in reducing CO_2 emissions, as demonstrated in studies by Elkafas and Shouman (2021). Their research indicates that a reduction in ship speed by 12.6% can lead to a 36% decrease in CO_2 emissions, showcasing the significant impact of operational measures on environmental performance (Elkafas & Shouman, 2021).

However, the success of these measures is not without challenges. As noted by Lindstad and Eskeland (2016), the global application of regulations designed for Emission Control Areas (ECAs) may not always yield the intended environmental benefits. Their study found that while stricter SOx and NOx limits in ECAs have led to significant reductions in local air pollution, extending these regulations globally could have unintended consequences, such as increased fuel consumption due to the adoption of energy-intensive end-of-pipe solutions like scrubbers (Lindstad & Eskeland, 2016).

Role of ShipNetSim in Policy Development

ShipNetSim plays a critical role in supporting the development and implementation of maritime environmental policies. By providing a comprehensive simulation platform that models the entire lifecycle of ship operations, including energy consumption and emissions, ShipNetSim offers valuable insights for policymakers. For instance, the tool can simulate the impact of different speed reduction scenarios, fuel types, and operational strategies on a ship's environmental footprint, helping to identify the most effective measures for reducing emissions.

Moreover, ShipNetSim’s ability to integrate real-time data and simulate various environmental conditions makes it an indispensable tool for evaluating the long-term effectiveness of policies like the EEDI and EEOI. As noted by Rony et al. (2019), the success of these policies depends heavily on the accuracy and quality of the data collected. ShipNetSim's robust data integration capabilities ensure that simulations are based on the most current and accurate information, thereby enhancing the reliability of policy assessments (Rony et al., 2019).

Future Directions and Challenges

Looking ahead, the shipping industry faces several challenges in its quest to meet increasingly stringent environmental regulations. The transition to zero-emission ships, as discussed by Vakili et al. (2022), represents a significant challenge, particularly in terms of the upfront investment required for new technologies and the development of supporting infrastructure. ShipNetSim can support this transition by simulating the performance of various zero-emission technologies under different operational scenarios, providing stakeholders with the data needed to make informed decisions (Vakili et al., 2022).

Gaps in Current Research and the Role of ShipNetSim

Despite the significant advancements in maritime simulation technology, there remain notable gaps in current research that limit the effectiveness and comprehensiveness of existing simulators. These gaps are particularly evident in areas such as the scalability of simulations and the ability to simulate complex multi-ship interactions under dynamic environmental conditions.

Scalability of Simulations

One of the critical challenges in maritime simulation is the scalability of simulations. Many existing maritime simulators are limited in their ability to scale up to accommodate large, complex operations involving multiple vessels. This limitation hinders the ability to conduct comprehensive studies on fleet operations or large-scale maritime exercises. According to Reiher and Hahn (2021), while there have been efforts to develop scenario-based validation and verification approaches for automated and autonomous maritime systems, the scalability of these systems remains a significant challenge, especially when dealing with the complexities of multi-vessel interactions (Reiher & Hahn, 2021).

ShipNetSim tackles this issue by offering scalable multi-ship simulation capabilities, enabling users to simulate interactions between multiple vessels in various operational scenarios. This scalability is crucial for understanding the dynamics of fleet operations and for developing strategies to optimize performance across large maritime networks.

Complex Multi-Ship Interactions

The ability to simulate complex multi-ship interactions under varying environmental conditions is another area where current maritime simulators fall short. Traditional simulators often lack the sophistication needed to accurately model the intricate dynamics of vessel interactions, particularly in congested or high-risk environments. Carson (2011) highlights the need for improved simulation tools that can model the full range of interactions and their potential impacts on maritime safety and operational efficiency (Carson, 2011).

ShipNetSim addresses this by incorporating advanced algorithms that simulate complex interactions between multiple vessels, considering factors such as collision avoidance, formation sailing, and coordinated maneuvers in confined waterways (a feature for a future release). This capability is particularly important for simulating scenarios in busy ports or narrow channels, where the margin for error is minimal.

The Role of ShipNetSim

ShipNetSim plays a pivotal role in addressing these gaps by providing a comprehensive simulation platform that integrates real-time data, offers scalable simulation capabilities, and accurately models complex multi-ship interactions. Its open-source nature allows for continuous updates and improvements, ensuring that it remains at the forefront of maritime simulation technology. By filling these critical gaps, ShipNetSim not only enhances the accuracy and applicability of maritime simulations but also supports the development of more effective and sustainable maritime operations.

Simulation Model

The simulation model in ShipNetSim is designed to address critical gaps in maritime simulation, particularly in integrating dynamic environmental conditions and scalable multi-ship interactions. This section details the key components of ShipNetSim's simulation model, including propulsion-resistance models, ship coexistence models, and pathfinding algorithms, each developed based on existing research while addressing identified needs for more comprehensive simulation tools. Table (1) lists all the variables definitions used in the model.

Table 1. Model Variables Definition

Variable	Definition
$\tilde{a}_n(t)$	Smoothed acceleration of ship n at instant t (m/s^2)
$a_n(t)$	Acceleration of ship n at instant t (m/s^2)
β	Ship Beam in m
$FCS_n(t)$	Fuel cell status of ship n in time t (%)
$FD_{Fuel\ Type\|n}(t)$	Fuel depletion of fuel type for ship n in time t
$F_{t\|n}(t)$	Propulsion force of ship n at instant t (N)
$Fr(t)$	The Froude number at instant t
P^{max}	Maximum engine power of the main engine (kW)
T_n	The time it takes to deactivate the propulsion thrust or revert the propeller rotating direction plus the operator perception reaction time (s)
L_{pp}	The ship length between perpendiculars (m)
m	The total mass of the vessel (kg)
$R_{t\|n}(t)$	Total Resistive forces on ship n at instant t (N)
$R_{CALM}(t)$	The calm water resistance component on ship n at instant t (N)
$R_{AW}(t)(\omega(t)\ \|u(t), \beta(t))$	The added resistance component on ship n due to waves of frequency Ω and wave heading angle β at instant t
$R_{awr}(t)(\omega(t)\ \|u(t), \beta(t))$	The added resistance component on ship n due to wave reflection with wave frequency Ω and wave heading angle β at instant n
$R_{awm}(t)(\omega(t)\ \|u(t), \beta(t))$	The added resistance component on ship n due to the ship motion with wave frequency Ω and wave heading angle β at instant n
$R_{awr}(t)(\omega(t)\ \|u(t), 0)$	The added resistance component on ship n due to wave reflection with wave frequency Ω and wave heading angle β in the longitudinal heading direction at instant n
$R_{awm}(t)(\omega(t)\ \|u(t), 0)$	The added resistance component on ship n due to the ship motion with wave frequency Ω and wave heading angle β in the longitudinal heading direction at instant n
$R_{AA}(t)$	The added resistance component on ship n due to wind at instant n

Variable	Definition
$R_F(t)$	The calm-water frictional resistance component on ship n at instant n
$R_w(t)$	The calm-water wave-making resistance component on ship n at instant n
$R_{bw}(t)$	The calm-water bulbous bow resistance component on ship n at instant n
$R_{TR}(t)$	The calm-water transom resistance component on ship n at instant n
$R_A(t)$	The calm-water model correction resistance component on ship n at instant n
k_1	The form factor of the ship
ρ_A	The air density in (kg/m^3)
C_{AA}	The wind resultant resistance coefficients $(of\ C_{AA\|x})$ and $(of\ C_{AA\|y})$ for various wind heading angles ψ
$C_{AA\|x}$	The wind resistance coefficients in the longitudinal direction for various wind heading angles ψ
$C_{AA\|y}$	The wind resistance coefficients in the lateral direction for various wind heading angles ψ
$\psi(t)$	The heading angle of the wind at instant n
A_{xv}	The transverse projected area above the waterline including superstructures in (m^2)
$V_{WR}^2(t)$	The relative wind speed at instant n
$X_i, \& Y_i, i \in [0, \dots 5]$	The coefficients for estimating (C_{AA})
$S_n(t)$	Spacing from the stern of ship n to the stern of the ship (n-1) is computed as $(x_{n-1}(t) - x_n(t))$ (m)
S_n^t	Most tight spacing (m). Equal to the length of ship n plus a buffer (taken to be the length of the ship)
t_1, t_2, t_3	Calibration parameters for the throttle input level
$u_d(t)$	Desired speed or max speed a ship can travel at instant t (m/s)
u_f	Maximum speed of the environment the ship is in (km/h)
$u_m(t)$	Ship speed at maximum throttle at instant t (m/s)
$u_n(t)$	Speed of Ship n at instant t (m/s)
λ^*	Throttle level that equates resistance forces at instance t $(0 \leq \lambda \leq 1)$
$\lambda(t)$	Throttle level at instant t $(0 \leq \lambda \leq 1)$
Δt	The solution time step (s)
g	Gravitational acceleration (9.8066 m/s^2)
η_n	Mechanical efficiency of the main engine of the ship n
$\delta_n(t)$	Rudder angle of ship n at time n
$z(t)$	Depth from sea level at instant n (m)
$\zeta_a(t)$	The wave amplitude at instant n (m)

