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Analyzing inland waterway competitiveness with electric autonomous RoRo vessels: A case study from Rotterdam to Ghent

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ABSTRACT

Adopting green vehicles in the transport sector is a highly effective policy for mitigating the sector's carbon footprint. Moreover, the EU transport policy acknowledges the pivotal role of inland waterways (IWW) in decarbonizing Europe, with a strategic objective to enhance its modal share through the transition from road to IWW. This paper investigates the potential of electric autonomous Roll-on Roll-off (RoRo) ships to enhance the competitive edge of IWW as compared to road transport. This paper examines the impact of this innovative transport system on sustainability by analyzing Key Performance Indicators (KPIs) across economic and environmental dimensions using a comparative case study approach and quantitative analysis data. The main result is that implementing electric autonomous RoRo ships can lead to a 45 % reduction in OPEX (operational expenditure), with profitability expected after about 3.5 years. Emissions decrease by more than 60 %, and by 2030, CO_2 emissions in the Well-to-Wake (WTW) cycle are projected to reduce by approximately 77,000 tonnes, aligning with EU transport and environmental policies.

1. Introduction

Reducing greenhouse gas (GHG) emissions remains a significant challenge given global population growth and rising energy demands (Park et al., 2022a). The transport sector, particularly road transport dominated by heavy trucks, is a major contributor to GHG emissions, accounting for 71.8 % of the sector's emissions, with trucks alone contributing 26.5 % (European Commission, 2020). Despite the urgency, the transport sector's decarbonization lags behind other industries like electricity and construction (Deshmukh et al., 2023). The European Union has set targets to shift 30 % of road freight to rail and water transport by 2030, and aims to exceed 50 % by 2050, according to the European Commission (2011). However, recent studies outline the complexity of transitioning road freight to sustainable modes, considering factors like economic benefits, regulatory challenges, and environmental policies (Psaraftis & Zis, 2020).

The European Commission's maritime transport policy (The European Commission, 2009) and the European Green Deal (2019) emphasize the importance of waterborne transport for Europe's sustainable growth. To enhance maritime competitiveness and its market share, the EU has promoted inland waterway (IWW) networks as safer, less congested alternatives to road transport, capable of handling various shipping services, including liner, bulk, and Roll-on Roll-off (RoRo) (Peng et al., 2024; Shangguan et al., 2024). Among these services, RoRo vessels are receiving significant attention as an ideal choice for transporting cargo from road to sea (Jia et al., 2023). The preference for this type of vessel stems from the nature of RoRo freight shipping, where cargo on trailers is transported directly. With RoRo vessels, wheeled cargo can be easily driven onto ships using integrated ramps, eliminating the need for additional handling (Lombardi et al., 2023). This seamless integration with road transport enhances the competitive advantages of RoRo shipping (Andersson et al., 2015; Seddiek & Ammar, 2023).

Additionally, collaborative EU R&D projects among universities, governments, and logistics companies, such as MOSES, AUTOSHIP, SEAMLESS, and AEGIS, are developing autonomous vessels to boost shipping efficiency and competitiveness. These vessels are expected to enhance decarbonization, operational efficiency, resilience, speed, and frequency, positioning maritime transport as a more viable alternative to land-based systems (Fjørtoft et al., 2023; Rødseth et al., 2020;

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Nomenclature

EF_{CO_2}	CO_2 emission factor (gr/kWh)
EF_{NO_x}	NO_x emission factor (gr/kWh)
$EF_{PM_{10}}$	PM_{10} emission factor (gr/kWh)
EF_{SO_x}	SO_x emission factor (gr/kWh)
EP_p	Engine power at port (kW)
EP_s	Engine Power at sea (kW)
EP_T	Engine Power for the baseline scenario (kW)
FC_p	Fuel cost in port (€)
FC_s	Fuel cost at sea (€)
FP_p	Fuel price in port (€/kWh)
FP_s	Fuel price at sea (€/kWh)
fc_p	Fuel consumption in port (kWh)
fc_s	Fuel consumption at sea (kWh)
fc_T	Fuel consumption for the baseline scenario (kWh)
THR	Terminal handling rate (Trailer/h)
THT	Terminal handling time (h)
CU	Capacity utilization rate ($[0,1]$)
DD	Driving distance (km)
DT	Driving time (h)
FS	Frequency of service (Shipments/week)
NT	Number of trucks
$Nmoves$	Total number of moves for each port
OC	Operational cost of trucks (€/km)
SD	Sailing distance (Nautical Miles–NM)
ST	Sailing time (h)
TC	Trailers carried
TD	Total distance traveled by one truck (km/truck per week)
TFC	Total fuel cost (€)
TL	Total load (trailers)
TP	Time at berth or port (h)
TtB	Total transport time for baseline scenario (h)
TtR	Total transport time for RoRo scenario (h)
TS	Truck speed (km/h)
VC	Nominal vessel capacity (trailers)
VS	Vessel speed (knots)
WOT	Weight of one trailer (tonnes)
WT	Waiting time (h)

Psaraftis et al., 2023; Liu et al., 2022; Zhao et al., 2023; Krause et al., 2022). Recent work by Wang et al. (2023) explores autonomous ships on national waterways, addressing regulatory and cost challenges with innovative fleet management. Kennard et al. (2022) investigate how deck officers are adapting to operate autonomous and remote-controlled vessels, noting significant training and role changes needed for safe operation. Furthermore, using eco-friendly fuel systems, improved hull designs, and smart routing strategies can provide further advantages (Lindstad et al., 2021; Kersey et al., 2022; Feng et al., 2024). While these technologies can be applied to non-autonomous vessels, their combination with reduced manning and energy requirements associated with autonomous operations can result in amplified savings (Psaraftis et al., 2023).

Indeed, to face the growth of the road transport sector, there are two main pillars. Firstly, the shift of traffic to greener modes of transport is paramount. Greener modes are basically short sea shipping (SSS), rail, and IWW, modes that trail road transport in terms of intra-EU freight traffic. Among these three alternative modes, IWW is the one with the least share of the traffic, with only 6 % of all intra-EU freight transport (Eurostat, 2022). Additionally, its energy consumption per km/ton of transported goods is approximately 17 % of that of road transport and 50 % of rail transport (European Commission, 2021). Thus, IWW exhibits strong opportunities for further growth, provided that such opportunities are exploited. The second pillar is the utilization of sustainable infrastructure and innovative vehicles employing environmentally friendly fuels (Naumov et al., 2023). This paper explores both pillars, with a focus on the use of electric autonomous vessels on IWW. The landscape of these vessels is rapidly evolving, with numerous papers focusing on advancements in ship design, propulsion, integration tasks, electronics, safety, and security (Yuen et al., 2022; Sharma & Kim, 2022; Kooij & Hekkenberg, 2022; Costello & Xu, 2023).

This paper contributes to advancing sustainable waterborne transport by analyzing the potential of innovative systems that leverage the latest developments in the Connected and Automated Transport fields. Specifically, it examines the concept of a next-generation IWW transport system featuring autonomous RoRo vessels powered by electric propulsion. This aligns with the European Union's Green Deal policies aimed at, inter alia, reducing GHG emissions and enhancing the sustainability of the transport sector. Key contributions of this research include:

1. We analyze the design and operation of RoRo vessels that use electric propulsion for environmentally sustainable operations. These vessels are autonomous and use standardized cargo units, which streamline operations and reduce transshipment costs
2. The study conducts a detailed sustainability analysis using Key performance indicators (KPIs) that address economic and environmental factors. This evaluation assesses the system's feasibility and compares its performance with traditional land-based transport modes
3. A case study conducted along a selected transport route in Europe demonstrates the feasibility and potential advantages of the system analyzed over road transport. This case study provides practical insights into the system's effectiveness in a real-world context
4. The findings of this study offer valuable insights for policymakers and stakeholders, helping them evaluate and consider the implementation of sustainable transport systems in regions where IWW could support regulatory objectives

The subsequent sections of this paper are structured as follows: Section 2 presents the literature review. Section 3 introduces the real case study that forms the basis of our analysis and provides the data sets utilized. Section 4 outlines our methodology, while Section 5 discusses the results obtained. Finally, Section 6 covers the conclusions drawn from our findings.

2. Literature review

Based on the contributions introduced, this section reviews recent advancements and trends in the field of autonomous shipping to identify research gaps. IWW is also examined, with particular attention to the role of autonomous vessels and RoRo vessels within this transport system. Furthermore, the integration of electric propulsion systems, including shore power technologies, is studied as a pathway to achieving sustainable and efficient maritime operations.

Most research studies have been conducted on maritime autonomous surface ships (MASS), focusing on technological, economic, and regulatory aspects. Ahmed et al. (2024) emphasized the need for regulatory frameworks to address gaps in existing conventions. They proposed a classification of gaps by severity and recommended amendments or new developments to accommodate MASS. Munim et al. (2025) identified critical factors for the commercialization of MASS, including navigation systems, cybersecurity, and capital costs, using a multi-criteria decision-making framework.

Fjørtoft et al. (2023) introduced a resilience assessment methodology for autonomous maritime transport networks, demonstrating its applicability through a case study on the Trondheim-Rotterdam corridor. Their study highlighted the importance of resilience in the successful deployment of autonomous systems. Additionally, Chang et al. (2024) analyzed the challenges in developing collision avoidance systems, identifying inconsistencies in research outcomes, and proposing future directions for more robust solutions. These studies highlight the multidimensional challenges in deploying autonomous shipping systems, including legal, operational, and technological hurdles.

Another critical aspect of autonomous shipping is human interaction and its implications. Shahbakhsh et al. (2022) examined the evolving role of seafarers in the context of Industry 4.0 and proposed a transition to Industry 5.0, which emphasizes human–machine collaboration. They argued that while automation reduces the need for traditional seafaring roles, new opportunities emerge in shore-based operations and system management. Meanwhile, Yiteng and Ling (2024) used grounded theory to understand industry acceptance of MASS, revealing complex factors influencing adoption, such as cost, safety, and regulatory compliance.

IWW represents a promising domain for the application of autonomous shipping, particularly for RoRo vessels (Parvasi et al., 2024). IWW offers significant advantages in terms of lower energy consumption and reduced emissions compared to road transport. Jovanović et al. (2022) evaluated the feasibility of autonomous low-emission RoRo ships in the Adriatic Sea, identifying electricity and methanol as the most viable energy sources for short- and medium-range routes. They also noted that autonomous operations could lead to substantial cost savings and environmental benefits.

