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SuTra2026

International Conference on Sustainable Transport

Proceedings

of the 3rd International Conference on Sustainable Transport

Opatija, Croatia • 4 – 6 November 2026

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Preface

The *SuTra 2026 Proceedings* bring together 38 papers developed from contributions presented at the 3rd International Conference on Sustainable Transport. The volume complements the *Book of Conference Contributions*, which captures the broader conference programme through research and student abstracts, project summaries, invited lectures and expert panel contributions.

The Proceedings provide space for a substantial part of that research to be presented in depth. Taken together, the papers reflect the breadth of contemporary transport research, but also how difficult it has become to consider individual transport problems in isolation. Digitalisation intersects with safety and resilience, decarbonisation affects technology, operations and training, infrastructure decisions reshape logistics and mobility, while data-driven systems continue to depend on human judgement and institutional capacity. Across the volume, technological, operational, environmental, economic and human perspectives repeatedly meet, overlap and move beyond the boundaries of individual topics.

For editorial clarity, the papers are organised into six thematic sections: Artificial Intelligence and Data-Driven Transport Systems; Navigation, Safety and Human-Centred Transport Systems; Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems; Logistics, Supply Chains, Ports and Freight Transport; Smart Mobility, Rail and Evidence-Based Transport Planning; and Urban Mobility, Road Safety and Transport Behaviour. These sections provide structure to the volume, while allowing the connections between individual contributions to remain visible.

The papers differ considerably in scale and methodological approach. Some focus on specific technologies, analytical methods and operational procedures, while others examine infrastructure, transport services, planning processes, environmental pressures, policy challenges or user behaviour. Read together, they provide a cross-section of the scientific and professional work developed within the conference and of the different ways in which contemporary transport problems are being approached. Bringing these contributions together has also made the scale of the work behind SuTra 2026 particularly visible. What began as individual research questions, methods and case studies now stands as a single volume in which different transport modes, disciplines and lines of inquiry can be read alongside one another. There is a particular satisfaction in seeing that work take shape and in knowing that it can continue to be used beyond the conference itself.

We thank all authors for preparing and submitting their full papers, as well as the reviewers, editors and colleagues whose work contributed to the preparation of this volume. We hope that the *Proceedings* will remain a useful reference for researchers, professionals and other stakeholders working across the fields represented at SuTra 2026, and across the spaces between them.

Editors

Cross-cutting dimensions

Distinct research themes, connected across papers and sections.

HOW TO READ

Each row is a paper; each column is a research dimension.

Darker cells indicate greater thematic prominence.

Coloured bands identify the six proceedings sections.

Editorial assessment of themes; not a measure of research quality.

MEAN SCORE ACROSS 38 PAPERS

Digitalisation AI & automation	Safety, risk & resilience	Energy & environment	Infra-structure & networks	Logistics & operations	Human factors & governance
1.8	2.0	1.5	2.0	2.4	2.1

		Digitalisation AI & automation	Safety, risk & resilience	Energy & environment	Infra-structure & networks	Logistics & operations	Human factors & governance
01	**ARTIFICIAL INTELLIGENCE AND DATA-DRIVEN TRANSPORT SYSTEMS**						**7 papers**
01	Artificial intelligence in maritime transport and seaport operations	3	1	1	1	2	1
02	Artificial intelligence applications for maritime safety challenges	3	3	1	1	2	2
03	Neural network-based ship performance prediction for autonomous navigation	3	2	2	1	3	1
04	Individual ship-motion components for attention-based sea-state classification	3	2	1	1	3	1
05	Observation-window length in sea-state classification from vessel motions	3	2	1	1	3	1
06	Multi-layer validation of AIS-derived mooring episodes in ports	3	2	1	2	3	1
07	Emerging sensor fusion technologies: electro-optical and radar systems	3	3	1	2	2	1
02	**NAVIGATION, SAFETY AND HUMAN-CENTRED TRANSPORT SYSTEMS**						**3 papers**
08	GPS L1 elevation mask angle effects on maritime positioning availability	1	3	1	1	2	1
09	Collision prevention using simulated ship-avoidance strategies	2	3	1	1	3	2
10	Human readiness for the digital transformation of maritime navigation	2	3	1	1	2	3
03	**DECARBONISATION, CLIMATE RESILIENCE & SUSTAINABLE COASTS**						**7 papers**
11	Green strategies for achieving IMO net-zero transition goals	1	1	3	1	2	3
12	Wind-assisted propulsion: maritime training and navigational safety	1	3	3	1	2	3
13	Key challenges in the blue economy sectors	1	1	3	2	2	3
14	Climate risk in the Rhine-Danube-Sava inland waterway corridor	1	3	3	3	2	2
15	Sustainable coastal management in Zadar County	1	2	3	2	1	3
16	Port-city relationships and sustainable development	1	1	3	3	2	3
17	Operational criteria for beach safety flag management	1	3	2	1	2	3
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18	Global supply chain disruptions and import resilience	2	2	1	2	3	2
19	Cargo consolidation and documentation flow in LCL logistics	2	1	1	2	3	2
20	Reconstruction of the Rijeka railway junction	1	1	2	3	3	2
21	Suspended steel-wheel string-rail systems for freight transport	2	2	2	3	3	1
22	Connected reefer containers for perishable cargo supervision	3	2	2	2	3	1
23	UAV delivery logistics in the UTM/U-space environment	3	2	2	2	3	2
24	Delivery vehicle allocation and routing with open-source tools	3	1	2	2	3	1
25	Simulation-based evaluation of urban freight delivery flows	3	1	2	2	3	1
26	Last-mile delivery for sustainable urban logistics	2	1	3	2	3	2
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THEMATIC PROMINENCE 0 Not material · 1 Secondary · 2 Substantial · 3 Dominant

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I. Artificial Intelligence and Data-Driven Transport Systems

Artificial Intelligence in Maritime Transport and Seaport Operations: A Literature Review

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ABSTRACT

Artificial intelligence (AI) has become one of the key drivers of digital transformation in the maritime transport sector by supporting safer, more efficient, and more sustainable maritime operations. As research in this field continues to expand, a comprehensive synthesis of current knowledge is needed to better identify the main areas of AI application and emerging research trends. This study presents a literature review of recent research on artificial intelligence in maritime transport and seaports. The findings indicate that current research primarily focuses on (smart) port operations and management, navigation (trajectory prediction, surveillance, safety and security), strategic planning and forecasting in shipping, and environmental sustainability and energy efficiency. While the reviewed literature demonstrates considerable potential for improving operational performance, safety, and environmental sustainability, several barriers continue to limit the wider adoption of AI, including data quality, interoperability, integration with existing systems, and reliable real-time data processing. Cybersecurity, regulatory requirements, and organisational resistance to change also remain important concerns.

Keywords: artificial intelligence; shipping; maritime transport; seaports; literature review

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FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

The maritime transport sector is undergoing an intensive digital transformation, with artificial intelligence (AI) increasingly recognised as an important technology for supporting data-driven decision-making and improving the efficiency, safety, and sustainability of maritime operations. Previous research has identified several major areas in which big data and AI are influencing the maritime industry, including digital transformation, the exploitation of Automatic Identification System (AIS) data, energy efficiency, and predictive analytics [1]. More recent research indicates that the application of AI in shipping has expanded considerably, particularly in areas involving machine learning, deep learning, trajectory analysis, anomaly detection, and energy-efficient ship operations [2]. AI-based methods are also increasingly investigated in relation to maritime safety and risk management, where they can support hazard identification, predictive maintenance, navigation, and real-time operational decision-making [3]. Despite this growing body of research and the considerable potential of AI, its implementation across maritime transport and seaport operations remains fragmented, highlighting the need for a structured synthesis of current applications, opportunities, and implementation challenges.

This paper provides a structured review of recent research on artificial intelligence applications in maritime transport and seaport operations. The study examines the main areas in which AI is currently applied, the research methodologies used to investigate these applications, and the principal opportunities and challenges associated with their implementation. The review is based primarily on peer-reviewed publications indexed in the Web of Science database. The selected publications were then analysed according to their AI application areas, research methodologies, and reported opportunities and implementation challenges. The results are organised into the main thematic areas identified in the literature, including smart port operations and management; navigation, safety and security; strategic planning and forecasting in shipping; and environmental sustainability and energy efficiency. The paper concludes by discussing the main research trends, current limitations, and areas requiring further empirical investigation and real-world validation.

2 METHODOLOGY

The review is based on peer-reviewed publications indexed in the Web of Science database and is complemented by recent industry reports and other relevant practice-oriented documents to provide additional context on current developments in the maritime sector. The initial literature search was performed on 5 August 2026 in the Web of Science using the Topic field (titles, abstracts, author keywords, and Keywords Plus®). Web of Science was selected to ensure a consistent and clearly defined search process. Future research could extend the search to additional databases, such as Scopus, to broaden the literature coverage.

The search employed the keywords (“artificial intelligence” OR AI) AND (“maritime transport” OR shipping OR seaport OR vessel OR “fleet management” OR “marine logistics”). The search identified a total of 274 records. After removing 17 duplicate records, 257 unique records remained for further screening. The selection was subsequently refined by focusing on studies that explicitly refer to AI in their titles. This refinement resulted in 219 records. This approach was used to establish a more clearly defined research scope and to prioritise studies in which AI is explicitly positioned as a key element of the research. The remaining records were screened for relevance to the operational context of maritime transport and seaport activities. A substantial number of records were excluded because the search term “vessel” also retrieved publications from unrelated research fields, particularly medical studies. At the end, 34 studies were included in the final analysis. The selected studies were analysed according to their application areas, research methodologies, and key opportunities and challenges.

Research methodologies were considered to understand how AI applications have been studied and evaluated across different maritime contexts.

Some previous reviews, such as [2], used a broad range of AI-related technologies and techniques as search terms. In contrast, this review focuses on studies that explicitly refer to AI in their titles, allowing for a more focused analysis of research that directly addresses AI in maritime transport and seaport operations. Therefore, specific AI techniques, such as machine learning, deep learning, reinforcement learning, or neural networks, were not used as separate search terms. Consequently, relevant studies focusing on these techniques without explicitly referring to "artificial intelligence" or "AI" in their titles may not have been included.

Additionally, studies focusing primarily on ship design, structural engineering, and military or naval-specific engineering applications were excluded, as these fall outside the operational scope of maritime transport and seaport activities considered in this review, for example [4] or [5].

3 RESULTS

The selected studies were grouped according to the main areas of AI application identified in the literature: (smart) port operations and management, navigation (trajectory prediction, surveillance, safety and security), strategic planning and forecasting in shipping, and environmental sustainability and energy efficiency.

Table 1 presents the key findings of each study together with the research methodologies used, providing an overview of how AI is currently applied and investigated across different areas of maritime transport and seaport operations.

Table 1. Overview of selected studies on AI applications in maritime transport and seaport operations.

Categories	Key research findings per paper	Research methodology
(Smart) port operations and management	AI is applied across a wide range of seaport operations, including berth allocation, quay crane optimisation, port traffic and vessel management. The study identifies gaps in the use of advanced AI techniques. [6]	Systematic literature review (PRISMA), network analysis, descriptive and content analysis.
	AI is mainly applied to vessel arrival forecasting and scheduling, berth and quay crane allocation, container handling, and predictive maintenance. [7]	Systematic literature review (PRISMA) – 30 included articles published between 2021 and early 2025.
	AI-based models were used to predict ship waiting and turnaround times to support port planning and resource allocation. [8]	Machine learning (XGBoost, Random Forest, Decision Tree) using AIS data.
	AI applications mainly focus on predicting truck arrivals, improving gate scheduling, and automating vehicle and cargo recognition. Practical AI integration remains a challenge. [9]	Systematic literature review (PRISMA), bibliometric and content analysis; 26 studies.
	The review identifies the potential of AI and computer vision to improve traffic management, parking space allocation, and container movement in seaports, supporting operational efficiency and sustainability. [10]	Systematic literature review; PRISMA guidelines; quality assessment; collaborative data extraction.

Categories	Key research findings per paper	Research methodology
(Smart) port operations and management	A conceptual framework is proposed to identify lanes and available parking spaces for container trucks using CCTV video data, supporting seaport traffic management and container movement. [11]	Literature review; conceptual mathematical framework; convolutional neural networks (CNN); transfer learning.
	The study identifies 13 key risks associated with AI transformation in container terminals and proposes a resilience-based AI governance model and strategic roadmap to support successful AI implementation. [12]	Text mining, Fault Tree Analysis (FTA), and backcasting-based scenario planning.
	AI can improve operational efficiency and decision-making, while implementation costs, data quality, workforce readiness, and resistance to change remain key barriers to adoption. [13]	Qualitative interviews and thematic analysis (Port of Rotterdam).
	Human-factor barriers that hinder the effective use of AI-driven digital collaboration in the Indonesian port context are identified. [14]	Qualitative interviews and quantitative survey; thematic analysis, Importance–Performance Matrix, and Adoption Matrix.
	AI applications in port ecosystems are concentrated in three main areas: operational efficiency and optimisation, digital and smart-port enablement, and governance, risk, and compliance. The literature shows a shift from operational applications toward more integrated approaches focused on sustainability and resilience. [15]	Systematic screening and bibliometric analysis of 80 peer-reviewed articles published between 2019 and 2025, using performance analysis and science mapping.
Navigation (trajectory prediction, surveillance, safety and security)	Different machine-learning and deep-learning methods are discussed, with recurrent neural networks showing strong capabilities in using historical Automatic Identification System data for accurate real-time ship trajectory prediction. [16]	Review and comparative analysis of machine-learning and deep-learning methods for ship trajectory prediction.
	AI reduced average fuel consumption by 12.4% and voyage duration by 8.2%, while improving ship stability. Predictive maintenance algorithms achieved 95% accuracy, enabling early fault detection and reducing unscheduled downtime. [17]	Development of a hybrid deep learning model using onboard telemetry data from 16 commercial vessels to predict vessel speed, fuel consumption, and stability.
	AI-based models are increasingly used to predict vessel traffic volumes, trajectories, velocities, destinations, and traffic patterns. Key challenges include integrating large datasets and enabling real-time data analytics. [18]	Literature review of 106 publications identified through Web of Science; bibliometric analysis using CiteSpace, including keyword co-occurrence analysis and keyword clustering.
	An ensemble learning approach improves positioning precision in SINS/GPS integrated ship navigation, including during GPS unavailability. [19]	Ensemble learning-based modelling of SINS/GPS integrated navigation, verified using ship-mounted experimental data from various trajectories.