Propulsion-Resistance Models

This section is based mainly on the work done by Tavakoli et al. (2021), in which calm-water ship resistances are calculated using the Holtrop method and the performance of the propeller is modeled using the B-Series thrust and torque coefficients (the user has the flexibility to use custom coefficients). In addition to the calm water resistance, the wave and wind resistances are estimated using the models proposed by Fujiwara et al. (1998) and Lang & Mao (2020).

The total resistance $R_t(t)$ on the ship at time t is divided into the calm-water resistance $R_{CALM}(t)$, added resistance due to wave $R_{AW}\big(\omega(t)\big|u(t),\beta(t)\big)$ and wind $R_{AA}(t)$:

$$R_{t|n}(t) = R_{CALM}(t) + R_{AW}\big(\omega(t)\big|u(t),\beta(t)\big) + R_{AA}(t) \tag{1}$$

Where $\omega(t), u(t), and\ \beta(t)$ are the wave frequency in Hz, vessel speed in m/s, and the wave relative heading angle respectively.

$$R_{CALM}(t) = R_F(t)\cdot(1+k_1) + R_W(t) + R_B(t) + R_{TR} + R_A(t) \tag{2}$$

Where $R_F(t),\ R_W(t),\ R_B(t),\ R_{TR},\ R_A(t)$ are the frictional, wave-making, bulbous bow, transom, and model correction resistances respectively at time t. k_1 is the form factor of the ship.

The added resistance due to wind $R_{AA}(t)$ is dependent on the area of structure above the waterline as well as the relative wind speed (Lewis, 1988). The R_{AA} is estimated using Equation (3) provided by (Ships, 2015).

$$R_{AA}(t) = \frac{1}{2}\rho_A C_{AA}\psi(t) A_{XV} V_{WR}^2 \tag{3}$$

where ρ_A is the air density in kg/m^3, A_{XV} is the transverse projected area above the waterline including superstructures in m^2, V_{WR} is the relative wind speed in m/s, ψ is the relative wind direction, C_{AA} are the wind resistance coefficients for various heading angles. The C_{AA} is estimated using the equation below provided by (Fujiwara et al., 1998):

$$\begin{aligned} C_{AA|X} &= X_0 + X_1\cos\ \psi + X_3\cos\ 3\psi + X_5\cos\ 5\psi \\ C_{AA|Y} &= Y_1\sin\ \psi + Y_3\sin\ 3\psi + Y_5\sin\ 5\psi \end{aligned} \tag{4}$$

Where $C_{AA|X}$ and $C_{AA|Y}$ are the wind resistance coefficients in longitudinal and lateral directions.

For the wave resistance prediction, we use the model proposed by (Lang & Mao, 2020; Ships, 2015). However, since the ShipNetSim adopts a modular structure framework, using any other prediction model is also feasible. The total added wave resistance is a sum of two components, added resistance due to wave reflection $R_{AW\,r}(\omega(t)|u(t),\beta(t))$, and due to ship motion $R_{aw\,m}(\omega(t)|u(t),\beta(t))$ (Moran, 1973) and can be expressed as follows:

$$R_{AW}(t) = R_{awr}(\omega(t)|u(t),\beta(t)) + R_{awm}(\omega(t)|u(t),\beta(t)) \tag{5}$$

$$R_{awr}\big(\omega(t)\big|u(t),\beta(t)\big) = R_{awr}(\omega(t)|u(t),0)\cdot Fr(t)^{X}\cos\beta(t)\,,$$
$$where\ X = \begin{cases} (\lfloor z(t)\cos\beta(t)\rfloor - \lceil\cos\ \beta(t)\rceil)Fr(t), & \text{for } 0\le\beta(t)\le\frac{\pi}{2} \\ -1.5(\lfloor\cos\ \beta(t)\rfloor + \lceil\cos\ \beta(t)\rceil)Fr(t), & \text{for } \frac{\pi}{2}<\beta(t)\le\pi \end{cases} \quad (6)$$

and the added resistance component due to ship motions is calculated as:

$$R_{awm}(\omega(t)\mid u(t),\beta(t)) = R_{awm}(\omega(t)\mid u(t),0)\cdot e^{-(\frac{\beta(t)}{\pi})^{4\sqrt{Fr}}} + \rho_w g\zeta_a(t)^2B^2/L_{pp}[\frac{\lambda(t)}{B}\cdot max(\cos\ \beta(t),0.45)]^{-6Fr}\sin\ \beta \quad (7)$$

On the other hand, values for thrust force and torque generated by the propeller, rotating with a speed of n, are required in order to solve equations of motion in the surge direction. B-series is assumed to calculate the thrust and torque coefficients. The thrust coefficient is calculated as:

$$K_T = \frac{T_p}{\rho_w n^2 D^4} \quad (8)$$

The Torque coefficient is defined as:

$$K_Q = \frac{Q_p}{\rho_w n^2 D^5} \quad (9)$$

Where D is the propeller diameter in (m), $\backslash rho_W$ is the water density in (kg/m^3), n is the rotational speed of the propeller (rad/s). The efficiency of the propeller is calculated by:

$$\eta = \frac{K_t}{K_Q}\frac{J}{2\pi} \quad (10)$$

The propulsion force on the ship is computed using Equation (11). The model includes the basic propulsion forces and the maximum force that can be sustained. The throttle function is discretized as described previously.

$$F_t(t) = \sum_l (\frac{1000\eta_n\lambda(t)P_l^{max}}{u(t)}) \quad (11)$$

Where P_l^{max} is the maximum power of the engine(s) and where the power is set to the economic power of the engine which corresponds to power point L2 in the engine layout curve (See Figure 1). However, if the ship speed is reduced by 20% of the max speed due to high resistance, the engine moves to higher engine power points (L3 or L1) sequentially. In addition, λ is the thrust level and is calculated by:

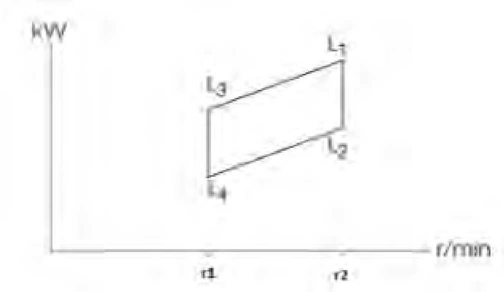

Figure 1: Engine Layout Curve

$$\lambda_n(t) = \begin{cases} \dfrac{\dfrac{u_n(t)}{u_d(t)}}{t_1 + \dfrac{t_2}{1 - \dfrac{u_n(t)}{u_d(t)}} + t_3 \dfrac{u_n(t)}{u_d(t)}}, & 0 \leqslant u_n(t) \leqslant u_m(t) \\ max(\dfrac{\dfrac{u_n(t)}{u_d(t)}}{t_1 + \dfrac{t_2}{1 - \dfrac{u_n(t)}{u_d(t)}} + t_3 \dfrac{u_n(t)}{u_d(t)}}, \lambda^*), & u_m(t) \leqslant u_n(t) \leqslant u_d(t) \end{cases} \quad (12)$$

Where variables t_1, t_2 and t_3 are calibrated parameters that were originally introduced in (Fadhloun & Rakha, 2020). These parameters are calculated based on the fact that vehicles almost never run at full capability or capacity. However, in ships, this does not apply since we account for it by applying dynamic P_l^{max}. Accordingly, these parameters are calibrated to reflect full usage of the ship power. The proposed values are 0.001, 0.050, and 0.030 respectively.