Dantas & Theotokatos (2023) developed a framework for assessing the economic and environmental feasibility of autonomous SSS vessels, focusing on converted and next-generation designs. Their findings demonstrated that autonomous ships could achieve cost reductions of up to 12 % over their lifecycle, along with a 4 % reduction in carbon emissions. Additionally, Wang et al. (2023) modeled the operational impact of autonomous ships in regional waterways, highlighting the potential for optimized routing and fleet deployment to enhance economic and environmental performance.

Kurt & Aymelek (2024) examined the interoperability requirements between ports and autonomous ships, emphasizing the need for operational adaptations to ensure seamless integration. They identified critical areas such as terminal infrastructure, digital communication systems, and regulatory compliance as prerequisites for successful implementation.

The transition to alternative fuels and energy sources is a pivotal component of the maritime industry's decarbonization efforts. Autonomous ships, particularly those operating in inland waterways, are well-suited to adopt battery-electric propulsion systems due to their relatively short distances and frequent port calls. Liu et al. (2022) investigated the emission reduction potential of autonomous ships using alternative fuels along major trade routes. Their findings indicated that electricity and methanol-powered vessels achieved the highest reductions, with electricity offering zero tank-to-wake emissions.

Bullock et al. (2023) explored the economic and environmental benefits of shore power systems, which enable vessels to connect to the electrical grid while at berth, reducing emissions and supporting battery recharging. However, they highlighted significant barriers, including high capital costs and the lack of standardized regulations. Similarly, Zou & Yang (2023) conducted a comparative analysis of alternative fuels, concluding that electricity and hydrogen are the most promising options for long-term decarbonization, although hydrogen's economic viability remains dependent on substantial cost reductions.

Havre et al. (2024) emphasized that batteries' effectiveness largely depends on the renewable energy share in the local grid, making them a viable "green" alternative in regions dominated by clean energy. Hybrid systems are also gaining traction as a practical solution for larger vessels (Pang et al., 2024).

Shore power, as another emissions mitigation strategy, has been extensively studied for its ability to replace on-board fossil fuels with electricity from renewable sources (Wang et al., 2023). Song et al. (2022) and Luo et al. (2024) highlighted that while batteries and shore power systems are highly effective, their integration with autonomous systems and reduced crew requirements can amplify cost and emission savings (Psaraftis et al., 2023). Table 1 shows the overview of the related literature.

Despite significant advancements in the research on autonomous shipping, inland waterway transport, and alternative energy sources, critical gaps remain, particularly in the comparative analysis of autonomous electric RoRo vessels versus road transport. While prior studies have extensively examined the feasibility, regulatory challenges, and environmental benefits of autonomous ships, there is limited research on their direct competitiveness with road transport in terms of operational costs, sustainability, and economic viability.

This study aims to fill these gaps by conducting a detailed analysis of the potential for electric autonomous RoRo vessels to enhance the competitiveness of IWW compared to road transport. By addressing these gaps, this study contributes to advancing autonomous shipping and its role in achieving sustainable and efficient freight transport.

3. Inland navigation case study: Analyzing the route between the port of Rotterdam and Ghent

The case study investigates the interface between Belgium and the Netherlands in terms of inland shipping. It focuses on the use of electric autonomous RoRo vessels that could be implemented on IWW connecting the terminal of DFDS company in the ports of Rotterdam and Ghent, alongside several other ports. These ports facilitate connectivity to smaller inland destinations in Flanders, thereby establishing waterway linkages.

The two countries serve as major cargo transport hubs linking Europe to global markets. Rotterdam, the largest port in Europe and a top global port, handled 436.8 million tonnes of cargo in 2020, accommodating diverse shipments from dry to liquid bulk and containers. Additionally, Ghent is part of the North Sea Port, which resulted from a merger with Vlissingen and Terneuzen (Fig. 1). This port stretches over 60 km and covers 9,100 ha spanning the Netherlands and Belgium. This port is the ninth largest in Europe by cargo volume. While IWW freight transport is well-established, potential for growth remains. Conversely, a 160 km road link between these ports supports significant truck-based cargo movement, leading to considerable congestion but presenting a competitive alternative to maritime routes.

In this case study, the primary goal of the transport system is to alleviate congestion and reduce GHG emissions by shifting cargo from road transport to an IWW barge service. To enhance cargo attraction, DFDS company plans to deploy autonomous electric vessels that can transport cargo closer to its final destination using small RORO vessels with zero-emission propulsion systems. The case study examines a transportation system composed of advanced inland navigation vessels operating specific routes in the Belgium and Netherlands region, including the ports along these routes and the transshipment processes from vessel to port. Consequently, this research will analyze two scenarios within the sustainability aspect discussed below.

a) The baseline scenario (road mode) entails transporting cargo between Ghent and Rotterdam (and in the opposite direction) using trucks, as shown in Fig. 2a.

b) The electric autonomous RoRo scenario (IWW mode) involves moving cargo along a canal between Ghent and Rotterdam (and vice versa) using electric autonomous RoRo vessels, as illustrated in Fig. 2b.

A primary factor for choosing this route is that DFDS operates terminals in both Rotterdam and Ghent, which are currently handling growing cargo volumes and undergoing expansion projects to accommodate this increase. Therefore, redirecting cargo between these terminals to the IWW system could help alleviate congestion and potentially have a wider positive impact on the overall movement of

Table 1
A summary of the main focus area and methodology of existing research.

Authors	Main focus area	Methodology
Shahbakhsh et al. (2022)	– Human factors and Industry 5.0 integration for autonomous shipping	– Literature review
Jovanović et al. (2022)	– Feasibility of low-emission autonomous RoRo ships	– Environmental and economic impact assessment – Key performance indicators
Liu et al. (2022)	– Emission reduction of autonomous shipping with route optimization	– Simulation and Bayesian probabilistic forecasting – Scenario analysis using historical shipping data
Makkonen et al. (2022)	– Digital transformation with autonomous shipping Maritime service ecosystems	– Framework development for service ecosystem analysis – Case study
Song et al. (2022)	– Shore power systems – Emissions mitigation	– Game theory (Nash equilibrium) – Policy evaluation on subsidies
Fjørtoft et al. (2023)	– Resilience in autonomous shipping – Sustainable transport systems	– Resilience assessment framework – Case study
Zis et al. (2023)	– Key performance indicator framework and performance evaluation for autonomous shipping	– Key performance indicator framework development – Case study
Dantas & Theotokatos (2023)	– Feasibility assessment of autonomous vessels	– Environmental and economic impact assessment – Scenario analysis
Bullock et al. (2023)	– Techno-economic assessment of shore power	– Multi-criteria decision analysis – Techno-economic assessment – Case study
Abreu et al. (2023)	– short sea shipping cost strategies – Competitiveness enhancements	– Environmental and economic impact assessment – Numerical modeling – Case study
Ahmed et al. (2024)	– Regulatory and legal frameworks for autonomous vessels	– Literature review – Regulatory gap analysis
Yiteng & Ling (2024)	– Technology adoption of MASS and stakeholder perspectives	– Qualitative data analysis – Semi-structured interviews with industry executives
Xing (2024)	– Environmental risks of autonomous vessels – Legal compatibility	– Regulatory analysis – Legal framework assessment
Kurt & Aymelek	– Operational adaptation of ports with autonomous vessels	– Survey-based analysis – Multiple regression modeling
Chang et al. (2024)	– Collision avoidance and regulatory challenges in autonomous shipping	– Literature review – Regulatory analysis
Li et al. (2024)	– Collision risk assessment in autonomous shipping	– Fault Tree Analysis, – Risk assessment – Survey-based data collection
Munim et al. (2025)	– Commercial feasibility of autonomous vessels	– Multi-criteria decision-making – Survey-based analysis
This paper	– Competitiveness of inland waterway transport with electric autonomous RoRo vessels	– Economic and environmental assessment – Case study – Scenario analysis – Key Performance Indicators analysis

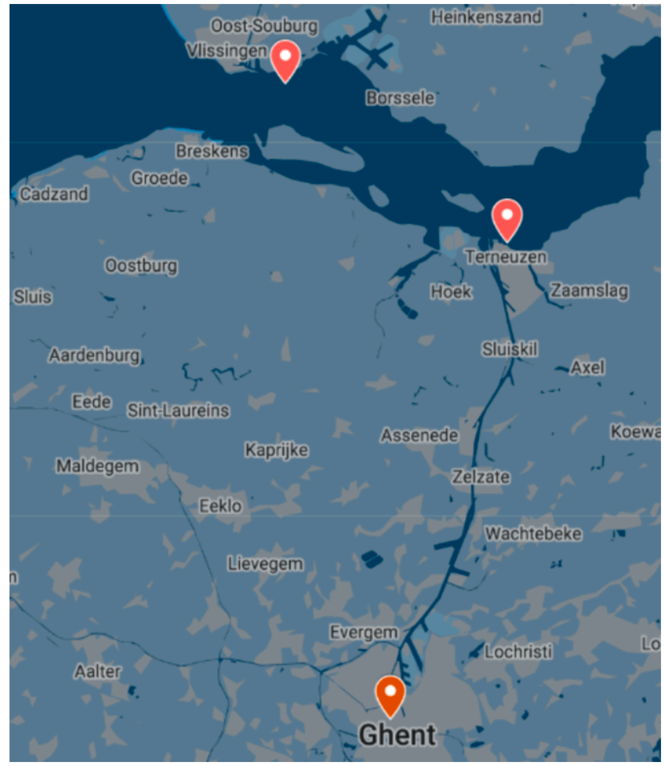


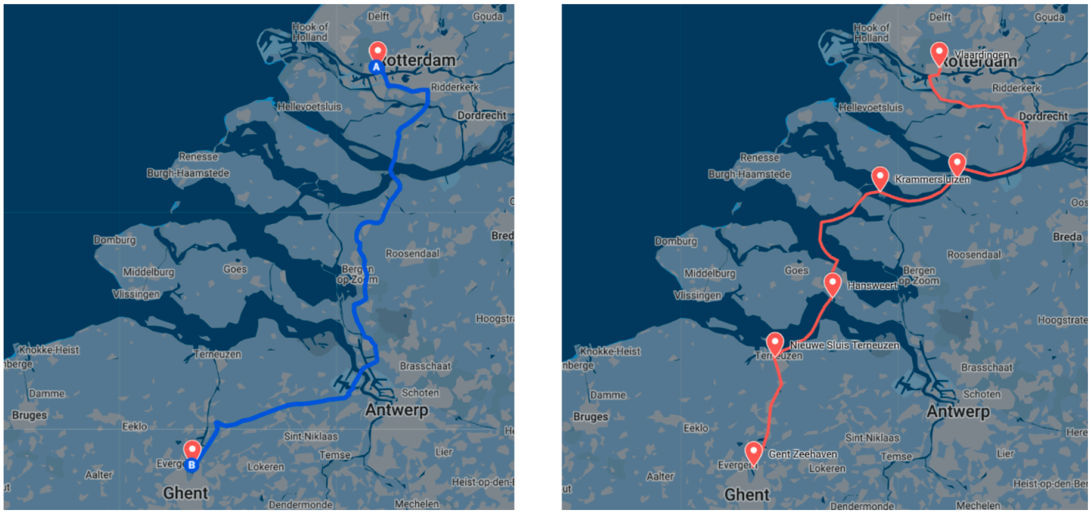
Fig. 1. The location of the port of Ghent.

cargo internationally through these terminals.