Categories	Key research findings per paper	Research methodology
Navigation (trajectory prediction, surveillance, safety and security)	The literature shows a growing shift from single-modality approaches towards the fusion and combination of systems. The integration of Synthetic Aperture Radar and Automatic Identification System data is identified as particularly promising for real-time vessel detection and anomaly identification. [20]	Literature review and bibliometric analysis of studies published from 2016 to 2025 (recent advances in machine-learning and deep-learning techniques for sea monitoring).
	AI is expected to play an important role in Maritime Autonomous Surface Ships, particularly in supporting decision-making. However, conventional manned ships are likely to adopt autonomous shipping gradually. [21]	Literature-based discussion of AI, autonomous ships, and related legal developments in the shipping industry.
	AI has applications in risk analysis, crew resource management, hazardous material handling, predictive maintenance, and navigation systems. It can support hazard identification, real-time decision-making, equipment failure prediction, and route optimisation. [3]	Systematic literature review of studies published between 2010 and 2023, complemented by case-study analysis.
	Convolution Neural Network and Random Forest models detect shoals in satellite imagery with accuracies ranging from 79% to 94% across two study sites. WorldView-2 imagery provides higher accuracy and lower omission errors, supporting the identification of hazards to navigation. [22]	Visual interpretation of satellite imagery and comparison of convolutional neural network (CNN) and Random Forest (RF) classification using Sentinel-2 and WorldView-2 imagery from two study sites.
	AI enhances intrusion and anomaly detection, cyber risk assessment, and cyberattack mitigation. Key limitations include dataset availability, validation, algorithm transparency, resistance to adversarial threats, and legal and regulatory alignment [23]	Systematic literature review (PRISMA), with qualitative / narrative synthesis of studies published between 2015 and 2025.
	AI and machine learning enable more accurate fault diagnosis and early identification of system failures, helping to prevent unplanned failures and costly downtime and improve operational safety and efficiency. [24]	Development of an AI- and machine-learning-based fault detection approach, evaluated on real shipboard data through tests on a seawater cooling system from an oil tanker.
Strategic planning and forecasting in shipping	Machine-learning algorithms are used to determine the optimal route of cargo ship movement based on the number of ports, fuel quantity, cargo destination, distances between ports, and intermediate ports of call. The approach simplifies freight calculations and helps reduce fuel and human-resource costs. [25]	Machine-learning-based modelling, four models are used in order to build an optimal cargo transportation system; traveling wave equation.
	Long Short-Term Memory networks outperform traditional econometric models in forecasting dry bulk freight rates and steel scrap prices. The decision-support framework helps shipowners assess continued vessel operation versus recycling and evaluate fleet-renewal scenarios. [26]	Comparison of Long Short-Term Memory networks with traditional econometric models using weekly data from 1996–2025; scenario analysis in a real-time simulation environment.

Categories	Key research findings per paper	Research methodology
Strategic planning and forecasting in shipping	AI-powered big data analytics positively affects sustainable practice performance in shipping organisations. Organisational flexibility and interpartner resource sharing support this effect, contributing to a strategic mechanism for sustainable management. Potential issues include data security and third-party service platforms. [27]	Empirical analysis based on data from 182 shipping organisations, using a nine-tier hierarchical moderating regression model and three-way interaction analysis.
	Among the five forecasting models, the deep learning model had the highest goodness of fit and was selected to estimate bunkering demand by country and region. [28]	Meta-regression, analogy method, and comparison of five forecasting models, including deep learning, for liquefied natural gas bunkering demand forecasting.
Environmental sustainability and energy efficiency	AI and machine learning can support intelligent ship optimisation and operation, improving energy efficiency and ship intelligence. However, these technologies have not yet been effectively promoted or widely applied in green and intelligent shipping. [29]	Systematic literature review of Web of Science publications, primarily covering 2019–2025.
	AI is identified as an enabler of nuclear-powered shipping by enhancing operational efficiency, reducing operational costs, and improving safety and security. [30]	Review based on existing AI applications in land-based nuclear energy systems and conventionally powered maritime vessels.
	The multi-agent AI framework reduced waiting times, fuel consumption and CO_2 emissions while maintaining throughput, with cost reductions also observed in the simulations. [31]	Multi-agent artificial intelligence framework based on game-theoretic principles, evaluated through operational simulations using data from the Ports of Piraeus and Valencia.
	Technological innovation, policy development, and industry collaboration are key drivers of sustainable shipping. AI can support the analysis of ship performance, fuel consumption, and emission patterns to inform operational decisions and reduce environmental impacts. [32]	Structured literature review using ChatGPT-4 for keyword frequency and sentiment analysis, with results cross-validated using NVivo and manual checks.
	AI and machine learning are applied to emissions prediction, route and speed optimisation, predictive maintenance, and other areas to improve environmental performance. Despite high predictive performance, their large-scale application is constrained by limited robustness, fragmented data standards, and scarce real-world validation. [33]	PRISMA-based systematic literature review of 78 peer-reviewed studies published between 2010 and 2025.
	AI can support sustainable shipping and green port operations through route optimisation, fuel consumption and emissions reduction, predictive maintenance, and smart energy management. [34]	Extensive literature review with thematic, comparative, and gap analysis, supported by case studies of Maersk Line and the Port of Rotterdam.

Categories	Key research findings per paper	Research methodology
Environmental sustainability and energy efficiency	AI is applied across waste classification, collection and vehicle routing, decision-making, and site selection, with hybrid and advanced algorithms showing high accuracy and performance. The study proposes an AI-based framework for integrated port waste management to improve operational efficiency, sustainability, and resilience. [35]	Systematic literature review of 50 scientific records published between 2014 and 2024, including a comparative analysis of municipal and port waste management systems.
	AI, applied through Bayesian network modelling, is used to analyse factors influencing liquefied natural gas use in European short sea shipping. Transport, international trade, and economic and financial factors are identified as the most important. [36]	Data-mining techniques and Bayesian network modelling using 35 indicators across five categories, based on data from 30 European countries.

Source: Made by authors

The reviewed studies show that AI is being applied across a wide range of maritime transport and seaport operations, with particular attention to port operations, navigation and safety, and environmental sustainability. However, a considerable part of the selected literature consists of systematic and bibliometric reviews, while fewer studies examine AI applications using operational data or in real-world maritime settings. Similar concerns have been raised in previous research. Study [7] notes that further empirical research is needed to support scalable AI deployment in different port environments, while [28] highlights limited real-world validation as a constraint on the wider application of AI in maritime operations.

4 DISCUSSION

AI-based solutions can contribute to greater operational efficiency, safety and prediction accuracy, while reducing fuel consumption, emissions and downtime. However, their broader adoption is still constrained by several challenges.

When considered across the four application areas, several common and application-specific challenges to AI adoption can be identified. The strongest recurring challenges in (smart) port operations and management are: data-related challenges (quality, availability, standardisation, sharing and security) [7-9, 11-15], interoperability and system integration [7, 9, 14, 15], scalability, generalisability and real-world validation/deployment [7-11, 15], cybersecurity, privacy and data governance [7, 9, 10, 12, 14, 15], human and organisational challenges (workforce readiness, skills, resistance to change, stakeholder integration) [9, 12-15], implementation/resource costs [7, 12-14] and governance and regulatory issues [9, 12, 14, 15]. This indicates that the challenges in port-related AI adoption extend beyond technical performance, with data management, system integration and organisational factors playing an important role in practical implementation.

The strongest recurring challenges in navigation (trajectory prediction, surveillance, safety and security) are: data-related challenges (e.g., data quality, missing or insufficient data) [3, 16, 18, 20, 22-24], generalisation, scalability and real-world validation/deployment [16, 18, 20, 22-24], computational and real-time processing requirements [16, 18, 22], cybersecurity and adversarial vulnerability [3, 23], explainability, reliability and trustworthiness [20, 21, 23], infrastructure and technological limitations (compatibility with existing infrastructure, sensor and hardware requirements, GPS availability) [3, 19, 22, 24], regulatory and compliance issues [3, 23] and implementation and operational costs [3, 16, 22].

This suggests that the adoption of AI in navigation depends strongly on the ability of AI systems to operate reliably in complex and dynamic maritime environments, supported by adequate data, infrastructure and computational capabilities.

The main challenges in strategic planning and forecasting in shipping are: forecasting uncertainty and changing external conditions [26, 28], data availability and historical-data limitations [28], complexity of modelling maritime systems and markets [25, 26], and data security and organisational conditions [27].

The main challenges in environmental sustainability and energy efficiency are: data quality, availability and standardisation [29, 33, 34], scalability, generalisability and real-world validation [29, 33, 34], regulatory and compliance challenges [30, 33, 34], implementation and technological challenges [30, 34] and stakeholder coordination [31, 32].

A comparison across the four application areas shows that several challenges recur across different maritime contexts. Data-related limitations are the most widespread, while scalability, generalisability and real-world validation also recur across several areas. However, some challenges are more application-specific, such as organisational and interoperability issues in port operations, reliability and computational requirements in navigation, and uncertainty in strategic planning and forecasting. These findings suggest that AI adoption in maritime transport is constrained by both common and application-specific challenges.

5 CONCLUSION

The findings indicate that AI research in maritime transport and seaport operations is expanding across a broad range of operational and strategic areas, but the level of practical implementation remains uneven. Although the reviewed studies demonstrate substantial potential for improving efficiency, safety, forecasting, and environmental performance, a considerable share of the existing literature is still based on systematic reviews, bibliometric analyses, or experimental applications rather than extensive real-world deployment. This suggests that the maritime sector is moving from the exploration of AI capabilities towards practical implementation, but further empirical validation using operational data and different port and shipping environments is still required. Technological benefits cannot be considered independently of implementation conditions, as data quality, interoperability, cybersecurity, regulatory requirements, system integration and organisational readiness may significantly influence the successful AI adoption.

A key limitation of this study is that the literature search was intentionally restricted to publications explicitly referring to “artificial intelligence” or “AI” within the defined search strategy and was subsequently refined to studies that included AI in their titles. This approach helped maintain a focused scope but may have excluded relevant research addressing specific AI-related techniques, such as machine learning, deep learning, computer vision, or predictive analytics, without explicitly using the term artificial intelligence. In addition, the predominance of review-based and bibliometric studies in the selected literature, together with the relatively limited number of studies based on operational datasets and real-world maritime environments, further constrains the extent to which the findings can be generalised across different ports, shipping segments, vessel types, regulatory settings, and technological contexts.

Future research should place greater emphasis on the empirical validation of AI applications using real-world operational data from diverse maritime transport and seaport environments. Particular attention should be given to the scalability and interoperability of AI-based solutions, as well as to their safe integration into existing maritime operations. Further research should also examine the interaction between human operators and AI systems and appropriate governance frameworks in supporting reliable AI adoption.

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I. Artificial Intelligence and Data-Driven Transport Systems

Leveraging Artificial Intelligence Applications for Maritime Safety Challenges: A Feature-Based Analysis

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ABSTRACT

This paper aims to provide an analytical overview of the use of Artificial Intelligence (AI)-supported applications in relevant challenges for maritime safety, reduction of ship collision risks, and autonomous shipping. Maritime autonomous ships are considered a new chapter in future maritime transportation, and it is expected that through integrated machine learning (ML) models, they will be capable of avoiding collisions, responding smartly and quickly in case of emergencies, planning the optimal navigation paths, reducing human errors, and providing overall operational and situational awareness. Using algorithms for classifying and clustering Automatic Identification System (AIS) data significantly contributes to the detection of maritime anomalies, timely prevention of potential collisions at sea, together with anticipatory risk management in infrastructure contexts. Therefore, the main applications of AI-based technologies and their features are focused on the analysis of vast amounts of Big Data using ML methods to provide a better operational picture. For example, deployment of ML algorithms enables identifying voyage paths and ship types, predicting trajectories, destination ports and estimated time of arrival and detecting maritime anomalies and route deviations. To summarize, current disruptive AI developments in the maritime context enable several applications: in predictive analytics for forecasting future states, in protecting the ships and maritime infrastructure from collision, cyber and other risks, in supporting humans with accurate information in the decision-making process and in advancing the operational automation that leads to improvement of functions such as cargo handling and autonomous vessel concept development.

Keywords: maritime safety; AI; collision risks; autonomous shipping; Big Data

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FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

In the last few years, following the huge technological advancement in data science and the development of sophisticated devices and systems, the operational processes onboard ships and in maritime authorities are increasingly being automated through the use of AI systems. Similar to other transport branches, one of the goals of maritime authorities is to detect critical situations early and react accordingly, which is of utmost significance for maritime Vessel Traffic Service (VTS) departments and coordination of Search and Rescue (SAR) operations [1].