Ship Motion and Coexisting Models

This section is dedicated to proposing a model for ship-following dynamics, which encompasses the integration of external force vectors, including resistive and throttle forces. Furthermore, the model accounts for the operator's perceptual latency and the temporal lag inherent in the ships' stopping system actuation. The resultant formulation yields a temporal profile of the ships' acceleration as a function of the inter-ship spacing and the relative velocities of both the following and leading ships at discrete time intervals.

The max ship acceleration $a_n^{max}(t)$ is computed using the below equation as the difference between the total propulsion force ($F_n(t)$) and the total resistance forces ($R_n(t)$) relative to the total mass (m_n).

$$a^{max}(t) = \frac{F_t(t) - R_t(t)}{m} \quad (13)$$

The total mass of the ship is the summation of the vessel's total weight and the surge-added mass due to the ship's movement. Research done by (Zeraatgar et al., 2020), found that the surge in added mass could be estimated by:

$$x_{\dot{u}} = \rho \cdot \nabla \cdot K_1 \tag{14}$$

Where ∇ is the displacement volume of the ship, k_1 is the added mass coefficient and can be calculated by:

$$K_1 = \frac{\alpha_0}{2 - \alpha_0} \tag{15}$$

Where:

$$\alpha_0 = \frac{2(1 - e^2)}{e^3}[0.5\ln(\frac{1 + e}{1 - e}) - e] \tag{16}$$

and the eccentricity (e) is estimated by:

$$e = \sqrt{1 - \frac{\frac{3\nabla}{2\pi L/2}}{(L/2)^2}} \tag{17}$$

We use a simple linear ship-following model to compute the safe spacing between ships at steady-state conditions, (s) using:

$$s_n(t) = s_n^j + T_n u_n(t) \tag{18}$$

Here, s_n^j is the spacing when stopped, which is taken to be twice the length of the ship n; T_n is the time it takes to deactivate the propulsion thrust or revert the propeller rotating direction plus the operator perception reaction time, t_{pr} and $u_n\ (t)$ is the ship's velocity. T_n is estimated using:

$$T_n = \frac{L_c^{max}}{u_s} + t_{pr} \tag{19}$$

Where L_c^{max} is the longest distance the thrust reduction signal needs to travel from the controlling room and is taken to be half the ship's length. The signal is assumed to travel at the speed of sound u_s taken to be 343 m/s. t_{pr} is the operator perception reaction time (taken to be 3.0s) for small boats and 10.0s for larger ships but can be user-specified). Using Equation (18), the terms are re-arranged to estimate the ship following speed the next time step based on the current spacing, as demonstrated below:

$$\tilde{u}_n(t + \Delta t) = min(\frac{s_n(t) - s_n^j}{T_n}, u_f) \tag{20}$$

Here u_f is the maximum velocity the ship is allowed to travel at in this region. The time-to-collision (TTC) is computed assuming the ship continues at its current speed, as shown below:

$$TTC = min(\frac{s_n(t) - s_n^j}{max(u_n(t) - u_{n-1}(t), 0.0001)}, TTC_{max}) \quad (21)$$

The desired acceleration, at some time into the future using the spacing at time t and incorporating it in the range policy presented in Equation (20), is computed twice. First assuming the speed is achieved over a time interval TTC (Equation (22)) and the second is assumed to occur over a time interval T_n (Equation (24)).

$$a_{n,1-1}(t) = max(\frac{\tilde{u}_n(t + \Delta t) - u_n(t)}{TTC}, -d_{max}) \quad (22)$$

Where d_{max} is the max deceleration level the ship can achieve by water resistance and/or reverse thrust and is estimated by:

$$d_{max} = \frac{R_t(t) + \beta_0 F_t(t)}{m} \quad (23)$$

where β_0 is a binary term that indicates a reverse thrust availability in the ship in case of 1 and 0 if vice versa.

$$a_{n,1-2}(t) = min(\frac{\tilde{u}_n(t + \Delta t) - u_n(t)}{T_n}, a_n^{max}(t)) \quad (24)$$

We then compute the ship acceleration as a weighted combination of the two accelerations, where the term (β_1) is computed using Equation (26). The coefficient β_1 is a binary variable that is equal to zero when the acceleration is negative and equals one when the acceleration is either zero or positive. The first acceleration term is used for the ship's negative accelerations (decelerations) while the second term is used for positive accelerations.

$$a_{n,1-3}(t) = (1 - \beta_1)a_{n,1-1}(t) + \beta_1 a_{n,1-2}(t) \quad (25)$$

$$\beta_1 = \frac{a_{n,1-1}(t) + |a_{n,1-1}(t)|}{2 \times max(|a_{n,1-1}(t)|, 0.0001)} \quad (26)$$

An alternate ship acceleration is computed by taking the Lagrangian derivative of Equation (20), as formulated in Equation(27).

$$a_{n,1-4}(t) = max(min(\frac{u_{n-1}(t) - u_n(t)}{T_n}, a_n^{max}(t)), -d_{max}) \quad (27)$$

We then compute the ship acceleration as a weighted combination of these two accelerations, where the term β_2 varies in the range [0,1]. The first acceleration term $a_{n,1-3}(t)$ ensures that the ship spacing between it and the ship ahead complies with the range policy presented in Equation (20). The second acceleration term $a_{n,1-4}(t)$ ensures that the ship adjusts its speed to the speed of the ship directly ahead of it. This is useful in case ships are following each other in a narrow canal similar to the Suez Canal in Egypt.

$$a_{n,1}(t) = \beta_2 a_{n,1-3}(t) + (1-\beta_2) a_{n,1-4}(t) \tag{28}$$

The complete ship longitudinal motion model is a modification of the Fadhloun-Rakha car-following model (Fadhloun & Rakha, 2020) that is formulated in the equation below. The first term computes the ship's acceleration when the speed of the ship ahead of it is greater than or equal to its speed while the second term computes the ship's acceleration while approaching a slower-moving ship. It ensures that the ship attempts to decelerate at the desired deceleration level (d_{max}). Again the (γ) term is a binary variable that is either 0 or 1. It equals zero if the speed of the ship ahead is greater than or equal to the subject ship's speed and is 1 if the speed of the ship ahead is less than the subject ship's speed.

$$a_n(t) = (1-\gamma) a_{(n,1)}(t) - \gamma a_{(n,2)}(t) \tag{29}$$

The other parameters are computed as:

$$a_{n,2}(t) = min(\frac{(u_n(t)^2 - u_{n-1}(t)^2)^2}{4(max(s_n(t) - s_n^j - T_n u_n(t), 0.0001))^2 d_{max}}, d_{max}) \tag{30}$$

$$\gamma = \frac{u_n(t) - u_{n-1}(t) + \sqrt{(u_n(t) - u_{n-1}(t))^2}}{2 \times max(|u_n(t) - u_{n-1}(t)|, 0.0001)} \tag{31}$$

When the ship spacing is greater than (s_{lad}), the movement of the ship is assumed to be free of ship interaction and is achieved using the vehicle dynamics alone, i.e. $a_n^{max}(t)$.

$$s_{lad} = s_{j_{n-1}} + x_{des} + s_n \tag{32}$$

Where the x_{des} is the total length required for the vessel to reach a complete stop from the current speed $v(t)$ due to either only ship resistance (for small boats) or ship resistance and reversed propulsion (for large ships) and is calculated by:

$$x_{des} = \int_{v(t)}^{v(t)=0} (v(t) - d_{max} \cdot \Delta t) \cdot dt \tag{33}$$