The vessel concepts for this study, detailed in Table 2, include CEMT class VI RoRo vessels with transversal loading (double deck) designed to operate at low draughts of about 4.5 m for navigation during low water levels in summer. As shown in Table 2, we consider autonomy level 3 for the vessels, where the ship is operated entirely remotely from a control center room without any crew onboard, as outlined by the International Maritime Organization (IMO). Specifically, at the first level, ships are equipped with automated systems to assist with decision-making, but crew members are onboard to operate and manage the ship. At the second level, the ship is remotely controlled from a control center, while crew members remain onboard to support operations and take control if needed. At the third level, the ship operates entirely remotely from a control center, with no crew onboard. Finally, at the fourth level, the ship is fully autonomous, capable of making decisions and performing operations independently without any human involvement (IMO, 2021). Additionally, for CEMT class IV+ vessels, transverse loading is feasible for wheeled cargo, as shown in Fig. 3. In this design, a RoRo vessel accommodates 69 trailers with a breadth of 15 m. The vessel's speed-power analysis (SPA), presented in Fig. 4, was initially calculated for calm water conditions, with a 5 % canal margin added to account for resistance factors such as streams, waves, and wind. This data is integral to determining the vessel's energy consumption, further discussed in Section 4. It should be noted that, for efficient loading and unloading processes at all ports, this paper assumes the use of the "Vera" autonomous vehicle designed by Volvo. This practical autonomous cargo-handling solution would be at the ports to facilitate seamless operations (Daskalaki & Podiotis, 2021).

For the trucks in the baseline scenario, we referenced the data provided in Table 3. This truck model was chosen for analysis because it is utilized by DFDS. Also, according to the report of IRU, the road freight cost breakdown, which is consistent with the data provided by DFDS, can be seen in Table 4. Further information will be presented in the remaining sections.

It is important to note that the terms "trailer" and "truck" are distinct



(a) Baseline (land-based system) (b) Electric autonomous RoRo scenario (sea transport)

Fig. 2. Route details of the scenarios.

Table 2
Electric autonomous RoRo vessel specification.

Data	Vessel
Vessel Description	IWW CEMT Class VI
Vessel Type	RoRo IWW vessel
Route deployed in	Rotterdam – Ghent
Length Overall, Loa	139.20 m
Length between perpendiculars, Lbp	125.50 m
Beam Waterline, Bwl	15.00 m
Design Draft, T	4.50 m
Depth to main deck, D	9.35 m
Displacement	6,716 tonnes
Gross Tonnage	4,630 GT
Main Engine Type	Fully electric, swappable batteries
Main Engine Fuel Type	battery
Design Speed	8 knots
Vessel capacity	69 trailers (incl. 3 battery trailers)
Autonomy Level	3
CAPEX	€ 16,000,000

in this paper. Specifically, each RoRo vessel can carry 69 trailers. Additionally, in the baseline scenario, each truck is capable of transporting a single trailer. Also, the payload of each trailer is 33 tonnes.

4. Methodology

KPIs are the metrics used to assess the effectiveness of the developed solutions (Larsen et al., 2023). The KPIs can be calculated for two distinct scenarios: the baseline scenario, which is centered on a land-based transport system utilizing trucks, and the electric autonomous RoRo scenario, operating within the IWW setting. These KPIs are organized into economic and environmental categories.

The task of defining KPIs for a project can be complex since different stakeholders may have distinct preferences on transport system performance (Zis et al., 2023; Zanobetti et al., 2023). The selection of appropriate KPIs is crucial for accurate performance measurement and

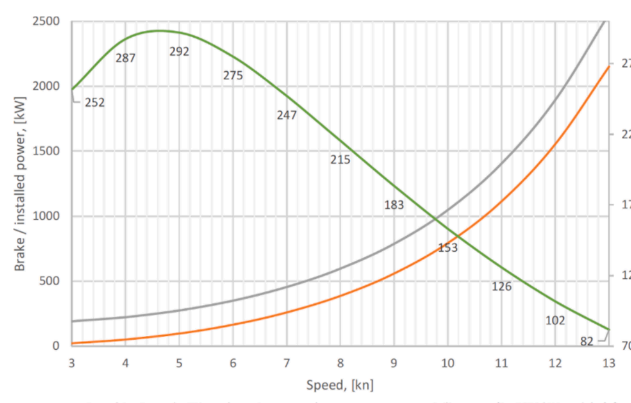
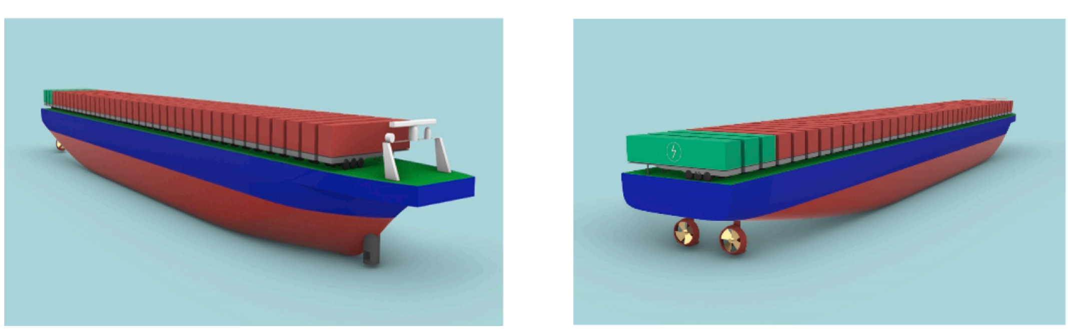


Fig. 4. SPA of the RoRo autonomous vessel. .
Source: ISE



(a) RoRo ship design from the bow view (b) RoRo ship design from the aft view

Fig. 3. Illustration of the autonomous ship utilized. .
Source: ISE

Table 3
Specifications and energy consumption of the truck (Martensson, 2018; Daskalaki & Podiotis, 2021).

Volvo truck name	Volvo FH
Engine	D13k500 Euro 6 Diesel Engine
Engine Power	368 kW
Fuel	Diesel EN590
Consumption	26 Liters/100 km
Emission standards	Euro 6
CAPEX	€ 148,000

Table 4
Truck OPEX cost breakdown.

Cost type	Percentage (%)
Wages	50 %
Fuel cost	30 %
Maintenance	20 %
Total (OPEX)	100 %

improvement, as well as for evaluating the potential solutions proposed in this study (Dağıdır & Özkan, 2024). Given the challenges associated with this endeavor and the specific context of the current study, which develops a new waterborne transport system and new RoRo vessels, a 7-step methodology is presented in Fig. 5 as adapted from Zis et al. (2023).

In summary, project partners, stakeholders, and an industry advisory group (AG) assessed the case study mentioned in the previous section based on the validity of KPIs. The accuracy and availability of data for these KPIs were also examined. Furthermore, data input sources and necessary assumptions were reviewed. The subsequent part of this section will present the KPIs in terms of their economic and environmental dimensions, along with their calculation methods.

In the following subsections, KPIs requiring mathematical calculations are explained. The estimation of the remaining KPIs, which can be obtained directly from the data in Section 3 or based on the calculations in this section, is explained in Section 5.

4.1. Economic KPIs

The essential data for calculating the KPIs consists of details about the sailing routes (such as distance and trip time) and specifics about the vessels (including consumption of fuel and operating costs). These data are crucial for determining most of the KPIs. This subsection describes

Table 5
Economic KPIs.

KPI level	KPI sublevel	KPI name	KPI unit
Economic	Cost	Total capital costs (CAPEX)	€
Economic	Cost	Operational costs (OPEX)	€/week
Economic	Cost	Maintenance costs	€/week
Economic	Cost	Terminal handling charges (THC)	€/week
Economic	Cost	Total fuel cost (TFC)	€/week
Economic	Cost	Wages	€/week
Economic	Cost	Cost per unit cargo	€/week
Economic	Time	Loading time	H
Economic	Time	Unloading time	H
Economic	Time	Sailing time (ST) or Driving time (DT)	H
Economic	Time	Waiting time (WT)	H
Economic	Others	Energy consumption	kWh/week
Economic	Others	Trailers carried (TC)	Number of trailer/trip
Economic	Others	Capacity utilization rate (CU)	Number of trailer/ nominal capacity
Economic	Others	Number of trailers moves	Number of trailer/routes per week
Economic	Others	Frequency of service (FS)	Shipments/week

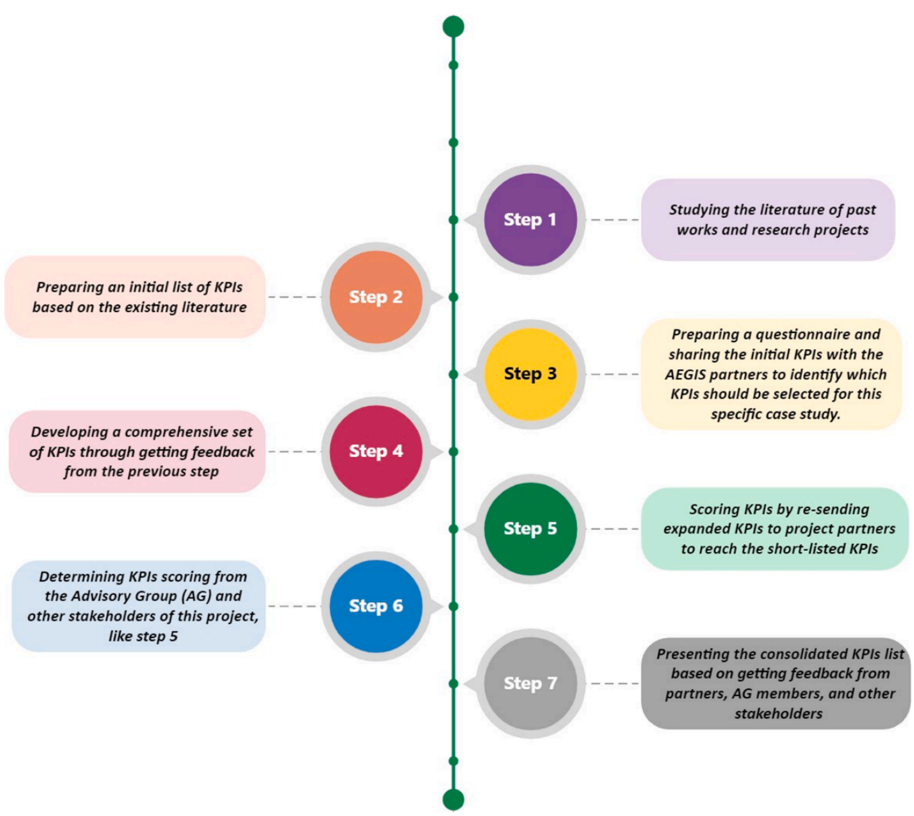


Fig. 5. The methodology to identify KPIs.
Adapted from Zis et al. (2023).

the equations used to estimate the economic KPIs, which are outlined in Table 5. In general, economic KPIs are divided into three subcategories: cost, time, and others.