The maritime market analysis shows that AI systems are primarily used to identify obstacles, create a situational awareness picture, predict the behaviour of other vessels, and plan and optimize routes. Specifically, in the broader scope of Autonomous Maritime Systems (AMS), including its subset Maritime Autonomous Surface Ships (MASS), AI plays an essential role, since the market has reached a high level of technological maturity, with an annual market growth rate of 10% [2]. In light of the level of AI development and possible mistakes made by AI, special attention is paid to testing the safety and functionality of any AI system in the future, focusing on whether and how a system generally works. Considering the increasing application of AI technology in the maritime industry, it is expected that the maritime AI market will increase from $ 1.4 billion to more than $122 billion by 2030 [3].

The mentioned features rely on one of the core subsets of AI, Machine Learning (ML), which is a range of algorithms and methods that involve regression, predicting continuous numeric values, or classification, determining classes or types for data points. Specifically, for maritime purposes, ML models could be used for anomaly detection of vessel movements, identification of vessels from imagery, satellites data, and sensor readings, optimisation of fuel consumption and maintenance, and in autonomous shipping as well [4].

This paper unfolds as follows: after introductory considerations, Section 2 presents the research methodology, Section 3 provides insights and analysis of AI technologies applied in the maritime sector, specifically in maritime safety and autonomous shipping, Section 4 offers an overview of research results, while Section 5 concludes the paper.

2 RESEARCH METHODOLOGY

This study employs a qualitative research design combining thematic analysis and narrative synthesis, drawing upon recent scientific, bibliographic and document analysis of the latest trends in AI technology range and application in the maritime industry, specifically in the field of maritime safety and AMS. The paper consists of an overview of the most recent developments of AI-supported technologies and algorithms with significant application in the maritime industry and sector, including a comparative and feature-based breakdown analysis that contains the categorization of layers and essential functions performed by each component of the AI supported systems range used for maritime purposes.

The methodological approach of the paper consists of a bibliographic database and literature analysis focusing on AI/ML impacts on maritime safety, collision risk mitigation, and the capabilities of deploying AI technologies in autonomous shipping. The goal of this research is to make an overall evaluation of the strong and weak points of the considered AI/ML features as well as maritime use cases with appropriate ML methods that are given comparatively as a table overview respectively.

3 ANALYSIS OF AI APPLICATIONS IN THE MARITIME INDUSTRY

3.1 Recent AI applications in the maritime safety area

Contemporary integrated AI-powered systems are developed to provide real-time visibility, predictive capabilities, and automated decision support across voyage operations and supplier networks, in order to proactively manage and optimize risks with the ultimate goal of reducing operational costs and enhancing the profitability of maritime organizations. Based on Big Data, AI technologies provide the analytical sophistication needed to understand and manage complex interdependencies, while modern computing infrastructures provide the computational power required to process the associated data and models (e.g. maritime CISE models for EU countries), and operational transparency in real time [3, 5].

In order to produce an output such as the analysis of accident factors, probability/likelihood, severity, and description, ML applied to maritime safety and risk assessment relies on several datasets with Big Data collected from various sources aboard ships, large databases, and international platforms, stored in Data Lakes. In that sense, this study proposes a framework containing multilayered sets of AI technologies necessary for integrated response to challenges in complex maritime environments to achieve better performance of authorities regarding decision support, port process optimization, and risk monitoring. This framework is illustrated in **Figure 1**. In order to make accurate predictions and decisions, ML algorithms must be designed and trained to consider multiple factors and their interactions.

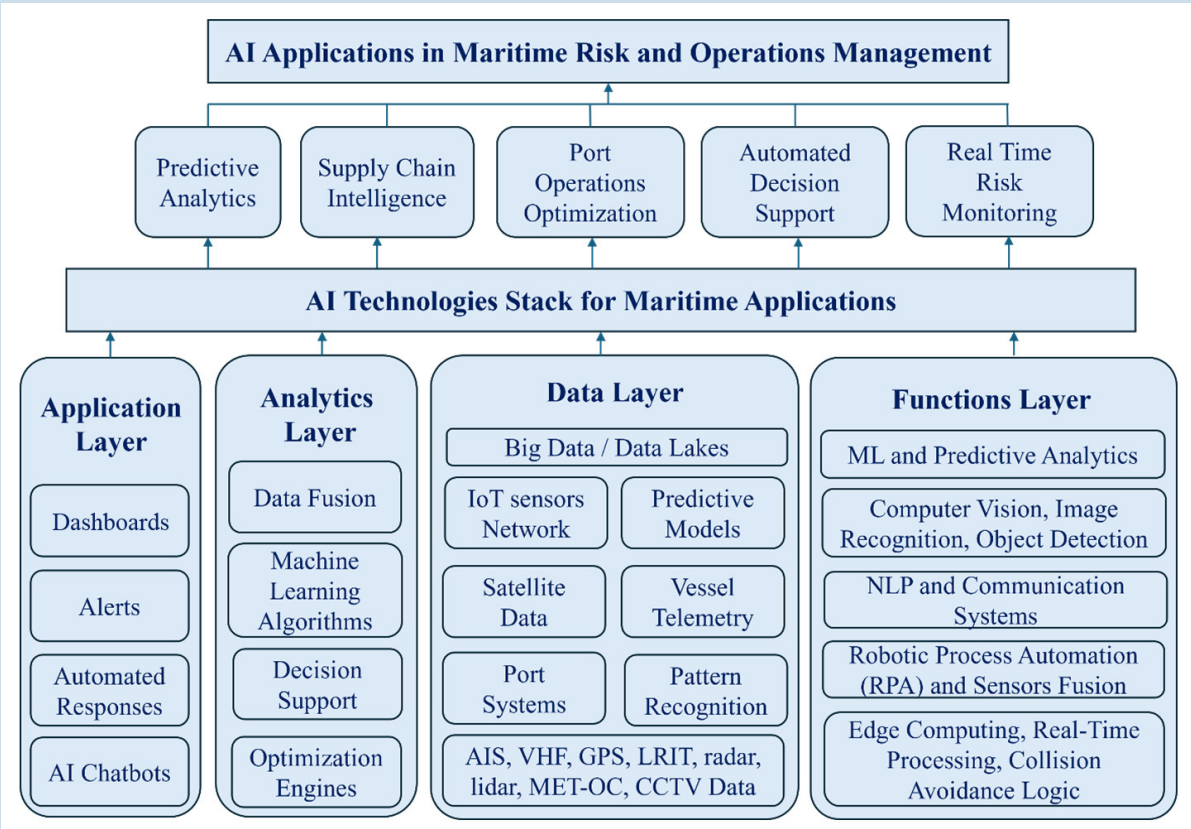


Figure 1. Overview of AI technologies as applications in maritime risk and operations management

Source: Made by authors according to [3, 5]

As a result of this consideration, ML algorithms can then use information collected from various ship data sources to accurately and quickly calculate the Critical Point of Approach (CPA) between vessels and predict the risk of their collision [6, 7]. These encompass the following databases: Automatic Identification System (AIS) data, Accident Databases, Vessel Movement Data, Lists of Vessels/Designs, Textual and Simulator Data, Inspection Data, Expert Judgments, Vessel and Voyage details, MetOcean Conditions, Incident History, and Vessel Management [8]. Also, among frequently used ML methods/algorithms in maritime applications of AI integrated technologies are supervised learning methods such as the Logistic Regression, Artificial Neural Network (ANN), Random Forest, Bayesian Networks, Naïve Bayes, Support Vector Machine (SVM), Decision Tree Algorithm, and Long Short-Term Memory (LSTM) which is a Deep Learning (DL) technique, and a specialized subfield of ML [4, 9, 10].

Logistic Regression is a type of generalized linear model for making predictions that are representative of probability, and it is mostly used for assessing accidents involving tankers, fishing, or detained vessels by outputting the probabilistic likelihood of an accident occurring. ANNs have three types of layers: the input layer with independent variables, the hidden layer, and the output layer with a dependent variable. A support vector machine (SVM) performs linear and non-linear classification applied in collision risk assessment [4].

Following the mentioned problems in addressing the maritime safety and particularly, maritime anomalies and collision risks mitigation in narrow waterways, appropriate methods use historical data sources and specific time-series data based on AIS, which can anticipate vessel traffic situations in navigational channels relying on previous statistical data of ship movements, retrieved from the national Vessel Traffic Monitoring and Information System (VTMIS) [11]. Specifically, AIS data encompasses vessel data, both static data like IMO and MMSI (Maritime Mobile Service Identity) numbers, class, shipname, shiptype, callsign, length, beam, deadweight, the dynamic data like latitude (lat), longitude (lon), speed over ground (SOG), and course over ground (COG), tagblock times (UTC), navigation status and heading of ships, and voyage-related data (information about the current voyage). Also, the mentioned ML techniques could be used to detect maritime anomalies by analysing the large AIS databases. For example, Neural Networks are used to predict future movements of vessels based on historical AIS data. At the same time, Bayesian networks consider deviation from standard routes, unexpected AIS activity, unexpected port arrival, approach, and entry into a zone as maritime anomalies [10]. Based on the mentioned DL technique of LSTM network including the AIS datasets, a model for Maritime Traffic State Prediction could be integrated within the overall vessel traffic management system in order to anticipate reliable vessel trajectory predictions, direction of movement, and speed of vessels, and to assist in monitoring of navigation in port areas, anchorage positions, berthing, and leaving the port [8]. The DL technique, combined with other ML techniques, proved to be more efficient than when used separately, i.e., by assembling models through the amalgamation of algorithms, an accuracy of 93.33% is reached, highlighting the enhanced robustness achieved by joint use of ML/DL algorithms [9]. Therefore, ML methods are necessary to cover the particular requirements of specific maritime application use cases, as categorised in **Table 1** by their features, goals, products and results of use.

Table 1. Proposed ML methods to be implemented in specific maritime application use cases

Application use case	Goals	AI/ML Tools and Products	Main features and results
Improved targeting of vessels and focus areas for inspection	Improving overall maritime safety, environmental aspects of vessels, preventing incidents and marine pollution from happening, identifying the high-risk ships, focusing on inspection priorities.	Random Forest Algorithm and Decision Tree with high level of accuracy	Random Forest has flexible model form with lot of variables, that results in superior prediction, gives decision-makers a clear interpretation of the output of the model conducting, increases the transparency of the used model, enhances decision-makers' confidence in the risk assessment results.
Enhanced maritime domain awareness	Enabling accurate and timely intervention when potentially dangerous situations might occur, better SAR response, fast deployment of equipment.	Long Short-Term Memory (LSTM), Bi-directional Gated Recurrent Units (BiGRU), You Only Look Once (YOLO) models, Density-Based Spatial Clustering of Applications with Noise (DBSCAN)	LSTM – processing AIS data (coordinates, predict routes and speed, warns on deviations) BiGRU – sequential trajectory prediction, anomaly detection YOLO – CNN for processing optical satellite imagery, identifying small ships, icebergs, marine life, and shorelines DBSCAN – groups complex, arbitrary-shaped maritime routes and points to illegal activities
Quantification of potential marine incident consequences	Conducting a cost-benefit analysis for potential incident costs, advanced strategic planning and policy development.	Extreme Gradient Boosting (XGBoost) and Light Gradient Boosted Machines (LightGBM)	The LightGBM algorithm was developed to improve the efficiency of the XGBoost algorithm on large datasets and multiple features. It can handle large datasets more accurately without too much memory.
Strategic planning and maritime asset allocation	Managing risk occurrence by running prediction scenarios and improving maritime infrastructure and safety assets allocations.	Deep Reinforcement Learning (DRL), Support Vector Regression (SVR), Hierarchical Risk Parity (HRP), LASSO & Elastic Net	DRL – a reinforcement learning decision-making to handle complex, high-dimensional inputs SVR – identifying macroeconomic trends, market regimes, fuel prices and risks.
Maritime Anomaly detection	To automatically acquire monitoring, analysis and understanding of route, movements and other activities at sea.	Neural Networks (NN) Based, Anomalous Routes Pattern Recognition, Image processing Methods	NN can perform highly specific tasks and pattern recognition. They have intensively been applied for computing vessel behaviour state, position and trajectory predictions.
Port State Control (PSC) Inspections	Enhancing the risk identification and prioritization in PSC inspections.	Multi-criteria decision-making (MCDM) methods: Analytic Hierarchy Process (AHP) and TOPSIS	MCDM models allow for more accurate forecasting of vessel detention probabilities and improved assessment of safety-related factors.

Source: Made by authors according to literature [12-17]

3.2 Recent AI applications in autonomous shipping

The application of AI and especially ML, in the safety of AMS and MASS, encompasses various domains, including collision avoidance, voyage planning, emergency response and environmental adaptation. These challenges and application use cases are most successfully covered with specific techniques such as deep reinforcement learning (DRL), convolutional neural networks (CNNs), Bayesian networks, and generative adversarial networks (GANs). Therefore, the main objective of AMS is to predict and prevent incidents before they might occur, while human-machine synergy remains one of the prerequisites for optimal conditions to manage any critical situations by a human operator.

To achieve a high level of maritime safety, recent trends in technological advancement of supportive devices in bridge department comprise the following systems and functions: Natural Language Processing (NLP) for Multilingual Operations, Bio-Inspired Sensors, Quantum ML, and Self-Healing Systems [18].