The smoothed acceleration $\tilde{a}_n(t)$ is then computed using an exponential smoother, as demonstrated in the equation below. Here α is the exponential smoother. A smoothing factor value of 1.0 provides no smoothing and lower values provide more smoothing.

$$\tilde{a}_n(t) = \alpha \times a_n(t) + (1-\alpha) \times \tilde{a}_n(t) \tag{34}$$

The ship speed is then computed using the first-order Euler approximation:

$$u_n(t + \Delta t) = max(min(u(t) + \tilde{a}(t) \times \Delta t, u_f), 0) \tag{35}$$

In addition to linear motion, ShipNetSim also simulates the rotational dynamics of ships when executing a circular motion. This maneuver is essential for navigating through tight passages or avoiding collisions in busy maritime routes. The rate of turn $ROT_n(t)$ of ship n at time t is calculated based on its current speed and turning radius (TR_n) using the formula:

$$ROT_n(t) = \frac{u_n(t)}{TR_n} \quad (36)$$

Where the TR_n is approximated using the formula:

$$TR_n = \frac{L_{pp}}{\delta_n(t)} \quad (37)$$

Where $\delta_n(t)$ is the rudder angle at time t. The max $ROT_n(t)$ is achieved at $\delta_{n(t)} = 35°$. The simulator dynamically adjusts the rudder angle based on the desired turning angle and the ship's speed. The engine output is assumed to be constant without the deployment of additional maneuvering aids like bow thrusters or kick turns. However, the simulator allows for a custom utilization of maneuvering mathematical models.

Visibility Graph Modelling and Path Finding

The use of visibility graph modeling is a fundamental approach in maritime simulations for efficient and safe navigation, particularly when navigating through complex environments with various obstacles. Visibility graphs, which represent navigable paths as nodes connected by mutually visible edges, simplify the pathfinding process by focusing on direct, collision-free routes. This method has been especially effective in static environments, but its application has expanded to handle more dynamic and complex scenarios.

To ensure accurate distance calculations and optimize pathfinding, ShipNetSim employs the World Geodetic System 1984 (WGS-84), a global reference system for geodetic coordinates. This system is crucial for long-distance maritime navigation as it accurately reflects the Earth's curvature, enabling the simulation to provide precise positioning and geodetic path planning. The use of WGS-84 allows ShipNetSim to simplify the map into points and lines rather than full areas, reducing the computational burden and improving the efficiency of the pathfinding process.

Figure 2: Transformation for depth considerations

In addition to accurate distance modeling, ShipNetSim addresses the challenge of varying water depths, which can pose significant risks during navigation. The simulator dynamically adjusts the shapes on the map—particularly the points and lines representing navigable areas and obstacles—based on real-time depth data, ensuring that vessels avoid shallow areas that could be hazardous. This is done by creating obstacles or adding buffers to existing obstacles (Figure 2). This capability is particularly valuable for large vessels with significant drafts, enabling safer and more efficient route planning.

The primary objective of ShipNetSim's visibility graph module is to plan geodetic paths that consider terrestrial formations and other obstacles between the origin and destination. The visibility graph technique involves creating hypothetical links between vertices or waypoints, with connections only where these points are within mutual visual contact and no obstacles intervene. Typically, a visibility graph constructed in this manner should have approximately $\frac{n(n-1)}{2}$ links, where n is the number of vertices.

Once the visibility graph is constructed, ShipNetSim employs a heuristic shortest path algorithm to identify the most efficient route. The heuristic function is primarily based on spatial distances, allowing for reliable and efficient pathfinding across expansive and complex maritime environments (Figure 3). This function can be adapted to incorporate additional factors, increasing the algorithm's adaptability in various navigational scenarios, such as avoiding high-traffic areas or adjusting to changing weather conditions.

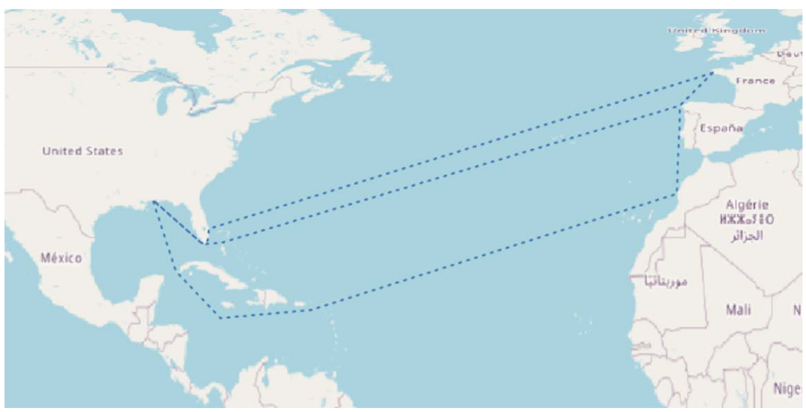

Figure 3: Simplified Visibility Graph between two points

To further enhance the efficiency of path planning, ShipNetSim uses the QuadTree data structure to index vertices and waypoints. The QuadTree excels in dividing two-dimensional space, enabling quick querying, retrieval of points, and faster checking of intersections during the pathfinding process. Each QuadTree node is recursively split into four quadrants until the number of vertices in each section is manageable, typically capped at 50 vertices in ShipNetSim's implementation. This approach significantly reduces the computational complexity involved in constructing visibility graphs and executing shortest-path algorithms, making it an efficient tool for large-scale maritime simulations.

The utility of visibility graphs in maritime pathfinding has been well-documented. For instance, Lazarowska (2019) developed a graph theory-based algorithm that effectively plans ship trajectories in collision-prone situations, demonstrating the importance of visibility graphs in ensuring safe navigation. Similarly, Nuñez et al. (2023) explored the application of spherical visibility graphs for optimal ship routing, highlighting their effectiveness in accounting for the Earth's curvature in long-distance maritime routes. Moreover, J.-H. Li et al. (2017) introduced the concept of a rubber band visibility graph (RBVG), which allows for time-optimal path planning in dynamic and unknown environments, further underscoring the flexibility and adaptability of visibility graph models in complex scenarios.

By integrating these advanced features, ShipNetSim not only addresses the traditional challenges of visibility graph modeling but also enhances the accuracy and efficiency of pathfinding in dynamic and complex maritime environments. This makes it an invaluable tool for both researchers and practitioners seeking to optimize navigation and safety in maritime operations.

Simulator Description

ShipNetSim is an advanced maritime simulation tool designed to model the longitudinal movements of multiple ships within a given water boundary, offering insights into propulsion, resistive forces, and ship interactions. The simulator is built to operate in a dynamic, time-driven environment, where the movements of each vessel are calculated at every time step, enabling precise tracking of travel time, distance, energy consumption, and fuel usage. A key feature of ShipNetSim is its capability to simulate GPS-based localization, which not only facilitates accurate navigation but also allows for the study of cybersecurity threats, such as GPS spoofing attacks, that could disrupt a ship's intended path.

Network Module

The Network Module in ShipNetSim is engineered for rapid pathfinding using a Quadtree data structure. The Quadtree efficiently partitions the simulation space, enabling quick identification of visible paths and significantly reducing computational overhead during pathfinding operations. This approach is particularly beneficial when dealing with complex environments where numerous obstacles must be considered.

Currently, the module focuses on calculating the shortest path between waypoints, ensuring that ships navigate efficiently through the simulated environment. While the current implementation prioritizes minimizing distance, future versions of ShipNetSim are expected to integrate additional parameters such as fuel efficiency, environmental impact, and avoidance of high-risk areas to provide a more comprehensive pathfinding solution.

Regarding dynamic environmental factors, a proposed enhancement could involve real-time updates to the visibility graph based on changing conditions such as tides, currents, and weather patterns. These updates would enable the simulation to more accurately reflect the challenges of maritime navigation, providing a more realistic and adaptable simulation environment.