4.1.1. Energy consumption and fuel cost KPIs

In the following subsection, the method for calculating energy consumption and fuel cost for the RoRo scenario will be explained first, followed by an explanation for the baseline scenario.

Equation (1) determines the energy consumption for a one-way trip between two ports during sailing (fc_s) in kilowatt-hours (kWh).

$$fc_s = EP_s \times ST \tag{1}$$

where EP_s refers to the engine's power (or brake power) in kW and ST refers to sailing time in hours.

Molland et al., 2017 elucidate the methodology employed to determine the engine power of the vessels, as depicted in Fig. 6 via a flowchart. In short, the calculation entails accounting for the ship's speed, the engine's nominal power, and the energy efficiency associated with the chosen fuel source.

For the RoRo scenario, the major cost component is the actual fuel consumption during sailing between two ports, including the fuel consumption for operations at both ports (Rotterdam and Ghent). (Solakivi et al., 2022). To compute the energy cost (FC_s) during the voyage, the energy price (FP_s)- in €/kWh- is used to calculate the amount based on the vessel's energy consumption while sailing, as outlined in Equation (2).

$$FC_s = EP_s \times FP_s \times ST \tag{2}$$

The energy consumption at each port (fc_p), measured in kWh per call, can be calculated using a similar activity-based method, as detailed in Equation (3):

$$fc_p = EP_p \times TP \tag{3}$$

where EP_p refers to the engine's power at port in kW and TP refers to Time at port in hours.

The energy cost at each port is calculated as shown in Equation (4):

$$FC_p = fc_p \times FP_p \tag{4}$$

The total fuel cost per voyage is estimated by summing the energy consumption for each leg and each port stay, and then multiplying each energy consumption by the respective energy price. This process is detailed in Equation (5), in which i is the index for the number of ports.

$$TFC = FC_s + \sum_{i=1}^{2} FC_p^i \tag{5}$$

For the baseline scenario the energy consumption in kWh (fc_T) for a trip between two ports is calculated based on the Equation (6).

$$fc_T = EP_T \times DT \tag{6}$$

Where EP_T refers to the engine's power in kW and DT refers to driving time in hours. Also, to calculate the fuel cost in the baseline scenario, we have used the data in Table 4.

It is important to note that this paper considers a service operating between two ports that covers the entire round trip. This includes traveling from the port of Rotterdam to the port of Ghent, time spent at the port of Ghent, the return trip to the port of Rotterdam, and the duration of stays at that port. Since all the aforementioned calculations pertain to a one-way trip between two ports, to determine the total cost of fuel and energy consumption for a round trip during a week, the calculated values should be multiplied by the number of trips made during the week (FS).

4.1.2. Time-based KPIs

The next group of economic KPIs focuses on time. The first two KPIs concern the loading and unloading time of the vessel (measured in hours) while at the port, respectively. These times are influenced by the terminal's efficiency, the ship's capacity, and the amount of cargo being loaded or unloaded (Yan et al., 2021). The entire loading and unloading times vary across different ship sizes and types.

For Ro-Ro scenarios, the efficiency of the loading and unloading operations depends on the vessel's layout, the width of the ramp, and the sequence the operators follow. In most IWW routes, this time is

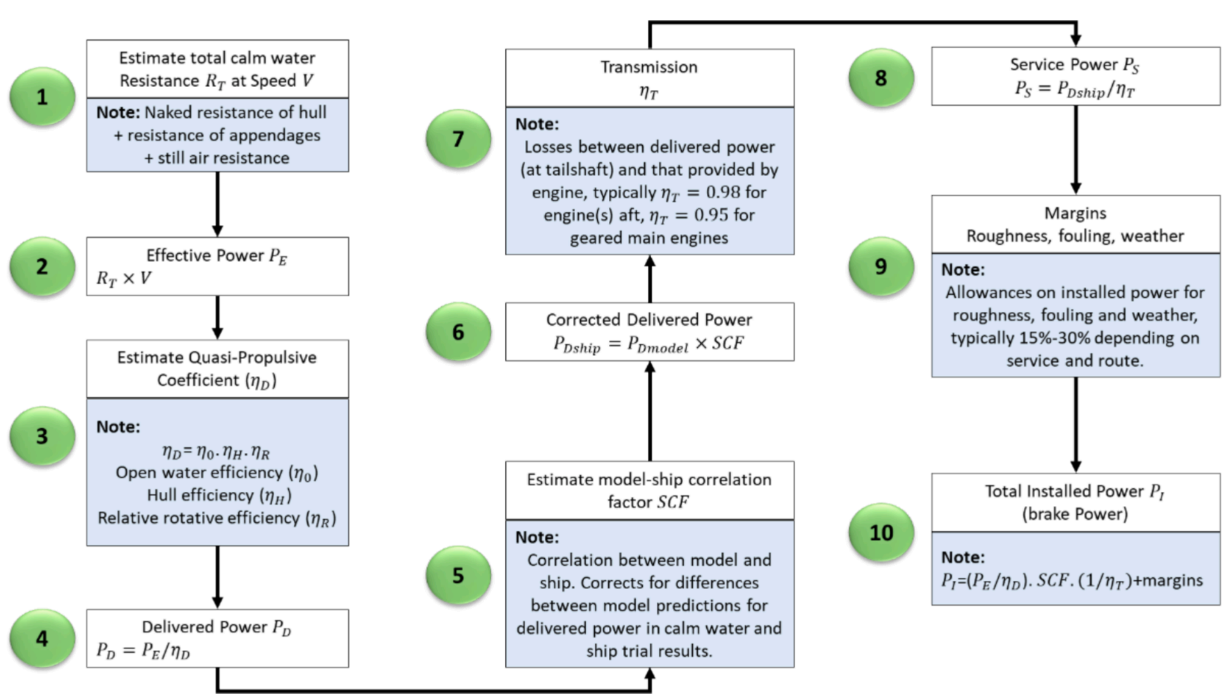


Fig. 6. Steps for the estimation of the engine power (brake power). Adapted from Molland et al. (2017).

estimated based on the number of trailers to be handled at port. The terminal handling time (*THT*) is calculated using the equation below:

$$THT = Nmoves/THR \tag{7}$$

Where *Nmoves* and *THR* represent the total number of moves at each port and terminal handling rate (Trailer/h), respectively. It's important to recognize that the rate of cargo handling is influenced by various factors, including the type of equipment used, how automated the equipment is, and the skill level of the workforce (Densberger & Bachkar, 2022).

For voyages between two ports, *Nmoves* is determined by the vessel's nominal capacity VC (in the trailer) and the cargo capacity utilization rate of the vessel CU, which is expressed as a number between 0 and 1 (refer to Equation (8)).

$$Nmoves = VC \times CU \tag{8}$$

For the baseline scenario, loading and unloading time calculations at the ports have been obtained directly from DFDS, and will be explained in Section 5.

The sailing time (ST) and driving time (DT) KPIs, measured in hours, can be obtained from the service's published schedule or by calculating the sailing or driving distance of the route (usually in Nautical Miles – NM for the RoRo scenario and km for the baseline scenario) and the designated service speed (in knots for the RoRo scenario and km/h for the baseline scenario). These calculations are performed for the RoRo and baseline scenarios using Equations (9) and (10), respectively:

$$ST = (SD \times 1.852)/(VS \times 1.852) \tag{9}$$

$$DT = DD/TS \tag{10}$$

It is important to note that, in Equation (11), to convert the voyage distance from NM to km and speed from knots to km/h, we multiply both by 1.852.

The total transport time between two ports is calculated by adding the traveling time to the time spent at terminals (both at origin and destination ports) and including any waiting time at the ports. Waiting time (WT) can occur due to delays in intermodal transitions, such as waiting for cargo to be picked up by trucks or rail cars, or delays in transshipment activities (Zhang et al., 2024; Cai et al., 2024). The total transport time, expressed in hours, is determined by summing these three times that can be seen for RoRo scenario (TtR) and baseline scenario (TtB) in Equations (11) and (12), respectively.

$$TtR = ST + WT + THT \tag{11}$$

$$TtB = DT + WT + THT \tag{12}$$

4.1.3. Other economic KPIs

The final set of economic KPIs includes a variety of indicators that have economic implications but do not directly measure efficiency in monetary or time terms. For instance, one of the KPIs in this group is trailers carried (TC). The calculation of this KPI for the RoRo scenario follows the same method as described in Equation (8). This is because the number of trailers handled at each terminal is equal to the number of trailers transported along the route. Additionally, this number is equal to 1 for each truck in the baseline scenario.

The final economic KPI to consider is the frequency of service (FS), measured as sailings or driving per week, which helps estimate the revenue generated by the services offered. This KPI correlates with the amount of cargo carried for both scenarios, measured in trailer, as demonstrated in Equation (13):

$$FS = TL/TC \tag{13}$$

Where TL represents the weekly demand, or more precisely, the number of trailers moved during the week between the ports of Rotterdam and Ghent.

4.2. Environmental KPIs

Table 6 presents the outlined environmental KPIs to be estimated in this paper. The key required data for calculating these KPIs include energy consumption and route information. The equations that connect these data inputs will be detailed subsequently.