Within the concept of autonomous shipping, the auxiliary AI-supported system used for navigation of these ships is the autopilot, which can reduce the use of the helm on the bridge and ensure the ship remains on the same path and course, especially in navigation in the open sea. To properly function, the autopilot should be well calibrated, with accurate parameters based on route coordinates and other relevant factors, which, through the optimisation of turns, leads to significant savings of fuel [19]. However, there are some significant market entry barriers for full adoption of autonomous shipping, consisting mostly of challenges with regard to legal frameworks and regulatory uncertainties, financial risks, as well as shortage of skilled personnel and capital intensity [2].

4 DISCUSSION

Considering all the mentioned and analysed AI technologies applied in the maritime field, several strong and weak points of each one are identified. It is also worth mentioning that, while AI systems are generating considerable benefits in the maritime industry, their implementation still faces significant challenges. Particularly, AIS data often contain errors, inconsistencies, and redundant entries, which in general reduce the reliability of ML models. Some of the significant global players in the implementation of AI technologies include AI-driven Predictive Maintenance system with Maersk Line, Regulatory Standards Compliance Automation at the Port of Rotterdam and Green Shipping Solution for reducing the fuel consumption and emissions with NYK Group [20].

Therefore, to illustrate and summarize overall contributions, features and limitations of AI in specific application fields, **Table 2** is provided as follows.

Table 2. Comparison of the strong and weak points of AI applications in the maritime field

Application field	Strong points	Weak points/challenges
ML Models for ship parameters and port management predictive analytics	Accuracy in predicting vessel fuel consumption, equipment failure probabilities, predictive maintenance, port congestion patterns forecasting, and emission prediction.	Degradation in accuracy when models encounter conditions outside the controlled experiment, and if many real-life factors are involved, such as novel weather patterns, unusual cargo configurations, and data quality fluctuations. Beside data quality, one of the challenges is the model generalization across contexts as well.

Application field	Strong points	Weak points/challenges
Ship energy predictions	Accurate ship energy demand prediction, based on combining multiple models.	A careful calibration and validation of data is required to avoid compounding individual model biases.
Decision support dimension of AI deployment	AI-based decision support systems could automate and enhance the analytical framework. Hybrid fuzzy multi-criteria decision models could contribute to sustainable supplier selection, by using AI in the operationalization of complex multi-objective evaluation frameworks.	For adequate decision support, several aspects should be considered, such as organization, data infrastructure, human factor, and governance conditions necessary for successful operational deployment. Among the challenges in this context are trust, explainability, integration with human judgment, which makes a full deployment limited.
Maritime Risk Management	Deep learning for crisis management prediction using time series data, aiming to prevent maritime and port facilities infrastructure.	AI-specific challenges, including algorithmic opacity, data dependency, and human-machine interaction should be rigorously considered when about safety, governance, and maritime risk management.
Maritime environment	ML algorithms are applied to enable environmental compliance monitoring with diverse sensor input.	Some of the challenges are efficiency in harsh physical conditions, different water clarity, sensitivity on sudden shifts in water temperature, salinity, and pressure.
Autonomous shipping	Automated cargo handling systems, autonomous vessel docking assistance, and semi-automated bridge watchkeeping, with great potential to be fully applied in autonomous commercial vessel operations.	This is the most governance-intensive AI layer, that requires a high level of comprehensive safety assurance, regulatory approvals, and liability frameworks, which is still underdeveloped. Other infrastructural, technological and safety conditions should be considered.
Maritime SAR operations	AI-assisted visual search support will decrease overall cognitive workload for operators, maintain detection performance over time, comprehensive understanding of operational environment and situational awareness.	The biggest challenges here are complex and changing marine environments, false alarms by AI systems, mostly because of picking up false targets like floating trash, large fish, or waves. Also, the installation of new AI systems on existing SAR ships incurs high integration costs.
Maritime Cybersecurity	AI-driven anomaly detection systems are very efficient for defending against novel attack patterns. In autonomous shipping, AI is an onboard cybersecurity agent. Improved anomaly and threat detection, faster incident response, support for autonomous and remotely operated vessels, enhanced management of complex interdependencies, continuous monitoring of Operational Technology (OT) environments.	The attackers use AI to speed up malware creation, automate phishing campaigns and e-mails, malicious AI Chatbots, and for cyber spoofing attacks that could manipulate the vessel's GPS-based location data. Among other challenges for maritime security are AI benefits attackers too, the lack of explainability, vulnerable maritime OT systems, the supply-chain exposure, and human skills gap.

Source: Made by authors according to literature [21-25]

5 CONCLUDING REMARKS

The main aim of maritime authorities and companies is to implement the analytical methods to predict, describe, quantify, and mitigate risks, to ensure safer and more resilient maritime transport in the navigation area. This is mostly done be deploying the advanced methodology that involves AI and ML models and techniques to analyse vast datasets from AIS, VHF, satellite, onboard sensor networks etc., to recognize navigational patterns and potential anomalies, and to improve predictive accuracy of monitoring systems and devices.

The AI/ML models tend to reach a high level of accuracy of predictions, optimally it would be more than 90% depending on the model, in order to be potentially useful in the future prevention and maritime risk management efforts. In this sense, the supervised algorithms of ML and some of the DL, together with NLPand reinforcement learning techniques with implementation in use cases such as collision risks and vessel traffic management, autonomous shipping, maritime Situational Awareness domain, marine environment and ship energy efficiency**,** are discussed and analysed pointing out the advanced features of their use in a specific area.

The paper considered the goals of relevant authorities and purposes of implementation of each ML method in accordance with their specific advantages and capabilities together with indicating the shortcomings of these models in respective use cases.

Therefore, each of the considered features and applications in this paper has the potential to provide decision-makers and coastguard authorities with actionable intelligence to identify possible accident occurrences and take decisions on the application of risk control measures to prevent maritime risks in the zone of responsibility effectively. It is expected that AI/ML based technologies will be even more improved after training on broader datasets, outputting a more accurate prediction of maritime risks and improved AMS performances in the near future.

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I. Artificial Intelligence and Data-Driven Transport Systems

Neural Network-Based Ship Performance Prediction for Intelligent Autonomous Navigation Systems

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ABSTRACT

The development of Maritime Autonomous Surface Ships (MASS) requires intelligent onboard modules capable of real-time assessment of vessel performance under varying environmental conditions. This paper presents a wide neural network (wNN) architecture for data-driven ship performance prediction, designed as a core component of autonomous navigation decision-making. The model estimates attainable ship speed as a function of significant wave height, encounter wave angle and intended reference speed, with the wave period entering implicitly through the spectral relationship. It is trained on a comprehensive dataset covering thirteen sea states and thirteen encounter-angle configurations generated from full-mission bridge simulator runs. The proposed architecture achieves a prediction accuracy of R^2 = 0.9990 on held-out data, with consistent accuracy across the sampled operational envelope. The model also captures directional sensitivity: at a significant wave height of 6 m and a commanded speed of 12.0 kn, head seas cause a speed reduction of approximately 36 %, whereas following seas at the same wave height reduce speed by only about 8 %. Integrated seakeeping safety constraints based on slamming, deck wetness and propeller emergence criteria ensure that the prediction module respects vessel structural integrity, functioning as hard constraints within an autonomous decision loop. The computational cost of the deployed networks, some 500 parameters and 800 floating-point operations per evaluation, permits sub-microsecond inference and therefore real-time use inside the optimisation loops required for MASS operations. Furthermore, the modular architecture is in principle amenable to transfer learning, which would allow adaptation to similar vessels with limited additional data.

Keywords: maritime autonomous surface ships; neural network; ship performance prediction; attainable ship speed; seakeeping safety constraints

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1 INTRODUCTION

Maritime Autonomous Surface Ships (MASS) are progressing towards regulated commercial service, and research attention has been directed primarily at collision avoidance and compliance with the collision regulations. Less attention has been given to a judgement that masters make continuously at sea, namely whether the commanded speed can be maintained in the conditions ahead without exposing the hull, cargo or propeller to unsafe conditions. On a conventional ship this judgement rests on the master's experience. On an autonomous ship it must be computed, repeatedly and in real time. The same judgement determines energy consumption, as speed loss in waves extends the passage and delays are compensated by increased power later in the voyage. In the context of the 2023 IMO greenhouse gas strategy (IMO, 2023), reliable speed prediction is therefore both a safety and an efficiency requirement. The computation of attainable speed from physical principles is well established. Added resistance in waves and wind is superimposed on the calm-water resistance, the propulsion system is returned to equilibrium, and the resulting speed is verified against motion criteria that may require voluntary power reduction (Prpić-Oršić and Faltinsen, 2012). The procedure is accurate, but coupled and iterative, since added resistance, propulsive efficiency and the motions governing voluntary reduction all depend on speed. An autonomous system requires an estimate for several hundred candidate combinations within a single control interval, for which it is too slow. This paper therefore treats ship performance prediction as an autonomy module rather than an offline design calculation. A compact feedforward network is coupled to a feasibility envelope from an independent seakeeping analysis, so that inadmissible predictions are rejected before they reach the controller. The underlying speed and consumption models, and the routing frameworks in which they were first embedded, have been reported elsewhere (Marjanović et al., 2026a, 2026b). This paper adds their re-framing as a self-contained onboard module, the coupling to hard seakeeping constraints, and the analysis of real-time deployability.

2 BACKGROUND

Total speed loss in a seaway is conventionally decomposed into an involuntary and a voluntary component. The involuntary component follows from the added resistance of waves and wind and from degraded propeller efficiency. The voluntary component follows from a decision of the master to slow down because slamming, deck wetness, propeller emergence or vertical accelerations have become unacceptable, against commonly applied limiting values (Lloyd, 1998; ITTC, 1984; Prpić-Oršić and Faltinsen, 2012), which are given in **Table 1**. The two are not additive, as a voluntary reduction alters the motions that prompted it. Prpić-Oršić et al. (2020) further showed that propeller emergence and ventilation dominate over added resistance in higher sea states, so a model calibrated on moderate conditions will mis-state the severe ones. Moreira et al. (2021) and Tarelko and Rudzki (2020) demonstrated that feedforward networks reproduce ship speed and fuel consumption with useful accuracy, while Mittendorf et al. (2022) compared tree-based ensemble methods with neural networks for added resistance in oblique waves. Most such work relies on full-scale monitoring data, which are noisy, affected by hull fouling and sensor drift, and unevenly distributed, since a well-run ship spends little time in the conditions the model most needs to characterise. Simulator-generated data reverse this trade-off, providing uniform coverage and freedom from measurement noise at the cost of inheriting the errors of the simulator itself. Model predictive control is now widely applied to chart-based path planning with collision-regulation compliance (Potočnik, 2025), and Perera and Guedes Soares (2017) argued for integrating weather routing with safe ship handling. The performance model itself has received less attention as an autonomy component, being evaluated as a regression problem and reported through goodness-of-fit statistics, with little said about inference latency, the interface to the controller, or the behaviour of the module outside its domain of validity.

3 METHODOLOGY

3.1 Reference vessel and generation of training data

The reference vessel is a bulk carrier of 28,189 DWT. It was selected because a validated mathematical model was available in both software environments used in this study. The length between perpendiculars is 160.40 m, the beam 27.20 m and the depth 13.60 m, at a design draught of 9.819 m. Propulsion is provided by a two-stroke diesel engine rated at 6,150 kW at 136 rpm, driving a four-bladed fixed-pitch propeller of 5.25 m diameter. The service speed is approximately 14 knots. Training data were generated on a Wärtsilä Navi-Trainer Professional 5000 full-mission bridge simulator, which integrates the six-degree-of-freedom (6DOF) equations of motion in the time domain and lets speed loss emerge from the force balance rather than imposing it (Transas Marine, 2011). The matrix combined:

(a) 13 sea states according to various significant wave heights, $H_S \in \{0, 1, 2, ..., 12\}$ (m)

(b) 13 encounter wave angles, $\alpha_{waves} \in \{0, 15, 30, ..., 180\}$ (°)

(c) 2 spectra, $S \in$ {'Pierson-Moskowitz', 'JONSWAP'}

(d) 2 loading conditions, $L \in$ {'Full load', 'Ballast'}

(e) 3 intended reference ship speeds, $V_{ref.} \in \{12, 13.5, 14.5\}$ (kn)

giving 2,028 runs. The three intended reference ship speeds correspond to the dominant clusters in the recorded voyage history of the vessel. A parallel batch of 1,014 quasi-static runs was executed in HydroComp NavCad for cross-comparison (HydroComp, 2024) through its scripting Application Programming Interface (API). The NavCad scripting permitted the use of environmental parameters and vessel conditions matching those used in NTPro 5000, thereby making direct comparison between the two approaches possible.

Each speed value was averaged over at least fifteen minutes of simulated time under stationary environmental conditions in order to suppress transient scatter. The results were extended from the simulated range of 0° to 180° to the full range of encounter angles by symmetry. Conditions in which the autopilot could no longer maintain the commanded course were recorded as missing entries rather than as low speeds. This represents a modelling decision rather than a data-cleaning procedure. Such conditions define the boundary of maintained-speed commercial operation, beyond which the objective is no longer optimisation of the voyage but the safety of the vessel. A detailed description of the simulation setup is given in Marjanović et al. (2026a). All data processing and analysis were performed using MATLAB R2024b and Python 3.13.5.