Ship Dynamics Module

ShipNetSim is designed to accommodate a wide range of ship types, with the ability to simulate various hull designs and engine specifications. However, the current version operates as a one-dimensional (1D) simulator, meaning it focuses solely on longitudinal motion without considering factors such as weight distribution or lateral movement. Despite this, the simulator still provides valuable insights by enforcing a minimum distance between ships, a crucial feature for collision avoidance and maintaining safe operations in congested waterways.

Environmental factors, such as wind and currents, are integrated into the simulation to affect the resistance experienced by each ship, providing a realistic depiction of how external conditions influence ship performance. While ShipNetSim currently handles these dynamics in a simplified manner, future enhancements will explore higher degrees of freedom, incorporating more complex ship behaviors and interactions.

The diagram in Figure 4 illustrates the flow of calculations in the time-step simulation process.

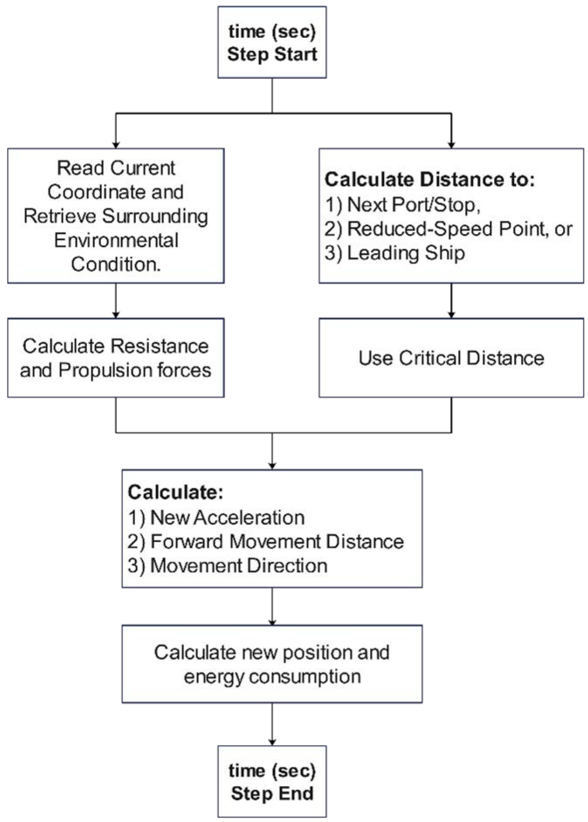

Figure 4: One-time step calculations

Simulator Module

The Simulator Module is the core of ShipNetSim, responsible for synchronizing all calculations and driving the simulation forward. It operates by predicting energy consumption and emissions on a step-by-step basis, ensuring that all ship movements and interactions are accurately reflected in the output data. This approach provides a detailed view of each ship's performance, allowing users to assess operational efficiency and environmental impact in real-time.

To further enhance the accuracy and scalability of the simulation, a proposed improvement could involve the implementation of parallel processing techniques. By distributing computational tasks across multiple processing units, the simulator could maintain its performance even as the number of ships or the complexity of the environment increases.

The overall schema of the simulator's architecture is depicted in Figure 5.

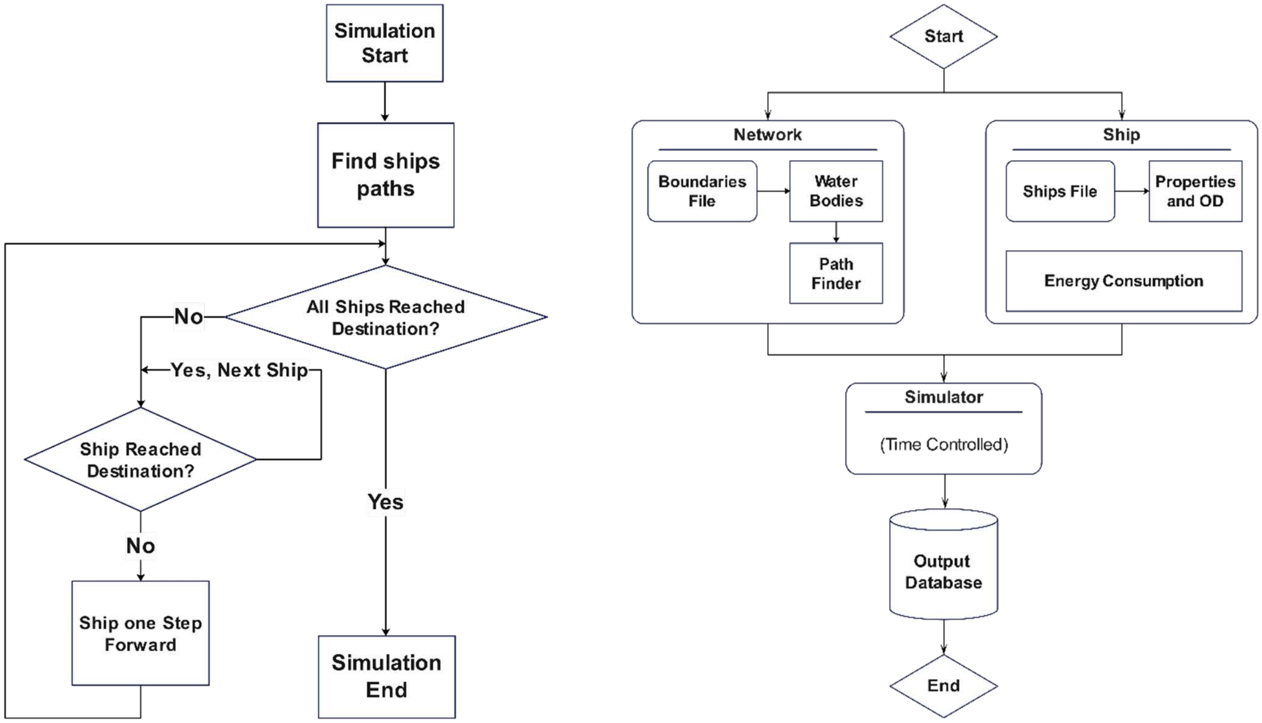

Figure 5: Simulator Schema

Fuel Management

Fuel management in ShipNetSim is governed by maritime policies, particularly those related to Emission Control Areas (ECAs). The simulator is equipped to switch between various fuel types based on geographic location and regulatory requirements, ensuring compliance with emissions regulations. For example, when a ship enters an ECA, the simulator automatically switches from conventional heavy fuel oil (HFO) to a low-sulfur alternative or other compliant fuels, if available.

The simulator models a wide range of fuel types, including Diesel, Heavy Fuel Oil (HFO), Liquefied Natural Gas (LNG), Marine Diesel Oil (MDO), Marine Gas Oil (MGO), Biofuel, and Electric propulsion. Each fuel type is characterized by its specific energy content, emissions profile, and operational limitations, allowing for a detailed analysis of fuel efficiency and environmental impact under different operational scenarios.

Energy Consumption Modeling

ShipNetSim calculates energy consumption in real-time, taking into account factors such as engine load, ship speed, and environmental conditions. This real-time feedback is critical for making informed decisions about route planning, speed adjustments, and fuel switching. By providing precise estimates of energy use, ShipNetSim helps operators optimize their fuel consumption, thereby reducing operational costs and minimizing environmental impact.

Cybersecurity Applications

The simulator also includes functionalities for simulating cybersecurity threats, particularly those related to GPS-based localization. In the event of a cyber attack, such as GPS spoofing, the simulator can model the impact of incorrect location data on a ship's navigation, potentially causing the ship to deviate from its intended route. This capability is crucial for studying the vulnerabilities of maritime navigation systems and developing strategies to mitigate the risks posed by cyber threats.

Regulatory Compliance

Currently, ShipNetSim's regulatory compliance features are focused on fuel switching within Emission Control Areas (ECAs). Users can also manually reduce ship speed in specific zones to comply with local regulations. In future versions, the simulator could be expanded to include more comprehensive compliance features, such as real-time monitoring of emissions and automated adjustments to ship operations based on the latest regulatory requirements.