For the RoRo scenario, the primary input is the actual energy consumption for each voyage. This consumption is multiplied by an appropriate emissions factor to calculate the voyage's emissions. It's important to differentiate between two types of emissions: Tank-to-wake or wheel (TTW) for operational emissions from the vessel or truck and Well-to-tank (WTT), which covers upstream emissions related to fuel production and delivery. For instance, battery electric vehicles emit zero TTW emissions, but the WTT emissions depend on the energy production methods used to charge the batteries. Additionally, the term Well to Wake (WTW), which is the sum of WTT and TTW, is used to describe total emissions (Mansour et al., 2018). Given the increased focus by policymakers, particularly in the EU and within the IMO, on WTW emissions for GHG, this paper includes calculations for WTW CO_2 emissions.

Equation (14) outlines the calculation of the CO_2 KPI, expressed in grams of CO_2 emitted per ton-kilometer of transport activity.

$$CO_2 = \frac{(EF_{CO_2} \times fc_s) + \left(EF_{CO_2} \times fc_p\right)}{(TC \times WOC) \times (SD \times 1.852)} \tag{14}$$

Where EF_{CO_2} is the CO_2 emissions factor, expressed in grams of CO2 per kWh of energy. The fuel-specific factor represents the ratio of CO_2 emissions to the energy of fuel consumed. fc_s denotes the total fuel consumption for each voyage, measured in kWh. Similarly, fc_p refers to the fuel consumption while at port, also in kWh. The estimated grams of CO_2 per kilometer are then divided by the total weight of the trailers in tonnes.

The same formula can be adapted for other emissions KPIs as long as the correct emission factor is utilized. Thus, the emissions of Sulphur oxides emissions (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) can be respectively determined using Equations (15) – (17):

$$SO_x = \frac{(EF_{SO_x} \times fc_s) + \left(EF_{SO_x} \times fc_p\right)}{(TC \times WOC) \times (SD \times 1.852)} \tag{15}$$

$$NO_x = \frac{(EF_{NO_x} \times fc_s) + \left(EF_{NO_x} \times fc_p\right)}{(TC \times WOC) \times (SD \times 1.852)} \tag{16}$$

$$PM_{10} = \frac{(EF_{PM_{10}} \times fc_s) + \left(EF_{PM_{10}} \times fc_p\right)}{(TC \times WOC) \times (SD \times 1.852)} \tag{17}$$

For the land-based system, fuel consumption data is sourced from the performance metrics of a truck, as shown in Table 3. Using this data, we can estimate the emissions for a loaded truck, which will be described in Section 5.

It is important to note that all emissions KPIs are measured in grams per tonne-kilometer, allowing for straightforward comparisons between two modes of transport. We further clarify that the WTT CO_2 emission

Table 6
Environmental KPIs.

KPI level	KPI sublevel	KPI name	KPI unit
Environmental	Emissions	CO_2	gr of CO_2/tkm
Environmental	Emissions	SO_x	gr of SO_x/tkm
Environmental	Emissions	NO_x	gr of NO_x/tkm
Environmental	Emissions	Particulate matter (PM_{10})	gr of PM_{10}/tkm

analysis reported here is only a first-order analysis and in a strict sense incomplete, being confined only to emissions produced during the production of the alternative fuel, or of the electrical energy to charge the batteries, as appropriate. Upstream emissions associated with the transportation of the fuel, the production of the batteries, or the recycling of batteries have not been considered, being second or third-order effects that are outside the scope of this paper. For a more comprehensive analysis of the entire emission cycle and to address prospective life cycle assessments (LCA), we recommend referring to Greene et al. (2020) and Park et al. (2022b).

5. Results and discussion

In this section, we use real data to calculate various KPIs for the scenarios presented in Section 3. We will also provide an analysis of KPI outcomes across economic and environmental factors and compare the two scenarios.

5.1. Economic analysis

5.1.1. CAPEX (Capital expenditures)

Demand calculations for the maritime route between Ghent and Rotterdam estimate weekly traffic of approximately 1,155 trailers one way, totaling 2,310 trailers for a round trip. Three autonomous vessels, operating daily and completing seven round trips per week, are required to meet this demand. CAPEX for each new RoRo ship is estimated at €16 M, supported by a cost breakdown of key components. This includes an investment of approximately €3M for the hull, €4–5 M for the lift system for each slot, and €0.3 M for the side ramps, resulting in a total of around €8M for the vessel's structure and outfit. Additionally, the energy storage system, a crucial component for fully electric propulsion, is estimated to cost €7.3 M, while the propulsion system itself is projected to cost €0.75 M. Combining these elements, the total CAPEX per vessel is approximately €16 M, leading to a total CAPEX of €48 M for deploying three vessels. For further details on estimating the cost of inland vessels, refer to Hekkenberg (2014).

To compare with land-based transport, the number of trucks to handle this cargo was analyzed. Each truck can carry two trailers per round trip, completing one round trip in 5.12 h, thus transporting approximately 9.375 trailers daily. Operating continuously, a truck can handle about 65.625 trailers per week. To transport the equivalent of 2,310 trailers weekly by road, 36 trucks are needed (calculated as 2,310 trailers divided by 65.625 trailers per truck per week). The CAPEX for these trucks, priced at €148,000 each, totals approximately €5.328 million.

5.1.2. OPEX

DFDS has estimated the OPEX associated with road haulage, which amounts to 1.34 €/km. The International Road Transport Union (IRU) report provides further insight into road freight transport costs, stating that the average transport cost is 1.5 €/km (IRU, 2021). It is worth mentioning that the transport cost for road haulage is influenced by several factors and market rates can fluctuate every quarter. Consequently, it is reasonable to consider an average road freight cost of 1.40 €/km in this paper. Therefore, the OPEX in €/week can be calculated using the following equation:

$OPEX = NT \times OC \times TD$, where NT (Number of Trucks) is 36, OC (OPEX of trucks in €/km) is 1.4, and TD (Total distance traveled by one truck in km/week) is 10,752. Thus, the weekly OPEX for the fleet of trucks is €529,200.

Also, the road freight OPEX breakdown is presented in Table 4, which can be used to calculate wages, maintenance, and fuel costs.

For the RoRo scenario, the OPEX is derived by aggregating costs related to maintenance, fuel (electricity), wages, and THC. According to DFDS, the maintenance cost per ship stands at approximately €6,700 weekly, totaling €20,000 for all three vessels. Fuel costs are calculated by considering the average non-household electricity price in Belgium and the Netherlands at €0.18 per kWh (Eurostat, 2023), assuming recharging at each port.

With the vessels operating at automation level 3, no deck crew is required (IMO, 2021), but a control room staff is necessary, with six employees working rotating shifts (MacKinnon et al., 2015) at an estimated wage cost of €11,900 per week. The THC, estimated at €85 per trailer, leads to a total weekly THC of €196,350 for 2,310 trailers transported weekly.

Thus, the total weekly OPEX for the RoRo scenario is estimated at €290,520. It's important to note that THC typically covers terminal operator expenses, including wages for port personnel handling cargo, so additional costs for these personnel are not separately counted to avoid double counting.

5.1.3. Time and energy consumption

To compute the fuel cost for the vessels, it's essential to calculate the energy consumption in kWh by considering the vessel's speed and battery output. At a speed of 8 knots (equivalent to 1.852 km/h), and given the travel distance, the transit time can be calculated. Including loading, unloading, and port waiting times, and considering 42 weekly trips and port energy use of 600 kWh, we estimate the weekly energy consumption for the maritime scenario.

Autonomous ships in this scenario are battery-powered, enabling them to travel up to 100 km before needing a recharge or a mid-journey battery swap. Based on the specifications, the energy needed for a one-way trip without recharging is estimated to be 6436.8 kWh. Taking into account losses and safety margins, a battery capacity of 7,000 kWh is selected. This configuration includes two packs, each containing six strings of batteries, providing 3,612 kWh and weighing 61.1 tonnes. The weight and volume of the batteries slightly reduce the vessel's carrying capacity.

Road transport, given the travel distance, takes about 2.56 h at an average speed of 65 km/h. Including minimal loading and unloading times of 0.03 h each, the total round-trip time by truck is calculated at 5.12 h.

5.1.4. Economic results

The economic outcomes are presented in Table 7. Generally, the

Table 7
Result of both scenarios in economic KPIs.

KPI name	KPI unit	Result		Winner
		RORO scenario (sea)	Baseline (road)	
CAPEX	€	48,000,000	5,328,000	*Road*
OPEX	€/week	290,520	529,200	*IWW*
Maintenance costs	€/week	20,000	105,840	*IWW*
THC	€/week	196,350	––	*Road*
TFC	€/week	62,270	158,760	*IWW*
Wages	€/week	11,900	264,600	*IWW*
Cost per unit cargo	€/week	125	230	*IWW*
Loading time	H	1	0.03	*Road*
Unloading time	H	1	0.03	*Road*
ST or DT	H	10.8	2.5	*Road*
WT	H	1	0	*Road*
Energy consumption	kWh/week	345,946	2,125,200	*IWW*
TC	Number of trailer/trip	55	1	*IWW*
CU	Number of trailer/nominal capacity	0.8	1	––
Number of container moves	Number of trailer/routes per week	2,310	2,310	––
FS	Shipments/week	42	2,310	*IWW*

RoRo scenario shows competitive advantages over road transport in several economic KPIs, such as OPEX and energy consumption, despite higher CAPEX and time related KPIs. Fig. 7 illustrates the percentage difference in economic KPIs between the two scenarios. Green lines indicate improvements in the new scenario, while red lines denote disadvantages. The next subsection will discuss in greater detail how to manage the performance indicators that highlight the weaknesses of the new scenario.

5.1.5. Discussion of economic results

Table 7 illustrates that the economic KPIs for the RoRo scenario generally outperform those of road transport, with the exceptions of CAPEX and Time KPIs. Notably, the electric autonomous RoRo ships in the IWW system can dock at both ports daily, ensuring timely fulfillment of daily demands and reducing the risk of cargo delays. This capability diminishes any significant advantages of the land-based scenario in the time KPI.

While the CAPEX for the baseline scenario is lower, a comprehensive assessment of both CAPEX and OPEX reveals that the IWW scenario becomes more economical than road transport after about three and a half years. This breakeven point (BEP) is depicted in Fig. 8. The analysis does not discount future cash flows, a simplification justified by the short timeframe and current low interest rates. Additionally, factoring in inflation further enhances the RoRo scenario's financial advantage due to its lower OPEX.

While the RoRo scenario promises economic benefits, the considerable initial investment required may lead the DFDS company to hesitate about fully committing to purchasing all three ships initially. Instead, they might opt to start with one or two autonomous ships. Despite this scaled-down approach, our findings suggest that even with fewer ships, the initiative could still align with the EU's goal of transferring 30 % of road transport to maritime or rail by 2030 and 50 % by 2050. Furthermore, increasing the ship's speed from 8 knots to 10 knots could enhance the frequency of trips, thereby enabling a higher transfer of cargo from road to maritime transport, as illustrated in Fig. 9.