3.2 Problem formulation

The encounter wave angle, $\alpha_{waves} \in [0, 2\pi)$, relates the ship heading $\psi \in [0, 2\pi)$ to the meteorological wave direction $\beta_{waves} \in [0, 2\pi)$, as shown in **Figure 1**, and is the geometric quantity through which heading choices enter the performance model. It is defined as

$$\alpha_{\text{waves}} = \begin{cases} \beta_{\text{waves}} - \psi, \text{for } \psi \leq \beta_{\text{waves}} \\ 2\pi + \beta_{\text{waves}} - \psi, \text{for } \psi > \beta_{\text{waves}}. \end{cases} \quad (1)$$

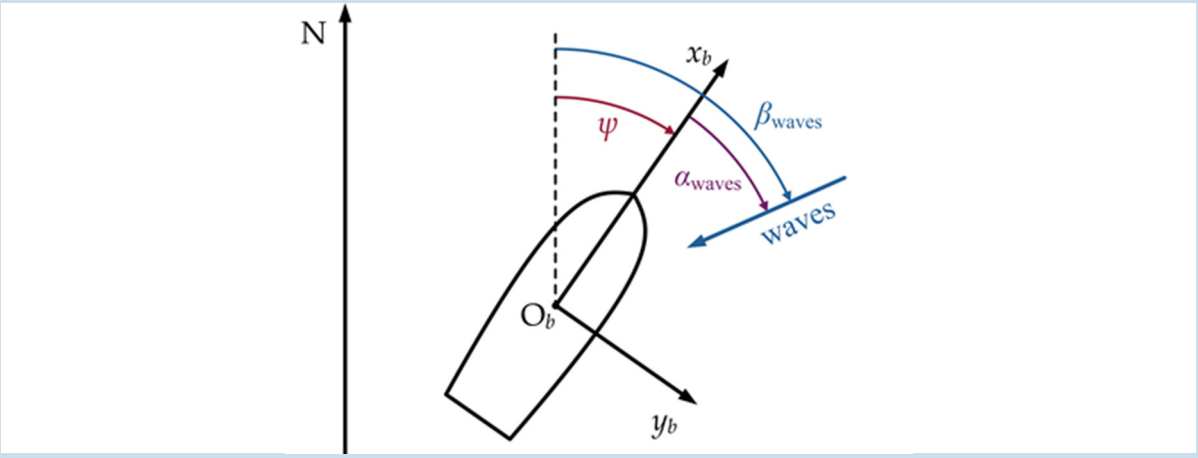


Figure 1. Definition of the encounter wave angle relative to the ship's heading. Source: Marjanović (2026)

Neglecting wind and current loads, the attainable ship speed can then be written as a function of the intended reference speed and the prevailing sea state,

$$V_{\text{att.}} = f(V_{\text{ref.}}, H_S, T_p, \alpha_{\text{waves}}). \tag{2}$$

The wave period appears in Eq. (2) but does not enter the trained model as an independent variable. In the simulator, the peak period of the Pierson-Moskowitz spectrum is determined once the significant wave height is specified, as height and period develop jointly in fully developed wind-generated seas, and the period therefore enters implicitly. The simplification is acceptable for North Atlantic conditions, where swell and wind sea are generally aligned, but not in the presence of a crossing swell.

3.3 Network architecture and training

A feedforward neural network consists of an input layer, one or more hidden layers and an output layer. Each element of the input vector **p** is connected to every neuron of a layer through the weight matrix **W**, and each neuron is assigned a bias, a summation function and a transfer function *f*. The outputs of the individual neurons form the output vector of the layer, which is given as

$$a = f(Wp + b), \quad a, b \in \mathbb{R}^S. \tag{3}$$

The number of inputs to a layer generally differs from the number of hidden neurons, giving rise to narrow, medium and wide configurations. The rectified linear unit (ReLU) was adopted as the transfer function throughout. The model for attainable ship speed is expressed as

$$\hat{V}_{\text{att.}}^{(PM)} = f_{NN,i}(V_{\text{ref.}}, \alpha_{\text{wave}}, H_S). \tag{4}$$

The network is trained by adjusting the weights and biases so as to minimise the mean square error between the predicted and target values, given as

$$F(\mathrm{x}) = E[e^2] = E[(t - a)^2] \tag{5}$$

where **x** is the vector of network weights and biases. Five network architectures were compared under identical training conditions. Three single-hidden-layer networks with 10, 25 and 100 neurons represent

the narrow, medium and wide configurations, and two deeper networks were configured with two and three hidden layers of 10 neurons each. All employed the ReLU transfer function and an iteration limit of 1,000. Nine-fold cross-validation was applied, with a further independent tenth of the dataset held out for testing, and four multivariate linear regression models were fitted as a baseline. The wide configuration comprises 501 trainable parameters and is therefore small enough for deployment on the hardware typically available on board.

3.4 Seakeeping-derived feasibility envelope

A predicted attainable speed is meaningful only if the corresponding operating condition is admissible from the standpoint of vessel safety. An independent frequency-domain seakeeping analysis was therefore performed to delimit the admissible conditions. Seven sea states with significant wave heights from 3 to 9 m were modelled using the ITTC two-parameter Pierson-Moskowitz spectrum, combined with thirteen headings at 15° increments and the same three reference speeds, yielding 182 primary conditions. Responses were evaluated at the bridge, the propeller tip, the slamming station near the bow and the forward perpendicular on deck, over encounter frequencies from 0.17 to 3.0 rad/s. The applied criteria are summarised in **Table 1**. Rather than entering the objective function as penalty terms, they are evaluated as a binary feasibility indicator over the domain of significant wave height, encounter angle and reference speed, defined as

$$\chi(H_S, \alpha_{\text{waves}}, V_{\text{ref.}}) = \begin{cases} 1, & c_j(H_S, \alpha_{\text{waves}}, V_{\text{ref.}}) \le c_{j,\text{lim}} \quad \forall j = 1, \dots, J \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where χ is the binary feasibility indicator, c_j is the value of the j-th seakeeping criterion, $c_{j,\text{lim}}$ is its limiting value given in **Table 1**, and J is the number of criteria applied.

Table 1. Seakeeping criteria applied as feasibility constraints

Criterion	Critical location	Limiting value	Operational concern
Slamming	Keel near the bow	20 events/h	Structural integrity
Deck wetness	Bow	30 events/h	Deck operations safety
Propeller emergence	Propeller tip	90 events/h	Thrust effectiveness
Roll / pitch amplitude	Centre of gravity	6° / 2–5° significant	Cargo securing, visibility
Vertical acceleration	Bow / bridge	0.5 g / 0.2 g RMS	Structure, watchkeeping

Source: Compiled by authors after Lloyd (1998) and ITTC (1984)

The criteria are applied as hard constraints rather than as penalty terms, which can be outweighed by a sufficiently favourable objective value. On a conventional ship the priority of safety over efficiency is maintained by the judgement of the master. On an autonomous ship it must be incorporated into the structure of the decision problem. The components described above are combined into a single on-board module. Forecast metocean fields and the own-ship state constitute the inputs, from which the encounter wave angle is obtained according to Eq. (1) and passed to the trained networks. These provide estimates of the attainable ship speed and the corresponding fuel consumption, and the resulting operating point is evaluated against the feasibility envelope defined by Eq. (6). Only admissible points are transferred to the decision loop, which selects the speed and heading and issues the commands to the autopilot and the engine control system. Motions and speeds observed during operation can be used to recalibrate the envelope, which enables the online adaptation discussed in Section 5.

4 RESULTS

4.1 Predictive accuracy

The validation and testing performance of the developed models is summarised in **Table 2**. Four representative models are included, namely the stepwise linear regression as the baseline, the medium and wide single-hidden-layer networks, and the trilayered configuration. The complete comparison of all nine models is reported in Marjanović et al. (2026a). The wide network achieves the best performance in both the validation and the testing phase, with R^2 = 0.9990 and an RMSE of 0.074 kn on the held-out test set. Two further observations can be drawn from **Table 2**. The difference between the linear baseline and the neural network models is substantial and consistent across both phases. This follows from the non-linearity introduced by the encounter angle, as speed loss is not monotonic with respect to heading and cannot be represented by an affine function of the three input variables. The deeper architectures do not outperform the single wide hidden layer. The additional depth provides representational capacity that the present problem does not require and, for a dataset of this size, primarily increases variance. This is evident in the testing RMSE of the trilayered network, which exceeds its validation value. An RMSE of 0.07 to 0.12 kn is less than one per cent of the commanded speed, and below the uncertainty of the wave forecasts used as model input, so the surrogate does not limit the routing decision (Marjanović et al., 2025). Accuracy of this order results from noise-free simulated data and would not be attained against full-scale measurements.

Table 2. Validation and testing performance for attainable ship speed estimation

Model	RMSE (kn), val.	R^2 val.	RMSE (kn), test	R^2 test
Stepwise linear	0.7582	0.8788	0.7970	0.8787
Medium NN (25)	0.2832	0.9831	0.2215	0.9906
Wide NN (100)	0.1248	0.9967	0.0736	**0.9990**
Trilayered NN (10,10,10)	0.1438	0.9956	0.1582	0.9952

Source: Made by authors, after Marjanović et al. (2026a)

4.2 Directional sensitivity

Heading is the principal control variable available to a routing algorithm, so the sensitivity of the model to the encounter wave angle is of greater practical relevance than its aggregate accuracy. At a significant wave height of 6 m and a commanded speed of 12.0 kn, the attainable speed in head seas is reduced to 7.68 kn, corresponding to a reduction of 36 %. In following seas at the same wave height, the attainable speed remains at 11.04 kn, corresponding to a reduction of 8 %. The vessel therefore attains approximately 44 % higher speed in following seas than in head seas under identical wave conditions. This directional asymmetry provides the basis for weather routing and indicates that a scalar representation of the sea state is not sufficient for an autonomous system. It does not follow, however, that following seas are always preferable, as shown in Section 4.3.

4.3 Feasibility envelope

As shown in **Table 3**, the feasibility envelope narrows progressively with increasing significant wave height, and the reduction is not uniform with respect to heading.

Table 3. Operability limitations by significant wave height and relative heading

Wave direction	Encounter angle	HS < 4 m	4–6 m	6–8 m	HS ≥ 8 m
Head seas	0°–30°	Safe	Safe	Reduced speed	Not operable
Bow quartering	30°–60°	Safe	Caution	Avoid	Not operable
Beam seas	60°–120°	Safe	Avoid	Avoid	Not operable
Stern quartering	120°–150°	Safe	Caution	Avoid	Not operable
Following seas	150°–180°	Safe	Safe *	Reduced speed **	Not operable

* Reduced directional stability; heading control margin should be monitored. ** Propeller emergence risk above HS = 7 m. Source: Made by authors

The directional distribution of the roll response and of the green water events is shown in **Figure 2** for significant wave heights of 4, 5, 6 and 7 metres.

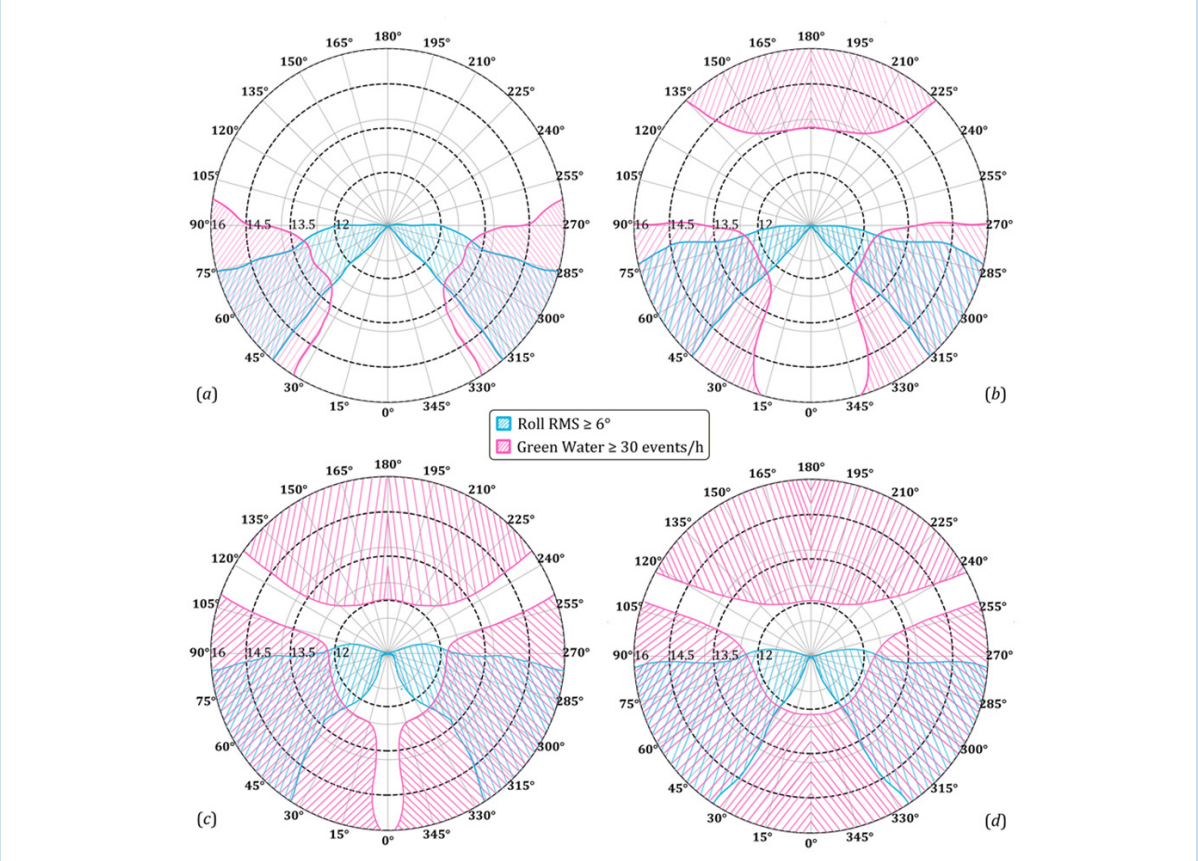


Figure 2. Roll RMS values and green water events for significant wave heights H_S = 4 m (a), H_S = 5 m (b), H_S = 6 m (c) and H_S = 7 m (d). Source: Marjanović (2026)

Below 4 m the vessel is unrestricted in all headings, and above 8 m no heading satisfies the applied criteria. Between 4 and 6 m the limiting condition is that of beam and quartering seas, as a consequence of the roll response, while between 6 and 8 m only head and following seas remain operable, and at reduced speed.