Computational Efficiency

ShipNetSim is developed in C++ and is compatible with a wide range of operating systems, including Windows, Linux, and macOS. The simulator is designed to be computationally efficient, avoiding memory-intensive operations that could limit its performance on less powerful hardware. However, it is important to note that scaling up the number of ships in the simulation may slow down the processing time. To address this, future enhancements may include the integration of parallel computing techniques to distribute the computational load and maintain simulation speed.

Modularity and Extensibility

The modular structure of ShipNetSim built around a class-based architecture with interfaces in C++, allows for easy integration of plugins and extended functionalities. This design not only facilitates the addition of new features but also ensures that the simulator can evolve to meet the changing needs of the maritime industry. Future updates may introduce new modules for autonomous navigation, real-time weather integration, and alternative propulsion systems, further enhancing the simulator's versatility and application.

Case Study

This section provides a detailed case study utilizing ShipNetSim to model the trajectory and energy consumption of the S175 container ship, traveling from Savannah, United States, to Algeciras, Spain. The case study aims to validate ShipNetSim's capabilities by comparing the simulation's energy consumption results with empirical data reported in the literature.

Ship and Environmental Data Integration

In line with the advancements discussed in the literature review, ShipNetSim is equipped to retrieve real-time environmental data corresponding to the ship's position, which is essential for accurately calculating resistance and other hydrodynamic factors. The environmental data, including wave characteristics and sea conditions, are extracted from geospatial TIFF files provided by the Copernicus Marine Environment Monitoring Service. This integration ensures that the simulation reflects realistic conditions encountered during the voyage, enhancing the accuracy of the resistance and energy consumption calculations.

The S175 container ship, used as the case study vessel, has its characteristics detailed in Table 2. These specifications, including the ship's length, beam, draft, and engine details, are crucial inputs for ShipNetSim's simulation engine. The engine's efficiency curve, depicted in Figure 1, is derived from manufacturer data, ensuring that the simulation accurately represents the ship's propulsion performance under various operational conditions.

Table 2: Ship Characteristics used in the case study

Ship Characteristic	Value
Ship Name	S175
Route	Savannah, U.S. to Algeciras, Spain
Length between perpendiculars (m)	175
Beam (m)	25.4
Average Draft (m)	9.5
Max Speed (knot)	20
Displacement (m^3)	24053
Block Coef	0.561
Prismatic coefficient	0.589
Position of LCG (m)	86.5
Fuel Type	HFO
Engine	6S60ME
Engine MCR @ L1 (kWh)	14940
Engine RPM @ L1	105
Propeller Diam (m)	6.5
Propeller Pitch (m)	9.88
Propeller Blade Count	5
Propeller Expanded Area Ratio	0.8
Weight (ton)	24610.0

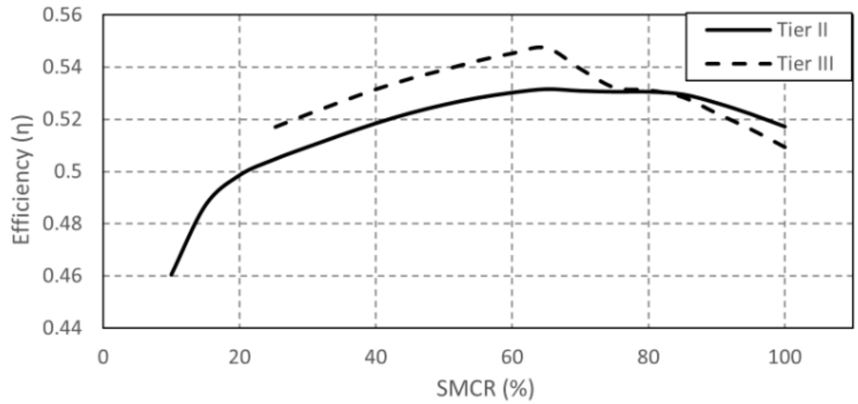

Figure 6: Engine 6S60ME Efficiency

Speed-Resistance Profile and Wave Interaction

ShipNetSim's ability to simulate the speed-resistance profile of the vessel is showcased in Figure 7. The profile illustrates how the ship's speed decreases as resistance increases, particularly when encountering rough sea conditions. This dynamic interaction between speed and resistance is a critical aspect of maritime simulations, as it directly impacts fuel consumption and overall energy efficiency.

The simulation results highlight that as the ship approaches the mid-point of its journey, increased wave resistance leads to a noticeable reduction in speed. This is consistent with the findings in the literature, where the relationship between wave-induced resistance and vessel speed has been extensively studied (Lazarowska, 2019; J.-H. Li et al., 2017).

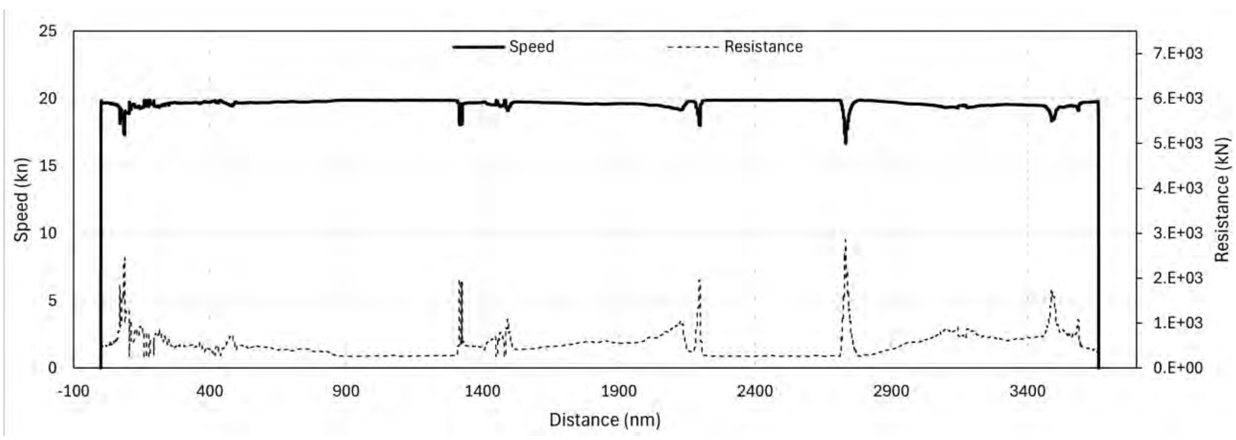

Figure 7: Speed vs Resistance profile of the Ship

Wave Characteristics and Their Impact on Resistance

The impact of wave characteristics, including wavelength and amplitude, on the ship's resistance is clearly illustrated in Figure 8. The figure highlights the fluctuating nature of wave conditions encountered during the voyage. Despite the maximum wavelength being around 90 meters—well below the ship's length of 175 meters—the amplitude of these waves, which reached up to 6 meters, had a pronounced effect on the vessel's resistance.

High wave amplitudes increase the hydrodynamic resistance significantly by enhancing the vertical motion (heaving and pitching) of the ship, which in turn disrupts the flow of water along the hull. This disruption not only increases drag but also forces the ship to consume more energy to maintain speed, as indicated by the spikes in resistance in the speed-resistance profile.