With the objective stated, we will utilize the mathematical Equation (18) presented by Psaraftis and Giovannini (2018), which is also applicable here and goes as follows:

$$t_0 = \frac{\overbrace{\underbrace{\sum_i \frac{L_i}{V_i}}_{T_i} + \sum_j G_j}^{T_0}}{N} i \in I, j \in J \quad (18)$$

Where: T_i = time to sail leg i of the route $i \in I$, T_0 = time for one ship to complete the route, N = number of ships deployed on the route, t_0 = service period defined as the period between two consecutive port visits by any ship in the fleet, L_i = length of the route leg, V_i = speed of the ship along the route leg, and G_j = represents the time spent at the port.

Using this equation, we obtain the service time (t_0) for each speed, as shown in Table 8.

The above results illustrate that an increase in vessel speed leads to a decrease in transit time, which can result in an increased frequency of service. As a result, each ship will be able to carry a greater number of trailers per week, enabling the transfer of more cargo from land to sea with the smaller number of ships. Fig. 9 shows this percentage increase is about 5 % for one vessel and about 10 % for two vessels.

5.2. Environmental analysis

As per Table 3, the Volvo FH truck model, equipped with an engine of type D13K500 Euro 6, is used in the baseline scenario. Using data on fuel type, fuel consumption (0.26 l/km), and the Euro 6 engine emission standards, TTW emissions per tonne-kilometer for a loaded trailer can be calculated. Emission factors for this model of truck, provided by Mårtensson, 2018, are detailed in Table 9.

To calculate the WTT CO2 emissions for the baseline scenario, the diesel emissions are considered as 14.2 g CO2/MJ of diesel. Consequently, the estimated emissions for the truck per ton-kilometer are computed using Equation (19). This calculation incorporates conversion coefficients of 35.4 MJ/l and 0.26 l/km (Daskalaki and Podiotis, 2021).

$$CO_2 emissions - WTT : \frac{(14.2 \times 35.49 \times 0.26)}{33} = 3.97 \quad (19)$$

For the autonomous RoRo scenario, emissions are limited to the WTT cycle due to the electric nature of the vessels, which results in zero TTW emissions. Table 10 presents the weekly CO_2 emissions for these ships, detailing emissions in gr/tkm. These emissions were estimated from the energy consumption of the autonomous vessels, the emission factors of the electricity grids in the Netherlands and Belgium, and the weekly payload. As the scenario includes a round-trip, the average emissions are considered.

5.2.1. Environmental results

Table 11 shows the result of environmental KPIs for both scenarios. As shown in Table 11, the implementation of the RoRo scenario is anticipated to result in significant improvements in most of the environmental KPIs. Fig. 10 displays the percentage difference in environmental KPIs between the two scenarios. Green colors signify that the new scenario has a better KPI, whereas red colors mean the opposite.

The following subsection will discuss managing the performance of environmental KPIs in more detail and highlight some weaknesses of the new scenario.

5.2.2. Discussion of environmental results

In environmental terms, Table 11 shows that while the baseline road transport scenario has a slight advantage in WTT CO2 emissions, this does not imply that the RoRo scenario is less effective overall in

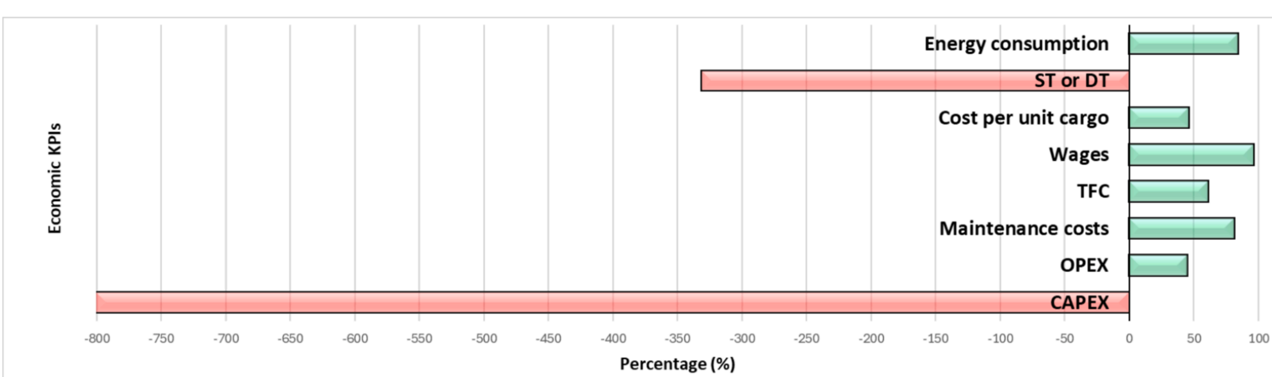


Fig. 7. Percentage difference in economic KPIs between two scenarios.

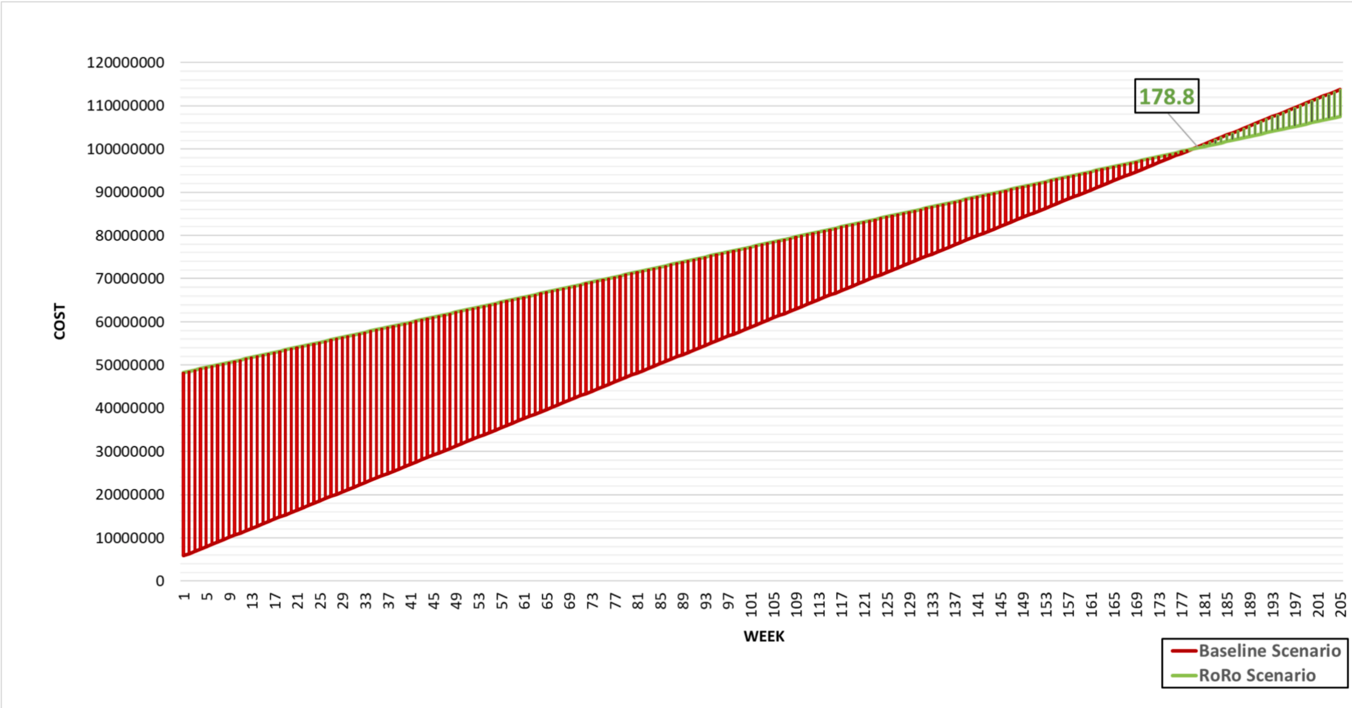


Fig. 8. Cost comparison of baseline and RoRo scenarios over time.

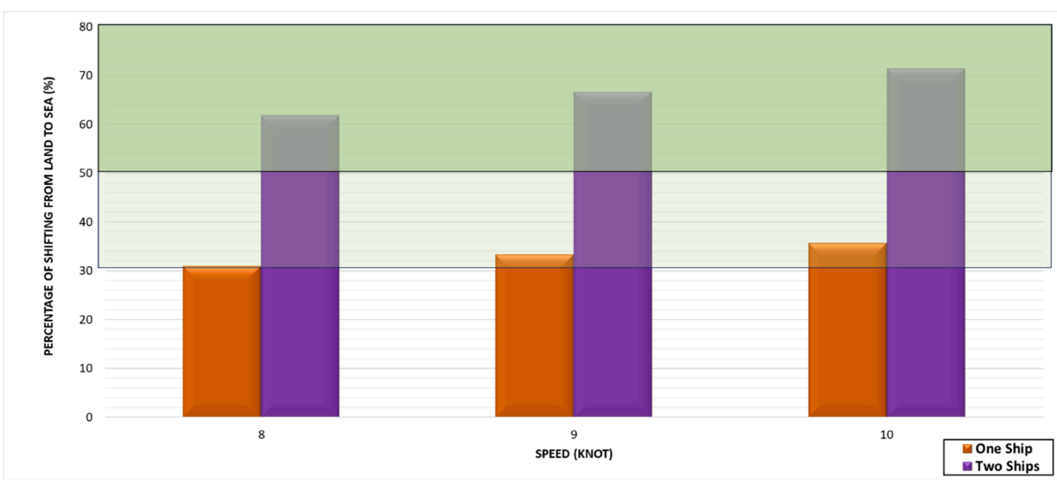


Fig. 9. Percentage share of the vessels on the transshipment at different speeds.

Table 8
Number of trailers that one vessel can carry on a weekly basis.

V_i(knots)	T_i(h)	t_0(h)	Cargo Carried (trailers)
8	21.6	9.2	715
9	19.2	8.4	770
10	17.2	7.8	825

emissions reduction. WTT emissions are only part of the story, and on a WTW basis the RoRo scenario is the winner. Further, implementing the RoRo scenario cuts weekly trips drastically, from 2,310 to 42, substantially reducing total emissions. The RoRo scenario demonstrates a significant long-term decrease in emissions, as detailed in Fig. 11. This comparison confirms that emissions per KPI are notably lower in the RoRo scenario than in truck transport, even when considering modern EURO 6 trucks.

Table 9
TTW emissions of one Volvo FH truck D13k500 Euro 6 diesel EN590 engine.