4.4 Computational cost

The applicability of the module in a real-time loop depends on the inference cost rather than on the accuracy. A single forward pass requires approximately 800 floating-point operations over 501 stored parameters, so a search over several thousand combinations of heading and engine setting consumes a negligible fraction of a control interval. The physical alternative, an iterative solution of the propulsion equilibrium coupled to a motion response calculation, is several orders of magnitude more expensive. The performance model is consequently not the limiting component, as the deterministic single-layer optimisation using its output requires 10 to 15 s per cycle (Marjanović et al., 2026b).

5 DISCUSSION

The results support a specific conclusion. A small feedforward network, trained on densely sampled simulator data and combined with an explicit feasibility envelope, provides an adequate and computationally inexpensive substitute for a physical performance calculation within an autonomous decision loop. The network does not, however, represent ship hydrodynamics. It reproduces the behaviour of the simulator that generated its training data and inherits the assumptions and errors of that simulator. This constitutes the principal limitation of the work, as the reported accuracy measures agreement with the simulator rather than with full-scale behaviour. Validation against measured voyage data would yield a considerably more modest figure, which would be the operationally relevant one (Prpić-Oršić et al., 2020). A second limitation follows from the spectral coupling described in Section 3.2, as the model cannot distinguish a developing wind sea from a decayed swell of equal height. A third is that the envelope in **Table 3** was derived for two loading conditions and a clean hull.

The modular structure of the model offers a means of addressing these limitations. Retraining is inexpensive, and the low-dimensional and physically interpretable input space allows a network trained on the present vessel to serve as a starting point for a similar one. Transfer learning in this context consists of retaining the hidden layer and refitting the output mapping on a limited set of vessel-specific simulations. The same property enables online adaptation from operational data without the infrastructure that continuous retraining would otherwise require. The contribution to sustainable transport is indirect. Improved speed prediction does not reduce fuel consumption in itself, but it improves the decisions that do, as a vessel that can quantify a 36 % speed reduction on one heading against 8 % on another can select between them, which is not possible on the basis of a scalar weather factor.

6 CONCLUSION

A wide single-hidden-layer neural network was developed as an onboard ship performance prediction module for autonomous navigation. Trained on 2,028 full-mission bridge simulator runs covering thirteen sea states and thirteen encounter angles, it estimates the attainable speed with an RMSE of 0.074 kn and R^2 = 0.9990 on held-out data, outperforming both the linear baselines and the deeper architectures. Head seas at 6 m and 12.0 kn reduce speed by 36 % against 8 % in following seas. The estimator is coupled to a feasibility envelope from an independent seakeeping analysis, in which the slamming, deck wetness, propeller emergence, roll, pitch and acceleration criteria are applied as hard constraints, so that the priority of safety over efficiency is preserved in the structure of the decision problem. At 501 trainable parameters, the model does not limit the computational performance of the autonomy stack. Further work should address validation against full-scale voyage data, re-examination of the seakeeping criteria for unmanned operation, and testing of the transfer-learning approach on a second vessel.

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Use of AI tools. During the preparation of this work, the authors used AI-assisted tools for language refinement. The authors reviewed and edited the content as required and take full responsibility for the content of the publication.

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I. Artificial Intelligence and Data-Driven Transport Systems

Analysis of Individual Ship-Motion Components for Attention-Based Sea-State Classification

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ABSTRACT

Accurate sea-state classification is important for maritime safety, route planning, and autonomous vessel operation. Building on previous work using an attention-based neural network for sea-state classification from ship-motion responses across common multi-degree-of-freedom (DOF) configurations, this paper investigates the relevance of individual ship-motion components. Simulated vessel responses were generated under irregular JONSWAP wave conditions and classified into five sea-state classes. The attention-based classifier was evaluated using the full 6DOF input (surge, sway, heave, roll, pitch, and yaw), six single-DOF configurations, and post-hoc channel-occlusion analysis of the trained 6DOF model. A speed-based evaluation of the full 6DOF and single-DOF models was also performed. Results based on macro-F1 show that pitch and heave are the most informative motion components, although their roles differ across evaluation settings. Heave achieved the highest standalone performance, with a macro-F1 score of 0.646, demonstrating strong independent discriminative capability. In contrast, pitch had the greatest influence within the full 6DOF model, as occluding the pitch channel produced the largest macro-F1 degradation (0.375). Surge also provided complementary information, with channel occlusion reducing macro-F1 by 0.338. Speed-based analysis showed that the full 6DOF model achieved the highest performance at all vessel speeds, while pitch and heave remained the dominant single-DOF contributors. Pitch achieved the highest mean single-DOF performance at 0 knots and was nearly tied with heave at 5 knots, whereas heave performed best at 10, 15, and 20 knots. Overall, the findings show that individual motion components do not contribute equally and identify pitch and heave as relevant signals for efficient ship-motion-based sea-state classification.

Keywords: sea-state estimation; sea-state classification; ship-motion components; degrees of freedom; attention-based neural network; wave buoy analogy

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1 INTRODUCTION

Reliable sea-state information is important for maritime safety, route planning, and the development of intelligent and autonomous vessel systems [1, 2]. Sea-state estimation (SSE) can support operational decision-making by providing information about the wave conditions encountered by a vessel [1, 3]. Conventional sea-state monitoring approaches, such as wave buoys, satellite observations, and onboard radar systems, provide valuable measurements, but they may be limited by deployment constraints, cost, spatial coverage, or temporal availability [1]. These limitations have motivated the use of the wave buoy analogy (WBA), where vessel-motion responses are used as indirect indicators of the surrounding sea state. In recent years, machine learning methods have increasingly been applied within this framework to estimate or classify sea-state conditions from ship-motion data [1, 4].

Ship motions responses are commonly described through six degrees of freedom (6DOF): surge, sway, heave, roll, pitch, and yaw. Since these motion components are physically related to wave-induced vessel behaviour, they can provide useful information for sea-state classification [3]. Existing machine learning-based SSE studies have used different motion-component subsets, ranging from selected 3DOF configurations to full 6DOF inputs [1, 5]. However, the relative relevance of individual ship-motion components remains insufficiently clarified, particularly when distinguishing between their standalone discriminative value and their contribution within a full multi-channel classifier.

This study extends the previously evaluated attention-based sea-state classification framework [5] by analysing the role of individual ship-motion components within both standalone and full 6DOF settings. First, six single-DOF models are trained to evaluate the independent discriminative capability of surge, sway, heave, roll, pitch, and yaw. Second, a post-hoc channel-occlusion analysis is applied to the trained 6DOF classifier to examine how the removal of each input channel affects model performance. Third, a speed-based evaluation of the full 6DOF and single-DOF models is performed to assess whether the relevance of individual motion components varies across different vessel forward speeds. Together, these experiments provide insight into the contribution of individual motion components for attention-based sea-state classification and support the development of more efficient input configurations.

The remainder of the paper is organised as follows. Section 2 provides an overview of related work on machine learning-based SSE and the use of different DOF configurations. Section 3 describes the simulated dataset, the attention-based classification model, and the experimental setup for the single-DOF, channel-occlusion, and speed-based analyses. Section 4 presents the classification results, while Section 5 discusses the relevance of individual motion components and the implications for reduced-input sea-state classification. Section 6 concludes the paper and outlines directions for future work.

2 BACKGROUND

Machine learning-based SSE has been investigated using a range of model types and input representations, from conventional machine learning algorithms to deep neural networks. Depending on the target output, SSE is commonly formulated as either a regression task, in which continuous sea-state parameters such as significant wave height, wave period, or wave direction are estimated, or as a classification task, in which observations are assigned to predefined sea-state categories [1]. In both cases, ship-motion responses represent the primary source of information in WBA-based approaches. Therefore, the selection of motion components used as model inputs can strongly influence estimation or classification performance.

Many studies rely on reduced DOF representations rather than the full 6DOF vessel response. A common choice is the 3DOF configuration consisting of heave, pitch, and roll, which combines vertical

translational motion with two rotational responses strongly associated with wave-induced vessel behaviour. Selimović et al. [6] proposed an attention-based model using 3DOF time-series signals for regression-based estimation of sea-state parameters. Nielsen et al. [7] compared several machine learning models, including LightGBM and a dense neural network, using spectra and cross-spectra derived from ship-motion measurements. Ko et al. [8] further extended WBA-based estimation by combining semi-supervised learning with spectral input representations, including power spectral density and cross-spectral density features.

Other studies have considered broader motion-response sets. Han et al. [9] used a 4DOF configuration based on sway, roll, pitch, and heave, with ship-motion signals used as time-series inputs and forward speed included as an additional input variable. Tu et al. [10] adopted a different 4DOF configuration, consisting of surge, sway, roll, and yaw, for sea-state classification using a multi-layer classification framework. These studies show that several DOF combinations have been explored, but they also indicate that the choice of motion components varies substantially across methods and problem formulations.

Studies that explicitly examine the role of individual input channels remain comparatively limited. Mittendorf et al. [11] investigated the effect of progressively expanding the input space by adding motion and structural-response channels to machine-learning models. Their analysis included configurations starting with heave and pitch acceleration, followed by the addition of roll, sway, surge, yaw, vertical bow acceleration, and deck strain measurements. Such progressive input-space evaluation provides useful insight into model sensitivity to different groups of signals. However, it does not directly isolate the standalone discriminative relevance of each individual ship-motion component or its contribution within a trained full 6DOF classifier.

The present study addresses this gap by evaluating individual motion components through single-DOF training and post-hoc channel-occlusion analysis of a trained 6DOF classifier. In addition, the analysis is extended across multiple vessel speed conditions to examine whether the relevance of surge, sway, heave, roll, pitch, and yaw changes with operating speed. This provides a more detailed assessment of the role of each motion component in attention-based sea-state classification and supports the development of more efficient input configurations.

3 METHODOLOGY

The dataset used in this study follows the generation procedure adopted in the authors' previous multi-DOF sea-state classification study [5], which was based on the worldwide joint wave-height/wave-period distribution proposed by Price [12]. In this framework, each simulated sea condition is assigned a sea-state class according to the corresponding wave-height interval, while the associated wave period is sampled according to its occurrence probability. This preserves the global sea-state distribution while providing labelled vessel-motion samples for classification.

Vessel-motion responses were generated using the S175 vessel model implemented in the Marine Systems Simulator (MSS) Toolbox [13]. Irregular wave excitation was modelled using the JONSWAP spectrum, while the corresponding response amplitude operator (RAO) functions were used to simulate the resulting vessel motions. The simulations were conducted at five forward speeds: 0, 5, 10, 15, and 20 knots, with wave encounter angles uniformly distributed over the full 360° range. Following the previous study [5] and Cheng et al. [14], only sea states 0–6 were considered, as these conditions account for more than 98% of worldwide sea-state occurrences. Sea states 0–2 were grouped into class C1, whereas classes C2–C5 correspond to sea states 3–6, respectively. The resulting class definitions, together with the corresponding significant wave-height intervals, global sea-state occurrence rates, and number of test samples, are summarised in **Table 1**.

Table 1. Sea-state class definitions, global occurrence, and test-set distribution.

Class	Sea state	Significant wave height [m]	Global sea-state occurrence [%]	Number of test samples
C1	0 - 2	< 0.5	11.25	484
C2	3	0.5–1.25	31.69	588
C3	4	1.25–2.5	40.19	1320
C4	5	2.5–4	12.80	513
C5	6	4–6	3.03	121

The simulated vessel responses were sampled at 2 Hz over 30 min intervals, yielding 3,601 time steps for each motion signal. The dataset contained 20,000 simulated vessel-response records, with 4,000 records generated for each vessel speed. Owing to the adopted worldwide sea-state distribution, the resulting classification problem was inherently imbalanced.

The attention-based classifier used in this study follows the architecture previously adapted for sea-state classification [5]. Since the objective of the present work is to analyse the relevance of individual motion components rather than to introduce a new classifier, the same classification framework and training protocol were used across all experiments. The full input configuration consisted of six ship-motion components: surge, sway, heave, roll, pitch, and yaw. For the single-DOF experiments, only one of these components was provided as input to the model.

The dataset was divided into training, validation, and test subsets using a nominal 70/15/15 ratio. Stratification was applied to preserve the distributions of sea-state classes and vessel forward speeds across all subsets. Channel-wise min–max normalisation was applied using scaling parameters computed from the training subset. Batch-wise data augmentation was applied during training following the same procedure as in the baseline attention-based framework [6].

For each experimental setup, three independent training runs were performed using different random seeds for model initialisation, while the dataset split was kept fixed to ensure comparability. Training was conducted for up to 150 epochs using the AdamW optimizer, a learning rate of 3×10^{-4}, a weight decay of 1×10^{-4}, and the cross-entropy loss function. Early stopping was applied based on the validation macro-F1 score, with a patience of 20 epochs and a minimum improvement threshold of 1×10^{-3}. The model weights corresponding to the best validation macro-F1 score were retained for final test-set evaluation.