The ShipNetSim model adeptly incorporates these environmental dynamics into its simulations, allowing for accurate prediction and analysis of their effects on ship performance. This capability is particularly valuable for energy consumption modeling and route optimization, where understanding the impact of wave conditions can lead to more informed decision-making. By simulating different scenarios, operators can plan routes that minimize energy use and emissions by avoiding or mitigating the effects of adverse sea conditions. This links back to the literature on the impact of sea states on ship performance (Nuñez et al., 2023)

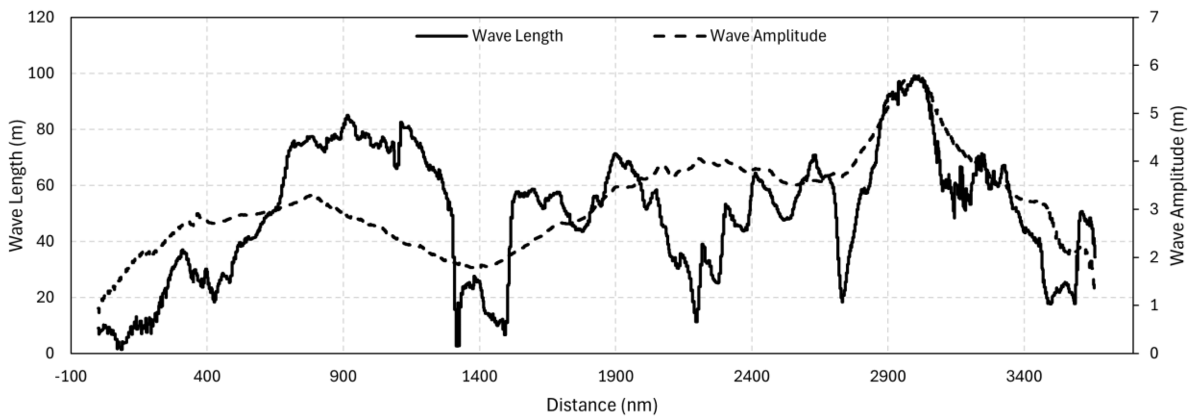

Figure 8: Wave characteristics along ship trajectory

Energy Consumption and Emissions

The case study demonstrates ShipNetSim's proficiency in simulating energy consumption and emissions, a key focus of the simulator's design. The simulation indicates that the ship consumed approximately 474 tons of heavy fuel oil throughout the voyage, resulting in 1,495.305 tons of CO_2 emissions. These results are in close alignment with the empirical data reported by Huotari et al. (2021), which estimated the fuel consumption for a similar voyage to be approximately 550 tons. This consistency validates ShipNetSim's energy consumption model, confirming its reliability for future studies focused on environmental impact and regulatory compliance.

The total energy consumption and emissions data align with the findings in existing literature, reinforcing the simulator's accuracy in replicating real-world conditions (Thiaucourt et al., 2022; Yang et al., 2019).

References

Aredah, A., Du, J., Hegazi, M., List, G., & Rakha, H. A. (2024). Comparative analysis of alternative powertrain technologies in freight trains: A numerical examination towards sustainable rail transport. *Applied Energy*, *356*(August 2023), 122411. https://doi.org/10.1016/j.apenergy.2023.122411

Aredah, A., Fadhloun, K., & Rakha, H. A. (2024). Energy optimization in freight train operations: Algorithmic development and testing. *Applied Energy*, *364*, 123111.

Aredah, A., & Rakha, H. (2024). Goal Programming using the A* Algorithm to Optimize Energy Consumption in Train Operations. *IFAC-PapersOnLine*, *58*(10), 126–133.

Aredah, A. S., Fadhloun, K., & Rakha, H. A. (2024). NeTrainSim: a network-level simulator for modeling freight train longitudinal motion and energy consumption. *Railway Engineering Science*. https://doi.org/10.1007/s40534-024-00331-x

Bocchetti, D., Lepore, A., Palumbo, B., & Vitiello, L. (2015). A Statistical Approach to Ship Fuel Consumption Monitoring. *Journal of Ship Research*, *59*, 162–171. https://doi.org/10.5957/JOSR.59.3.150012

Calleya, J., Pawling, R., & Greig, A. (2015). Ship impact model for technical assessment and selection of Carbon dioxide Reducing Technologies (CRTs). *Ocean Engineering*, *97*, 82–89. https://doi.org/10.1016/J.OCEANENG.2014.12.014

Cammin, P., Sarhani, M., Heilig, L., & Voß, S. (2020). *Applications of Real-Time Data to Reduce Air Emissions in Maritime Ports*. 31–48. https://doi.org/10.1007/978-3-030-49757-6_3

Carson, N. (2011). Modeling and simulation in support of understanding maritime security and defense capabilities and requirements (The maritime timeline and analysis requirements toolset (M-TART)). *2011 IEEE International Conference on Technologies for Homeland Security (HST)*, 43–48. https://doi.org/10.1109/THS.2011.6107845

Chen, C., Chen, X. Q., Ma, F., Zeng, X. J., & Wang, J. (2019). A knowledge-free path planning approach for smart ships based on reinforcement learning. *Ocean Engineering*, *189*, 106299. https://doi.org/10.1016/J.OCEANENG.2019.106299

Edition, F., Journée, J. M. J., & Massie, W. W. (2001). Offshore hydromechanics. *Delft University of Technology*.

Elkafas, A., & Shouman, M. (2021). Assessment of Energy Efficiency and Ship Emissions from Speed Reduction Measures on a Medium Sized Container Ship. *International Journal of Maritime Engineering*. https://doi.org/10.5750/ijme.v163ia3.805

Erdem, C. (2011). Corrigendum to "Identifying the factors affecting the willingness to pay for fuel-efficient vehicles in Turkey: A case of hybrids" [Energy Policy (38) (2010) 3038–3043]. *Energy Policy*, *39*(8), 4673. https://doi.org/10.1016/J.ENPOL.2011.04.042

Erto, P., Lepore, A., Palumbo, B., & Vitiello, L. (2015). A Procedure for Predicting and Controlling the Ship Fuel Consumption: Its Implementation and Test. *Quality and Reliability*

Engineering International, *31*, 1177–1184. https://doi.org/10.1002/qre.1864

Fadhloun, K., & Rakha, H. (2020). A novel vehicle dynamics and human behavior car-following model: Model development and preliminary testing. *International Journal of Transportation Science and Technology*, *9*(1), 14–28. https://doi.org/10.1016/J.IJTST.2019.05.004

Fujiwara, T., Ueno, M., & Nimura, T. (1998). Estimation of Wind Forces and Moments acting on Ships. *Journal of the Society of Naval Architects of Japan*, *1998*(183), 77–90. https://doi.org/10.2534/jjasnaoe1968.1998.77

Gammelgaard, B., & Nowicka, K. (2024). Next generation supply chain management: the impact of cloud computing. *Journal of Enterprise Information Management*, *37*(4), 1140–1160.

Initial IMO GHG Strategy. (n.d.). Retrieved August 25, 2024, from https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

Işıklı, E., Aydın, N., Bilgili, L., & Toprak, A. (2020). Estimating fuel consumption in maritime transport. *Journal of Cleaner Production*, *275*, 124142. https://doi.org/10.1016/J.JCLEPRO.2020.124142

Jasak, H., Weller, H. G., & Gosman, A. D. (1999). High resolution NVD differencing scheme for arbitrarily unstructured meshes. *International Journal for Numerical Methods in Fluids*, *31*(2), 431–449.

Jensen, S., Lützen, M., Mikkelsen, L. L., Rasmussen, H. B., Pedersen, P. V., & Schamby, P. (2018). Energy-efficient operational training in a ship bridge simulator. *Journal of Cleaner Production*, *171*, 175–183. https://doi.org/10.1016/J.JCLEPRO.2017.10.026

Kim, K.-I., & Lee, K.-M. (2018). Dynamic Programming-Based Vessel Speed Adjustment for Energy Saving and Emission Reduction. *Energies*, *11*, 1273. https://doi.org/10.3390/EN11051273

Kobayashi, E., Hashimoto, H., Taniguchi, Y., & Yoneda, S. (2015). Advanced optimized weather routing for an ocean-going vessel. *2015 International Association of Institutes of Navigation World Congress (IAIN)*, 1–8. https://doi.org/10.1109/IAIN.2015.7352247

Lang, X., & Mao, W. (2020). A semi-empirical model for ship speed loss prediction at head sea and its validation by full-scale measurements. *Ocean Engineering*, *209*, 107494. https://doi.org/10.1016/J.OCEANENG.2020.107494

Lazarowska, A. (2019). An Efficient Graph Theory-Based Algorithm for Ship Trajectory Planning. *International Journal of Maritime Engineering*. https://doi.org/10.3940/rina.ijme.2019.a2.530

Lewis, E. V. (1988). *Principles of Naval Architecture: Volume II - Resistance, Propulsion and Vibration* (second Ed). The Society of Naval Architects and Marine Engineers.