Emission	Emissions factor (gr/l)	Fuel Consumption per tonne transported (l/tkm)	Emissions (gr/tkm)
CO_2	2,600	(0.26/33) = 0.0079	20.5
SO_x	0.01		0.0000788
NO_x	0.9		0.00709
PM_{10}	0.01		0.0000788

6. Conclusions

This paper presented an analysis of the application of electric autonomous RoRo vessels for enhancing the competitive advantages of IWW transport compared to road transport systems. By integrating electric propulsion and autonomous operations, these vessels offer an

Table 10
CO_2-WTT emission of autonomous RoRo scenario.

Country	Ship energy consumption (kWh/km)	Payload (Tonnes)	Grid emission factor (gr/kWh)	Emissions intensity (gr/tkm)
Netherlands	51.48	1,821.6	441	12.46
Belgium			207	5.85
Average	**9.15**			

Table 11
Result of both scenarios in environmental KPIs.

KPI name	KPI Unit	Result		Winner
		RORO Scenario (sea)	Baseline (road)	
CO_2-WTT	gr of CO_2/tkm	9.15	3.97	*Road*
CO_2-TTW	gr of CO_2/tkm	0	20.5	*IWW*
CO_2-WTW	gr of CO_2/tkm	9.15	24.47	*IWW*
SO_x	gr of SO_x/tkm	0	7.88×10^{-5}	*IWW*
NO_x	gr of NO_x/tkm	0	7.09×10^{-3}	*IWW*
PM_{10}	gr of PM_{10}/tkm	0	7.88×10^{-5}	*IWW*

innovative solution that boosts the sustainability of IWW. By addressing economic efficiency and environmental sustainability, these vessels present a compelling alternative to road transport, promoting greener and more cost-effective freight movement.

The case study focused on the transport route between the Port of Rotterdam and Ghent, a significant cargo corridor in Europe. This route serves as an ideal setting to examine the potential benefits of shifting from road to IWW transport. The study details the operational and performance metrics of deploying electric autonomous RoRo vessels on this route, providing empirical evidence of their feasibility and superiority over traditional truck-based systems.

Economically, the findings reveal that while CAPEX for electric autonomous RoRo vessels is higher than for road transport, OPEX is significantly lower. These vessels also demonstrate enhanced energy efficiency and lower maintenance costs, further solidifying their long-term economic advantage over conventional road transport.

Environmentally, the implementation of electric autonomous RoRo ships results in considerable reductions in GHG emissions. The study projects a substantial decrease in emissions, particularly CO2 WTW emissions, aligning with the EU's transport and environmental policies.

Our results offer valuable insights for policymakers and stakeholders, highlighting the benefits of transitioning freight transport from road to IWW using electric autonomous vessels. The study supports the EU's strategic objective of increasing the modal share of IWW, providing essential insights for future investments in sustainable transport infrastructure and innovative technologies. These findings contribute significantly to the broader discourse on sustainable transport solutions.

Future research could study the comparative performance of multiple autonomous vessel designs to analyze their respective economic and environmental impacts and identify the most effective configurations for specific transport routes. Additionally, future studies could extend the analysis to include a comprehensive CBA, factoring in more detailed externalities related to environmental impacts, as well as considering social impacts. Operational challenges, such as bridge waiting times, mooring, and communication with fairway and port traffic managers, should also be further investigated. Collaborations with industry stakeholders and real-world pilot projects would provide valuable

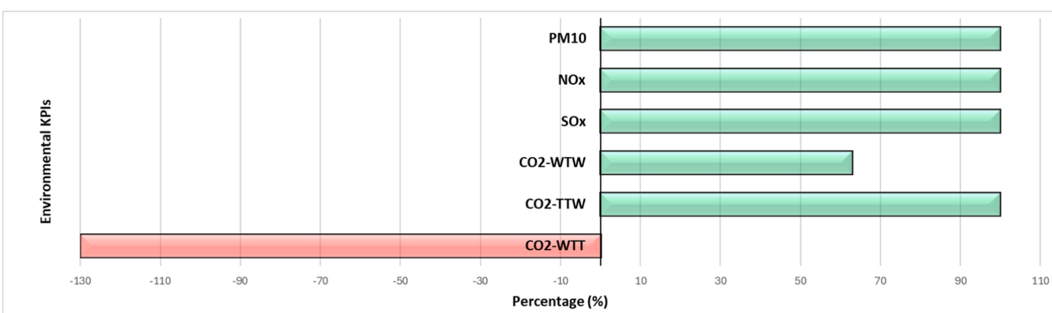


Fig. 10. Percentage difference in environmental KPIs between two scenarios.

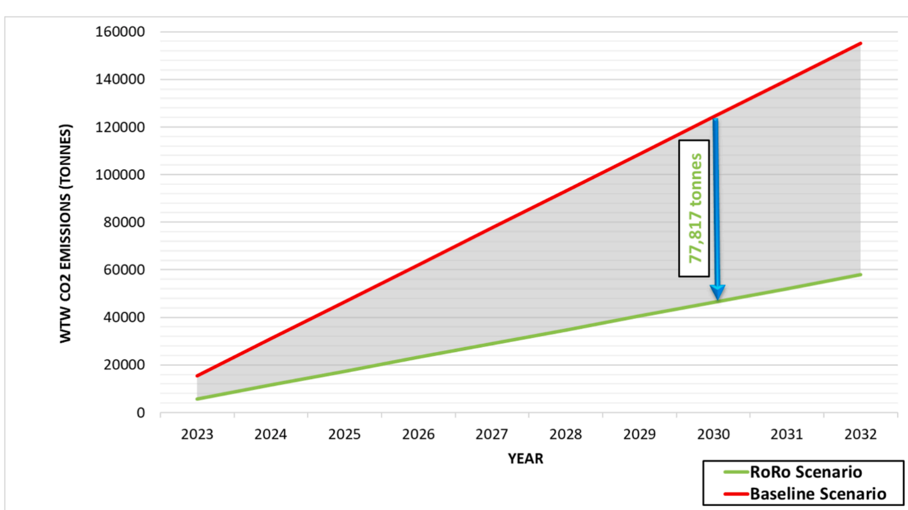


Fig. 11. WTW CO_2 emissions.

insights into the practical implementation and performance of autonomous vessels under these conditions.