Three complementary analyses were conducted. First, six single-DOF models were trained separately using only one motion component at a time: surge, sway, heave, roll, pitch, or yaw. This experiment evaluated the standalone discriminative capability of each individual ship-motion component.

Second, a post-hoc channel-occlusion analysis was applied to the trained full 6DOF classifier. During test-set evaluation, one normalised DOF channel was replaced by a constant zero-valued signal, while all remaining channels were kept unchanged. This procedure was repeated separately for each motion component to assess the sensitivity of the trained 6DOF classifier to the removal of individual input channels.

Third, a speed-based evaluation was performed for the full 6DOF and single-DOF models. For this analysis, the test samples were grouped according to vessel forward speed, namely 0, 5, 10, 15, and 20 knots. Macro-F1 score and balanced accuracy were then computed separately for each speed group to examine whether the relevance of individual motion components varied across operating conditions.

4 RESULTS

After training, the single-DOF models were evaluated on the test set and compared with the full 6DOF baseline. The full 6DOF classifier achieved a mean macro-F1 score of 0.845 and a mean balanced accuracy of 0.852. Macro-F1 was used as the primary evaluation metric due to the imbalanced class distribution, while balanced accuracy was reported as a complementary metric. All reported values represent mean results across three random initialisation seeds.

The aggregate test-set performance of the full 6DOF baseline and the single-DOF classifiers is shown in **Figure 1(a)**. Among the individual motion components, heave achieved the highest standalone performance, with a mean macro-F1 score of 0.646 and a mean balanced accuracy of 0.671. Pitch achieved the second-highest single-DOF performance, with a mean macro-F1 score of 0.615, followed by yaw with a mean macro-F1 score of 0.522. The remaining DOF components produced lower classification scores when used as the only input signal. Sway showed the largest standard deviation in macro-F1 score, indicating the highest variability across random initialisation seeds among the single-DOF models.

To assess the sensitivity of the trained 6DOF classifier to each input motion component, a post-hoc channel-occlusion analysis was conducted. For each experiment, one normalised DOF channel was replaced by a constant zero-valued signal during test-set evaluation, while all other input channels were kept unchanged. The macro-F1 degradation caused by occluding the *i*-th DOF channel was computed as

$$\Delta_i = mF1_{6DOF} - mF1_{occluded,i}, \tag{1}$$

where $mF1_{6DOF}$ denotes the mean macro-F1 score of the unoccluded 6DOF classifier, and $mF1_{occluded,i}$ denotes the mean macro-F1 score obtained when the *i*-th DOF channel was occluded.

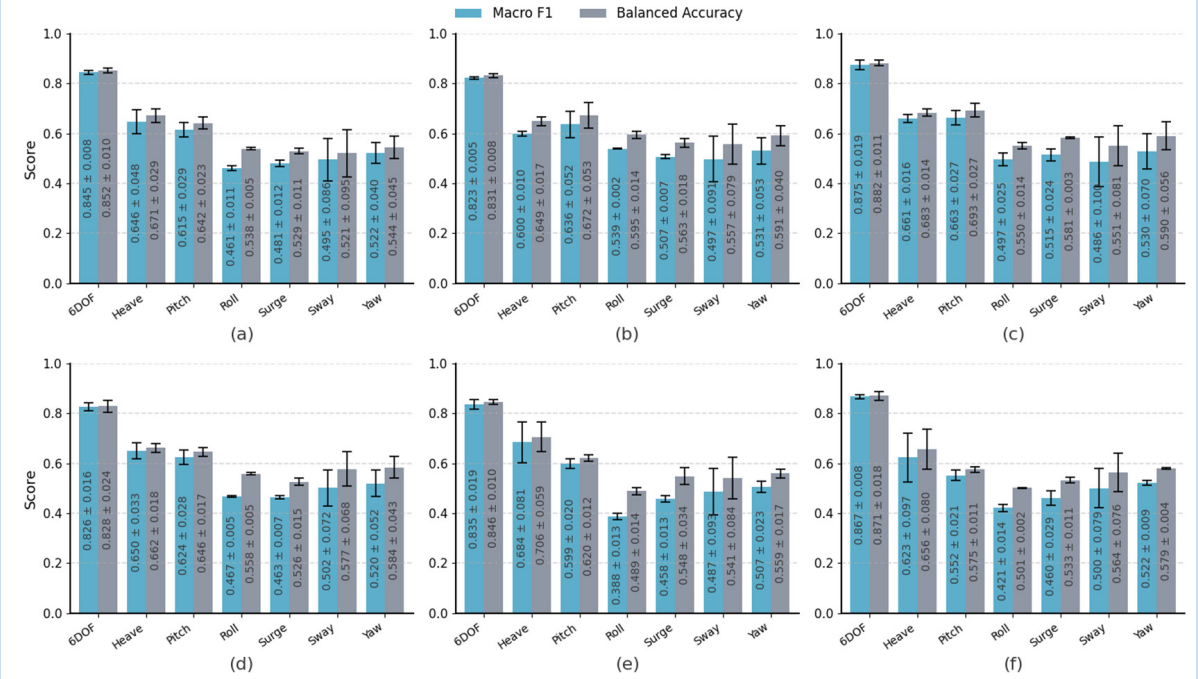


Figure 1. Test-set performance of the full 6DOF baseline and single-DOF classifiers: (a) aggregate performance, (b) 0 kn, (c) 5 kn, (d) 10 kn, (e) 15 kn, (f) 20 kn. Bars show mean values across three random initialisation seeds, and error bars denote standard deviation.

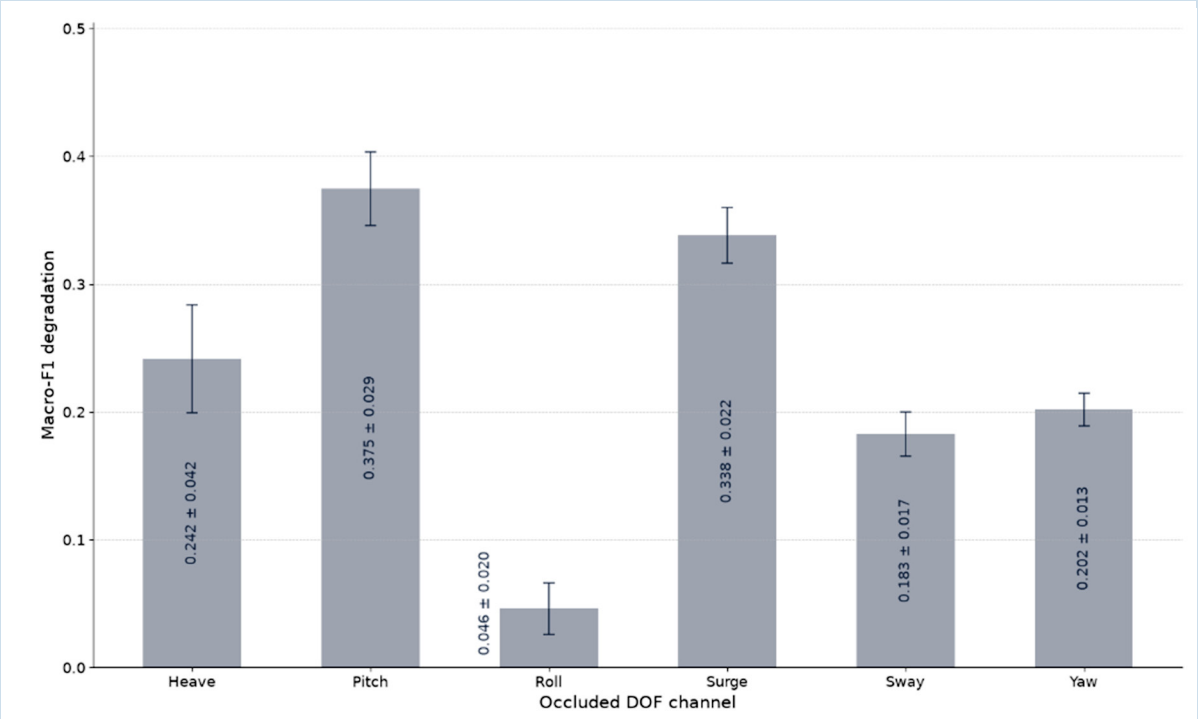
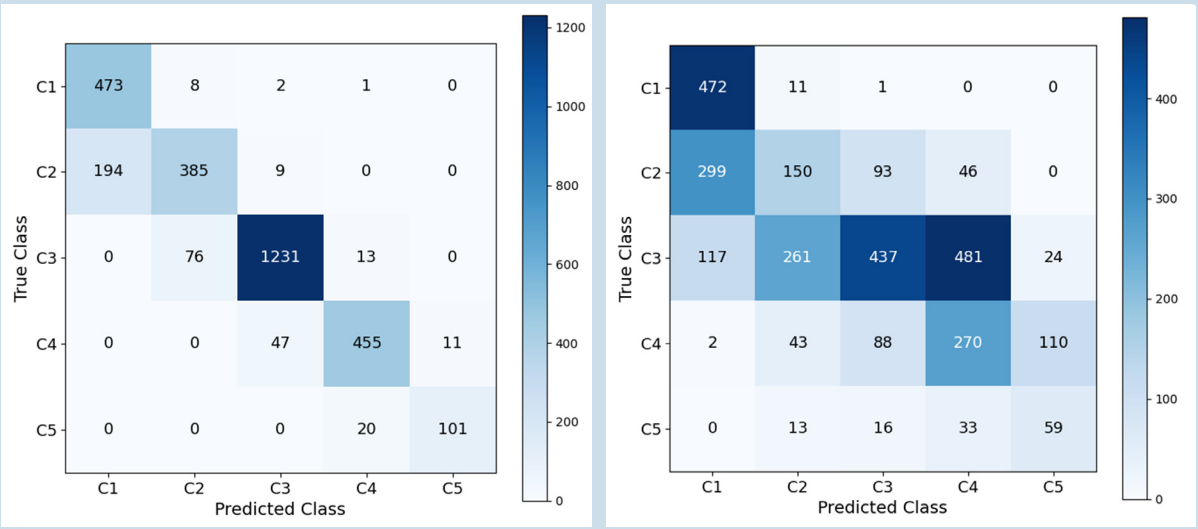


Figure 2. Macro-F1 degradation relative to the unoccluded 6DOF baseline after post-hoc single-channel occlusion.

The channel-occlusion results are shown in **Figure 2**. The largest macro-F1 degradation was observed when the pitch channel was occluded, with Δ_i = 0.375. In this case, the mean macro-F1 score decreased to 0.470, and the mean balanced accuracy decreased to 0.540. The second-largest degradation was obtained for surge, with a macro-F1 reduction of 0.338, followed by heave with a reduction of 0.242. Occluding yaw and sway produced smaller decreases in macro-F1, with reductions of 0.202 and 0.183, respectively. The smallest degradation was observed when roll was occluded, with a macro-F1 reduction of 0.046. In this case, the occluded model retained a mean macro-F1 score of 0.799 and a mean balanced accuracy of 0.827.



(a) (b)

Figure 3. Confusion matrices for the 6DOF classifier: (a) unoccluded 6DOF input and (b) pitch-occluded input.

Figure 1(b)–(f) presents the speed-based evaluation of the full 6DOF baseline and the single-DOF classifiers. The full 6DOF model achieved the highest mean performance at all vessel speeds, confirming the advantage of using the complete motion-response representation. Among the single-DOF models, pitch achieved the highest mean macro-F1 score at 0 knots, while pitch and heave produced nearly identical results at 5 knots. For the higher-speed cases of 10, 15, and 20 knots, heave achieved the highest mean single-DOF performance. Yaw generally showed intermediate performance across the speed range, whereas surge, sway, and roll produced lower scores. The observed differences between individual DOF models should be interpreted cautiously where standard deviations overlap, but the results consistently identify pitch and heave as the strongest single-DOF contributors.

Figure 3 compares the confusion matrices of the unoccluded 6DOF classifier and the pitch-occluded input case. The unoccluded 6DOF model shows a stronger diagonal structure, while the pitch-occluded case shows a larger number of off-diagonal classifications. This comparison is consistent with the aggregate channel-occlusion results, where occluding pitch produced the largest reduction in macro-F1 score among the evaluated DOF channels.

5 DISCUSSION

The results show that the relevance of individual ship-motion components depends on the evaluation setting. In the single-DOF experiment, heave achieved the strongest standalone classification performance, indicating that vertical vessel motion contains substantial discriminative information for sea-state classification. In contrast, the post-hoc channel-occlusion analysis showed that pitch had the greatest influence within the trained 6DOF classifier, since occluding the pitch channel produced the largest macro-F1 degradation. These findings are complementary, as single-DOF training evaluates the independent discriminative value of each signal, whereas channel occlusion evaluates the dependence of the full 6DOF model on each input channel.

The speed-based analysis further supports the relevance of pitch and heave across the tested operating conditions. The full 6DOF model achieved the highest performance at all vessel speeds, while pitch and heave remained the strongest single-DOF contributors. Pitch achieved the highest mean single-DOF performance at the lowest speed and was nearly tied with heave at 5 knots, whereas heave achieved the highest mean values at 10, 15, and 20 knots. However, because several standard deviations overlap, these differences should be interpreted as indicative trends rather than definitive speed-dependent rankings.