Li, J.-H., Kang, H., Park, G., & Suh, J. (2017). Real Time Path Planning of Underwater Robots in Unknown Environment. *2017 International Conference on Control, Artificial Intelligence, Robotics & Optimization (ICCAIRO)*, 312–318. https://doi.org/10.1109/ICCAIRO.2017.64

Li, X., Sun, B., Jin, J., & Ding, J. (2022). Speed Optimization of Container Ship Considering Route Segmentation and Weather Data Loading: Turning Point-Time Segmentation Method. *Journal of Marine Science and Engineering*. https://doi.org/10.3390/jmse10121835

Lindstad, H., & Eskeland, G. (2016). Environmental regulations in shipping: Policies leaning towards globalization of scrubbers deserve scrutiny. *Transportation Research Part D-Transport and Environment*, *47*, 67–76. https://doi.org/10.1016/J.TRD.2016.05.004

Liu, J., & Duru, O. (2020). Bayesian probabilistic forecasting for ship emissions. *Atmospheric Environment*, *231*, 117540. https://doi.org/10.1016/J.ATMOSENV.2020.117540

Luo, X., & Wang, M. (2017). Study of solvent-based carbon capture for cargo ships through process modelling and simulation. *Applied Energy*, *195*, 402–413. https://doi.org/10.1016/J.APENERGY.2017.03.027

Miao, K., Wang, R., Sun, J., & Deng, H. (2021). Mathematical Model of Ship Collision Avoidance in Narrow Channel Overtaking Situation. *Advances in Intelligent Systems and Computing*, *1304*, 120–127. https://doi.org/10.1007/978-3-030-63784-2_16/FIGURES/3

Mocerino, L., Soares, C. G., Rizzuto, E., Balsamo, F., & Quaranta, F. (2021). Validation of an Emission Model for a Marine Diesel Engine with Data from Sea Operations. *Journal of Marine Science and Application*, *20*(3), 534–545. https://doi.org/10.1007/s11804-021-00227-w

Moran, J. S.-T. H. Y. D. (1973). Added resistance in waves. *The Society of Naval Architects and Marine Engineers*, *81*, 109–143.

Nuñez, A., Kong, F. H., Seiler, K. M., Cantos, A. G., & Fitch, R. (2023). Optimal ship routing via Spherical Visibility Graphs. *OCEANS 2023-Limerick*, 1–6.

Park, H. Y., Han, K., Kim, H. H., Park, S., Jang, J., Yu, G. S., & Ko, J. H. (2020). Comparisons of combustion characteristics between bioliquid and heavy fuel oil combustion in a 0.7 MWth pilot furnace and a 75 MWe utility boiler. *Energy*, *192*, 116557. https://doi.org/10.1016/J.ENERGY.2019.116557

Reiher, D., & Hahn, A. (2021). Review on the Current State of Scenario- and Simulation-Based V&V in Application for Maritime Traffic Systems. *OCEANS 2021: San Diego – Porto*, 1–9. https://doi.org/10.23919/OCEANS44145.2021.9705781

Rony, A. H., Kitada, M., Dalaklis, D., Ölçer, A., & Ballini, F. (2019). Exploring the new policy framework of environmental performance management for shipping: a pilot study. *WMU Journal of Maritime Affairs*, *18*, 1–24. https://doi.org/10.1007/S13437-019-00165-Z

Salvesen, N., Tuck, E. O., & Faltinsen, O. (1970). *Ship motions and sea loads*.

Sato, Y. K., Miyata, H., & Sato, T. (2000). CFD simulation of 3-dimensional motion of a ship in waves: application to an advancing ship in regular heading waves. *Journal of Marine Science and Technology*, *4*, 108–116. https://doi.org/10.1007/S007730050013

Shi, J., Liu, Z., Feng, Y., Wang, X., Zhu, H., Yang, Z., Wang, J., & Wang, H. (2024). Evolutionary model and risk analysis of ship collision accidents based on complex networks and DEMATEL. *Ocean Engineering*, *305*, 117965.

https://doi.org/10.1016/J.OCEANENG.2024.117965

Ships, I. S. O. (2015). marine technology—Guidelines for the assessment of speed and power performance by analysis of speed trial data. *ISO: Geneva, Switzerland*.

Szlapczynski, R., & Szlapczynska, J. (2021). A ship domain-based model of collision risk for near-miss detection and Collision Alert Systems. *Reliability Engineering & System Safety*, *214*, 107766. https://doi.org/10.1016/J.RESS.2021.107766

Tavakoli, S., Najafi, S., Amini, E., & Dashtimansh, A. (2021). Ship acceleration motion under the action of a propulsion system: a combined empirical method for simulation and optimisation. *Journal of Marine Engineering and Technology*, *20*(3), 200–215. https://doi.org/10.1080/20464177.2020.1827490

Thiaucourt, J., Horel, B., Tauzia, X., & Ncobo, C. (2022). Numerical investigation to increase ship efficiency in regular head waves using an alternative engine control strategy. *Https://Doi.Org/10.1177/14750902221121895*, *237*(2), 436–454. https://doi.org/10.1177/14750902221121895

Thiaucourt, J., Horel, B., Tauzia, X., & Ncobo, C. (2023). Numerical investigation to increase ship efficiency in regular head waves using an alternative engine control strategy. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *237*(2), 436–454. https://doi.org/10.1177/14750902221121895

Ueng, S., Lin, D., & Liu, C.-H. (2008). A ship motion simulation system. *Virtual Reality*, *12*, 65–76. https://doi.org/10.1007/s10055-008-0088-8

Vakili, S., Ölçer, A. I., Schönborn, A., Ballini, F., & Hoang, A. T. (2022). Energy-related clean and green framework for shipbuilding community towards zero-emissions: A strategic analysis from concept to case study. *International Journal of Energy Research*, *46*(14), 20624–20649. https://doi.org/10.1002/ER.7649

Wada, Y., Yamamura, T., Hamada, K., & Wanaka, S. (2021). Evaluation of GHG Emission Measures Based on Shipping and Shipbuilding Market Forecasting. *Sustainability*. https://doi.org/10.3390/SU13052760

Wang, K., Yan, X., Yuan, Y., Jiang, X., Lin, X., & Negenborn, R. (2018). Dynamic optimization of ship energy efficiency considering time-varying environmental factors. *Transportation Research Part D: Transport and Environment*. https://doi.org/10.1016/J.TRD.2018.04.005

Wang, K., Yan, X., Yuan, Y., & Li, F. (2016). Real-time optimization of ship energy efficiency based on the prediction technology of working condition. *Transportation Research Part D-Transport and Environment*, *46*, 81–93. https://doi.org/10.1016/J.TRD.2016.03.014

Wu, G., Atilla, I., Tahsin, T., Terziev, M., & Wang, L. (2021). Long-voyage route planning method based on multi-scale visibility graph for autonomous ships. *Ocean Engineering*, *219*(June 2020), 108242. https://doi.org/10.1016/j.oceaneng.2020.108242

Yang, L., Chen, G., Rytter, N., Zhao, J., & Yang, D. (2019). A genetic algorithm-based grey-box model for ship fuel consumption prediction towards sustainable shipping. *Annals of Operations Research*, 1–27. https://doi.org/10.1007/S10479-019-03183-5

Yun, P. E. N. G., Xiangda, L. I., Wenyuan, W. A. N. G., Ke, L. I. U., & Chuan, L. I. (2018). A simulation-based research on carbon emission mitigation strategies for green container terminals. *Ocean Engineering*, *163*, 288–298. https://doi.org/10.1016/J.OCEANENG.2018.05.054

Zeraatgar, H., Moghaddas, A., & Sadati, K. (2020). Analysis of surge added mass of planing hulls by model experiment. *Ships and Offshore Structures*, *15*(3), 310–317. https://doi.org/10.1080/17445302.2019.1615705

Zhang, W., Zou, Z., & Deng, D. (2017). A study on prediction of ship maneuvering in regular waves. *Ocean Engineering*, *137*, 367–381. https://doi.org/10.1016/J.OCEANENG.2017.03.046