CRediT authorship contribution statement

Seyed Parsa Parvasi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Harilaos N. Psaraftis:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Sotirios Michailidis:** Validation, Investigation, Formal analysis, Data curation. **Kristoffer Kloch:** Validation, Resources, Methodology, Data curation. **Stefan Krause:** Visualization, Validation, Resources, Investigation, Data curation, Conceptualization. **Espen Tangstad:** Writing – review & editing, Validation. **Odd Erik Mørkrid:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abreu, H., Santos, T.A., Cardoso, V., 2023. Impact of external cost internalization on short sea shipping–The case of the Portugal-Northern Europe trade. Transp. Res. Part D: Transp. Environ. 114, 103544.
Ahmed, Y.A., Theotokatos, G., Maslov, I., Wennersberg, L.A.L., Nesheim, D.A., 2024. Regulatory and legal frameworks recommendations for short sea shipping maritime autonomous surface ships. Mar. Policy 166, 106226.
Andersson, H., Fagerholt, K., Hobbesland, K., 2015. Integrated maritime fleet deployment and speed optimization: Case study from RoRo shipping. Comput. Oper. Res. 55, 233–240.
Bullock, S., Higgins, E., Crossan, J., Larkin, A., 2023. Improving shore power project economics at the Port of Aberdeen. Mar. Policy 152, 105625.
Cai, L., Li, W., Zhou, B., Li, H., Yang, Z., 2024. Robust multi-equipment scheduling for U-shaped container terminals concerning double-cycling mode and uncertain operation time with cascade effects. Transp. Res. Part C Emerg. Technol. 158, 104447.
Chang, C.H., Wijeratne, I.B., Kontovas, C., Yang, Z., 2024. COLREG and MASS: analytical review to identify research trends and gaps in the development of autonomous collision avoidance. Ocean Eng. 302, 117652.
Costello, D., Xu, H., 2023. Generating certification evidence for the certification of collision avoidance in autonomous surface vessels. Marit. Policy Manag. 1–20.
Dağıdır, B.D., Özkan, B., 2024. A comprehensive evaluation of a company performance using sustainability balanced scorecard based on picture fuzzy AHP. J. Clean. Prod. 435, 140519.
Dantas, J.L., Theotokatos, G., 2023. A framework for the economic-environmental feasibility assessment of short-sea shipping autonomous vessels. Ocean Eng. 279, 114420.
Daskalaki, F., Podiotis, A. (2021). Cross disciplinary assessment of autonomous shipping, ports and intermodal innovations [master's thesis, DTU Department of Technology, Management and Economics].
Densberger, N.L., Bachkar, K., 2022. Towards accelerating the adoption of zero emissions cargo handling technologies in California ports: lessons learned from the case of the Ports of Los Angeles and Long Beach. J. Clean. Prod. 347, 131255.
Deshmukh, R., Weber, P., Deschenes, O., Hernandez-Cortes, D., Kordell, T., Lee, R., Malloy, C., Mangin, T., Meng, M., Sum, S., et al., 2023. Equitable low-carbon transition pathways for california's oil extraction. Nat. Energy 1–13.
European Commission (2021). "Inland Waterway Transport - Environmental Performance". Retrieved from https://transport.ec.europa.eu/transport-modes/inland-waterways_en.
European Commission. (2011). European Commission White Paper [Available at: https://ec.europa.eu/transpor t/themes/strategies/2011 white paper en].
European Commission. (2020, September). Statistical pocketbook 2020. eu transport in figures. Luxembourg. Eurostat. (2022). Eu transport in figures. eu statistical pocketbook. Published by Eurostat.
Eurostat (2022). "Freight transport statistics - modal split". Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split.
Eurostat. (2023). Retrieved from [2023, April]. https://ec.europa.eu/eurostat/statistics-explained/index.php?titl e=File:Electricity prices for non-household consumers, first half 2022.png.
Feng, Y., Dai, L., Yue, M., Hu, H., Fang, S., 2024. Assessing the decarbonization potential of electric ships for inland waterway freight transportation. Transp. Res. Part D: Transp. Environ. 129, 104151.
Fjørtoft, K., Parvasi, S.P., Nesheim, D.A., Wennerberg, L.A.L., Mørkrid, O.E., Psaraftis, H. N., 2023. Assessing the resilience of sustainable autonomous shipping: New methodology, challenges, opportunities. Cleaner Logist. Supply Chain, 100126.
Greene, S., Jia, H., Rubio-Domingo, G., 2020. Well-to-tank carbon emissions from crude oil maritime transportation. Transp. Res. Part D: Transp. Environ. 88, 102587.
Havre, H.F., Lien, U., Ness, M.M., Fagerholt, K., Rødseth, K.L., 2024. Network design with route planning for battery electric high-speed passenger vessel services. Eur. J. Oper. Res. 315 (1), 102–119.
Hekkenberg, R.G. 2014, September. A building cost estimation method for inland ships. In European inland waterway navigation conference. Budapest, Hungary.
International Maritime Organization (IMO), 2021. Outcome of the Regulatory Scoping Exercise for the Use of Maritime Autonomous Surface Ships (MASS) [Online PDF]. Available at: https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/MSC.1-Circ.1638%20-%20Outcome%20Of%20The%20Regulatory%20Scoping%20ExerciseFor%20The%20Use%20Of%20Maritime%20Autonomous%20Surface%20Ships...%20(Secretariat).pdf.
Iru, 2021. Annual Report. International Road Transport Union.
Jia, Q., Li, R., Li, J., Li, Z., Liu, J., 2023. Vessel traffic scheduling optimization for passenger RoRo terminals with restricted harbor basin. Ocean Coast. Manag. 246, 106904.
Jovanović, I., Vladimir, N., Perčić, M., Koričan, M., 2022. The feasibility of autonomous low-emission ro-ro passenger shipping in the Adriatic Sea. Ocean Eng. 247, 110712.
Kennard, A., Zhang, P., Rajagopal, S., 2022. Technology and training: How will deck officers transition to operating autonomous and remote-controlled vessels? Mar. Policy 146, 105326.
Kersey, J., Popovich, N.D., Phadke, A.A., 2022. Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping. Nat. Energy 7 (7), 664–674.
Kooij, C., Hekkenberg, R., 2022. Identification of a task-based implementation path for unmanned autonomous ships. Marit. Policy Manag. 49 (7), 954–970.
Krause, S., Wurzler, L., Mørkrid, O.E., Fjørtoft, K., Psaraftis, H.N., Vilanova, M.R., Zis, T., Coelho, N.F., van Tatenhove, J., Raakjær, J., et al., 2022. Development of an advanced, efficient and green intermodal system with autonomous inland and short sea shipping-aegis. J. Phys. Conf. Ser. 2311 (1), 012031.
Kurt, I., Aymelek, M., 2024. Operational adaptation of ports with maritime autonomous surface ships. Transp. Policy 145, 1–10.
Larsen, R.B., Guo, W., Atasoy, B., 2023. A real-time synchromodal framework with co-planning for routing of containers and vehicles. Transp. Res. Part C Emerg. Technol. 157, 104412.
Li, P., Wang, Y., Yang, Z., 2024. Risk assessment of maritime autonomous surface ships collisions using an FTA-FBN model. Ocean Eng. 309, 118444.
Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G.M., Valland, A., 2021. Reduction of maritime GHG emissions and the potential role of E-fuels. Transp. Res. Part D: Transp. Environ. 101, 103075.
Liu, J., Law, A.W.K., Duru, O., 2022. Reducing emissions of atmospheric pollutants along major dry bulk and tanker routes through autonomous shipping. J. Environ. Manage. 302, 114080.
Lombardi, S., Di Ilio, G., Tribioli, L., Jannelli, E., 2023. Optimal design of an adaptive energy management strategy for a fuel cell tractor operating in ports. Appl. Energy 352, 121917.
Luo, C., Zhou, Y., Mu, M., Zhang, Q., Cao, Z., 2024. Subsidy, tax or green awareness: Government policy selection for promoting initial shore power usage and sustaining long-run use. J. Clean. Prod. 442, 140946.
Martensson, L. (2018). Emissions from volvo trucks. retrieved from volvo trucks. https://www.volvotrucks.com/content/dam/volvo-trucks/markets/global/our-values/environmental-care/our-trucks/Emis eng 10110 14001.pdf.
MacKinnon, S. N., Man, Y., Baldauf, M. (2015). D8. 8: Final Report: Shore Control Centre. Maritime Unmanned Navigation through Intelligence in Networks.
Makkonen, H., Nordberg-Davies, S., Saarni, J., Huikkola, T., 2022. A contextual account of digital servitization through autonomous solutions: Aligning a digital servitization process and a maritime service ecosystem transformation to autonomous shipping. Ind. Mark. Manag. 102, 546–563.
Mansour, C., Haddad, M., Zgheib, E., 2018. Assessing consumption, emissions and costs of electrified vehicles under real driving conditions in a developing country with an inadequate road transport system. Transp. Res. Part D: Transp. Environ. 63, 498–513.
Molland, A.F., Turnock, S.R., Hudson, D.A., 2017. Ship resistance and propulsion. Cambridge University Press.
Munim, Z.H., Notteboom, T., Haralambides, H., Schøyen, H., 2025. Key determinants for the commercial feasibility of maritime autonomous surface ships (MASS). Mar. Policy 172, 106482.
Naumov, S., Keith, D.R., Sterman, J.D., 2023. Accelerating vehicle fleet turnover to achieve sustainable mobility goals. J. Oper. Manag. 69 (1), 36–66.
Pang, B., Liu, S., Zhu, H., Feng, Y., Dong, Z., 2024. Real-time optimal control of an LNG-fueled hybrid electric ship considering battery degradations. Energy 296, 131170.
Park, C., Jeong, B., Zhou, P., Jang, H., Kim, S., Jeon, H., Rashedi, A., 2022a. Live-Life cycle assessment of the electric propulsion ship using solar PV. Appl. Energy 309, 118477.

Park, H., Blanco, C.C., Bendoly, E., 2022b. Vessel sharing and its impact on maritime operations and carbon emissions. Prod. Oper. Manag. 31 (7), 2925–2942.
Parvasi, S.P., Psaraftis, H.N., Lam, J.S.L. (2024). Transformation in the Maritime Sector via Autonomous Vessels and Eco-Friendly Fuels. In EURO-2024 Copenhagen: 33rd European Conference on Operational Research.
Peng, X., Ding, Y., Yi, W., Laroussi, I., He, T., He, K., Liu, H., 2024. The inland waterway ship emission inventory modeling: the Yangtze River case. Transp. Res. Part D: Transp. Environ. 129, 104138.
Psaraftis, H.N., Giovannini, M., 2018. The profit maximizing liner shipping problem with flexible frequencies. Balancing Economic and Environmental Performance. EURO 2018 Conference on Operational Research.
Psaraftis, H.N., Zis, T., 2020. European policies for short sea shipping and intermodality. In: Short Sea Shipping in the Age of Sustainable Development and Information Technology. Routledge, pp. 3–21.
Psaraftis, H.N., Zis, T.P., Vilanova, M.R. (2023). The logistics of autonomous shipping and the aegis project. SNAME International Symposium on Ship Operations, Management and Economics, D021S005R004.
Rødseth, Ø.J., Psaraftis, H.N., Krause, S., Raakjær, J., Coelho, N.F., 2020. Aegis: advanced, efficient and green intermodal systems. IOP Conf. Ser.: Mater. Sci. Eng. 929 (1), 012030.
Seddiek, I.S., Ammar, N.R., 2023. Technical and eco-environmental analysis of blue/green ammonia-fueled RO/RO ships. Transp. Res. Part D: Transp. Environ. 114, 103547.
Shahbakhsh, M., Emad, G.R., Cahoon, S., 2022. Industrial revolutions and transition of the maritime industry: the case of Seafarer's role in autonomous shipping. Asian J. Shipping Logist. 38 (1), 10–18.
Shangguan, Y., Tian, X., Pang, K.W., Ruan, Q., Jin, Y., Wang, S., 2024. Navigating the green shipping: stochastic hydrogen hub deployment in inland waterways. Transp. Res. Part D: Transp. Environ. 129, 104126.
Sharma, A., Kim, T.E., 2022. Exploring technical and non-technical competencies of navigators for autonomous shipping. Marit. Policy Manag. 49 (6), 831–849.
Solakivi, T., Paimander, A., Ojala, L., 2022. Cost competitiveness of alternative maritime fuels in the new regulatory framework. Transp. Res. Part D: Transp. Environ. 113, 103500.
Song, Z., Tang, W., Zhao, R., Zhang, G., 2022. Implications of government subsidies on shipping companies' shore power usage strategies in port. Transp. Res. Part E: Logist. Transp. Rev. 165, 102840.
The European commission. (2009, January). Strategic goals and recommendations for the eu's maritime transport policy until 2018 (COM/2009/0008 final). Brussels.
The European Green Deal. (2019). A european green deal. Available at: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal en].
Wang, W., Wang, S., Zhen, L., Laporte, G., 2023. The impact of autonomous ships in regional waterways. Transp. Res. B Methodol. 178, 102851.
Xing, W., 2024. Contemplating Maritime Autonomous Surface Ships (MASS) under the international law on ship-source pollution. Mar. Pollut. Bull. 207, 116884.
Yan, R., Wang, S., Psaraftis, H.N., 2021. Data analytics for fuel consumption management in maritime transportation: status and perspectives. Transp. Res. Part E: Logist. Transp. Rev. 155, 102489.
Yiteng, L., Ling, Z., 2024. Exploring industry acceptance of maritime autonomous surface ships: a grounded theory approach. Res. Transp. Bus. Manag. 57, 101221.
Yuen, K.F., Koh, L.Y., Fong, J.H., Wang, X., 2022. Determinants of digital transformation in container shipping lines: a theory driven approach. Marit. Policy Manag. 1–16.
Zanobetti, F., Pio, G., Jafarzadeh, S., Ortiz, M.M., Cozzani, V., 2023. Decarbonization of maritime transport: sustainability assessment of alternative power systems. J. Clean. Prod. 417, 137989.
Zhang, X., Jia, N., Song, D., Liu, B., 2024. Modelling and analyzing the stacking strategies in automated container terminals. Transp. Res. Part E: Logist. Transp. Rev. 187, 103608.
Zhao, Y., Chen, Y., Fagerholt, K., Lindstad, E., Zhou, J., 2023. Pathways towards carbon reduction through technology transition in liner shipping. Marit. Policy Manag. 1–23.
Zis, T.P., Psaraftis, H.N., Reche-Vilanova, M., 2023. Design and application of a key performance indicator (kpi) framework for autonomous shipping in Europe. Marit. Transport Res. 5, 100095.
Zou, J., Yang, B., 2023. Evaluation of alternative marine fuels from dual perspectives considering multiple vessel sizes. Transp. Res. Part D: Transp. Environ. 115, 103583.