Surge also exhibited a notable performance degradation in the channel-occlusion experiment despite its relatively weak standalone performance, suggesting that it may provide complementary information when combined with other motion components. However, because occlusion replaces the normalised channel with zero, corresponding to its training-set minimum under min–max normalisation, part of the observed degradation may reflect an out-of-distribution perturbation rather than information removal alone. Roll showed both the weakest standalone performance and the smallest degradation under occlusion, indicating a comparatively limited contribution in the present pooled setting, whereas sway and yaw showed intermediate standalone performance, with their occlusion resulting in moderate degradation of the 6DOF model performance. Since the roll response is strongly dependent on encounter angle and resonance conditions, uniformly pooling samples over the full 360° range of encounter angles may partly reduce its discriminative contribution. Therefore, the observed result should be interpreted as specific to the present experimental setup rather than as a general indication of the limited relevance of roll motion.

The comparison between the single-DOF and channel-occlusion experiments indicates that sea-state information is distributed across multiple motion components, but not uniformly. The 6DOF classifier retained part of its performance when some channels were occluded, suggesting a degree of

redundancy among the motion responses. However, the larger degradation observed for pitch, surge, and heave shows that some DOFs contribute more strongly to the learned multi-channel representation.

From a practical perspective, the results identify pitch and heave as particularly relevant signals for future reduced-input configurations. Nevertheless, the present analysis should not be interpreted as direct evidence that a specific reduced configuration is optimal, since combined reduced-DOF models were not trained in this study. Future work should therefore evaluate selected reduced configurations directly, including pitch–heave and pitch–heave–surge inputs and examine whether their performance remains stable across vessel speeds.

Finally, the channel-occlusion experiment should be interpreted as a post-hoc sensitivity analysis rather than as a complete simulation of physical sensor failure, since occlusion was applied only during test-set evaluation. Further work should include leave-one-DOF-out retraining, training-time channel dropout, and validation using real shipboard measurements, additional vessel types, and broader operating conditions.

6 CONCLUSION

This paper analysed the relevance of individual ship-motion components for attention-based sea-state classification. Using simulated S175 vessel responses under irregular JONSWAP wave conditions, the study compared a full 6DOF input configuration with six single-DOF models and evaluated the trained 6DOF classifier using post-hoc channel occlusion. In addition, the full 6DOF and single-DOF models were assessed across different vessel speeds.

The results show that individual motion components do not contribute equally to classification performance. Heave achieved the strongest standalone performance, while pitch was the most influential channel within the full 6DOF classifier, producing the largest macro-F1 degradation when occluded. Surge also showed a relevant complementary contribution, whereas roll, sway, and yaw had more limited influence in the considered setup. The speed-based analysis showed that the full 6DOF model achieved the highest performance at all vessel speeds, while pitch and heave remained the dominant single-DOF contributors.

These findings identify pitch and heave as particularly relevant signals for future reduced-input configurations, while also confirming the robustness of the full 6DOF representation. Future work should directly evaluate selected reduced-DOF configurations, such as pitch–heave and pitch–heave–surge inputs, and validate the analysis using real shipboard measurements, additional vessel types, and broader operating conditions.

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Use of AI tools: AI-assisted tools were used to support the language refinement of the manuscript and code automation. All scientific content, analysis, interpretation, and conclusions were developed, and verified by the authors, who remain fully responsible for the content.

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I. Artificial Intelligence and Data-Driven Transport Systems

On the Influence of Observation-Window Length in Sea-State Classification from Vessel Motions Using Attention-Based Machine Learning

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ABSTRACT

This paper examines the effect of ship-motion signal duration on the performance of an attention-based neural-network framework for sea-state classification. Simulated six-degree-of-freedom (6DOF) vessel responses were generated at five vessel forward speeds under irregular JONSWAP sea conditions and grouped into five sea-state classes based on global wave statistics. For each original 30-min record, shorter input configurations were constructed by retaining the first 2, 5, 10, 15, 20, 25, or 30 min, while preserving the same dataset split and sample distribution across all experiments. In addition to the overall evaluation, a speed-based analysis was performed to assess whether the influence of observation-window length remained consistent across different vessel speeds. The results show that classification performance generally improves with increasing observation-window length. The 2-min input produced the lowest performance, with a macro-F1 score of 0.6597 ± 0.0197 and a balanced accuracy of 0.6885 ± 0.0133, whereas the highest mean performance was achieved using the 25-min window, with a macro-F1 score of 0.8484 ± 0.0042 and a balanced accuracy of 0.8573 ± 0.0078. The 30-min configuration did not further improve aggregate performance, indicating saturation in the 20–30-min range. The speed-based analysis showed broadly consistent trends across vessel speeds. Although it did not achieve the highest performance, the 10-min window provided a practical accuracy –latency compromise, reaching a macro-F1 score of 0.7961 ± 0.0630 and a balanced accuracy of 0.8070 ± 0.0687 while reducing the required observation time by 60% compared with the 25-min configuration.

Keywords: sea-state estimation; sea-state classification; vessel-motion responses; observation-window length; attention-based neural network

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FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Providing information on the current sea state is essential for maritime traffic management and navigational safety, as well as for improving vessel operational efficiency and reducing environmental impact [1, 2]. The process of deriving relevant information about sea conditions is commonly referred to as sea-state estimation (SSE). Sea state can be estimated using measurement systems such as wave buoys and wave radars, as well as remote-sensing approaches based on satellite imagery. However, many of these methods are associated with practical and economic limitations. To overcome these limitations, the concept of using a ship as a wave buoy (SAWB), more commonly referred to as the wave buoy analogy (WBA), has been proposed [3]. The central idea of this approach is to use vessel-motion responses induced by encountered waves to estimate or approximate the surrounding sea state.

Traditional WBA-based methods have generally relied on statistical approaches for estimating wave characteristics. More recently, machine-learning techniques have been increasingly applied to this problem, with particular emphasis on sea-state regression for estimating continuous wave parameters and sea-state classification for assigning observations to predefined sea-state code categories [3, 4, 5]. For onboard applications, classification accuracy alone is not sufficient; the observation window must also be short enough to support timely decision-making. However, the model must process a sufficiently long temporal signal to capture relevant vessel-response information, which introduces a trade-off between classification accuracy and observation latency. Here, observation-window length determines the amount of motion history required for each estimate and the initial time needed to fill the window; in a sliding-window implementation, the estimate update rate would instead be determined by the window stride and can therefore be independent of window length.

The main contribution of this paper is a systematic evaluation of observation-window length in attention-based sea-state classification from full six-degree-of-freedom (6DOF) vessel-motion responses. By comparing input durations of 2, 5, 10, 15, 20, 25, and 30 min using the same attention-based classifier and the same simulation, preprocessing, training, and evaluation protocol, this study quantifies the trade-off between classification accuracy and temporal responsiveness. In addition, a speed-based analysis is performed to examine whether the influence of observation-window length remains consistent across different vessel forward speeds.

The rest of the paper is organised as follows. Section 2 provides an overview of related work, with emphasis on time-window selection in machine-learning-based SSE. Section 3 describes the data generation process, the attention-based classification framework, and the experimental procedure used to evaluate different observation-window lengths. Section 4 presents the classification results, including the aggregate analysis and the speed-based evaluation. Section 5 discusses the implications of the obtained results for the accuracy–latency trade-off in ship-motion-based sea-state classification. Finally, Section 6 concludes the paper and directions for future work.

2 BACKGROUND

In machine-learning-based SSE, vessel-motion responses have been represented using a wide range of time-window lengths for model development and evaluation, from relatively short five-minute intervals [6] to longer one-hour windows [7]. This variation indicates that time-window length is an important methodological factor, particularly when considering the trade-off between model performance and temporal responsiveness. Shorter windows are commonly used with time-domain inputs, where the model directly processes measured or simulated vessel-motion signals. In contrast, longer windows are often used to derive spectral representations, such as motion spectra. This reflects the different types of information that can be extracted from short- and long-duration signals, as well as the balance between faster classification and more stable frequency-domain representations.

Several studies illustrate this diversity in time-window selection and input representation. Selimović et al. [6] used 5-min time-series intervals for regression-based estimation of sea-state parameters from ship-motion responses. Mittendorf et al. [8] considered both shorter time-domain inputs and longer 25-min frequency-domain representations derived from 6DOF vessel-response data. Long et al. [9] employed 40-min intervals of heave, pitch and roll motion signals to construct Welch power spectral density representations for estimating essential wave parameters. Longer windows have also been investigated; for example, Serr et al. [10] used 60-min intervals and cross-spectral density tensors based on heave, roll, and pitch motion components. In a classification-oriented study, Majidiyan et al. [11] transformed 18-min recordings of all 6DOF motions into wavelet scalograms for model-based sea-state classification.

The reported time-window configurations are often coupled with different motion-component selections, which makes it difficult to isolate the specific effect of temporal input duration. Since the authors' previous study [12] focused on DOF configurations for attention-based sea state classification, the present work fixes the input representation to the full 6DOF motion response and instead evaluates the influence of observation-window length. All models therefore use surge, sway, heave, roll, pitch, and yaw as time-series inputs, avoiding dependence on a specific reduced motion set.

A closely related study by Mittendorf et al. [8] investigated different time-series binning strategies for regression-based SSE. Their models estimated significant wave height, peak wave period, and wave encounter frequency using window lengths of 5, 10, 15, 20, and 25 min. The models were trained using combinations of heave, pitch, roll, sway, surge, and yaw motions, with the additional inclusion of vertical bow acceleration. Both time-domain and frequency-domain features were considered. The results showed that longer time windows generally improved model performance, although the optimal window length depended on the estimated parameter. In contrast, the present work focuses on sea-state classification using a fixed full 6DOF time-series input and evaluates whether the effect of observation-window length remains consistent across different vessel forward speeds.

3 METHODOLOGY

The training data were generated according to the global sea-state distribution framework proposed by Price [13]. For each simulated sea condition, the wave-height range corresponding to the selected sea-state class was first defined, and a random wave-height value was sampled within that interval. The associated wave period was then selected from the corresponding set of possible periods according to the prescribed occurrence probabilities. This procedure preserved the joint statistical relationship between wave height and wave period observed in worldwide sea-state data.

The dataset generation process followed the methodology described in the authors' previous work [12]. Simulations were performed using the Marine Systems Simulator (MSS) Toolbox [14], with irregular wave excitation represented by the JONSWAP spectrum. The S175 ship model was selected as the reference vessel, and its motion responses were obtained from the corresponding response amplitude operator (RAO) functions. To cover different operating conditions, the simulations included five vessel forward speeds, namely 0, 5, 10, 15, and 20 knots, while wave encounter angles were uniformly distributed across the full 360° range. Following Cheng et al. [15] and the authors' earlier work [12], only sea states 0–6 were considered, as they account for more than 98% of global sea-state occurrences. Sea states 0–2 were combined into a class C1, while classes C2–C5 correspond to sea states 3–6, respectively. The simulated vessel-motion responses were sampled at 2 Hz, and each simulation produced a 30-min record. In total, the dataset contained 20,000 samples, with 4,000 samples corresponding to each vessel speed. **Table 1** summarises the resulting class definitions, along with their associated significant wave-height ranges, global sea-state occurrence frequencies, and the corresponding number of test samples.

Table 1. Sea-state class definitions and corresponding dataset characteristics.

Class	Sea state	Significant wave height [m]	Global sea-state occurrence [%]	Number of test samples
C1	0–2	< 0.5	11.25	484
C2	3	0.5–1.25	31.69	588
C3	4	1.25–2.5	40.19	1320
C4	5	2.5–4	12.80	513
C5	6	4–6	3.03	121

The effect of observation-window length was evaluated using a prefix-based extraction strategy. After the original 30-min simulations had been divided into training, validation, and test subsets, shorter inputs were generated by retaining the first L minutes of each 30-min record, with L set to 2, 5, 10, 15, 20, 25, and 30. No additional overlapping or non-overlapping subsegments were generated from the same parent simulation. Consequently, each window-length configuration contained the same number of samples and preserved the same class distribution, vessel-speed distribution, and train/validation/test assignment as the original dataset. This design enabled a controlled comparison of temporal-context effects while avoiding leakage of correlated segments across dataset splits.

The adopted model follows the framework presented in the authors' earlier study [12], in which the attention-based regression model adapted from [6] was converted into a classification model by replacing the original regression output layer with a classification head. The model input consisted of full 6DOF vessel-motion responses, including surge, sway, heave, roll, pitch, and yaw. The same model architecture and training protocol were used for all observation-window lengths, so that performance differences could be attributed primarily to the duration of the input signal.

Preprocessing followed the original attention-based framework, with batch-wise augmentation retained due to its previously demonstrated effectiveness. All input signals were min–max normalised channel-wise, providing a consistent basis for comparing different observation-window configurations.

For each observation-window length, the models were trained using three different random initialisation seeds. The dataset was divided into stratified training, validation, and test subsets using a nominal 70/15/15 split, and the same split was kept fixed across all window-length configurations. Training was performed for up to 150 epochs using the AdamW optimizer, a learning rate of 3×10^{-4}, a weight decay of 1×10^{-4}, and the cross-entropy loss function. Early stopping was applied based on the validation macro-F1 score, with a patience of 20 epochs and a minimum improvement threshold of 1×10^{-3}.

In addition to the aggregate test-set evaluation, a speed-based analysis was performed. For this analysis, the test samples were grouped according to the corresponding vessel forward speed of 0, 5, 10, 15, or 20 knots. The same trained models and test split were used, and macro-F1 score and balanced accuracy were computed separately for each speed group and observation-window length. This allowed the influence of observation-window length to be evaluated both overall and under individual vessel-speed conditions.

4 RESULTS

The classification results show a clear dependence of model performance on observation-window length. Macro-F1 was used as the primary evaluation metric because of the imbalanced class distribution, while balanced accuracy was used as a complementary metric to assess average class-wise recall. All values are reported as mean ± standard deviation across three training runs.

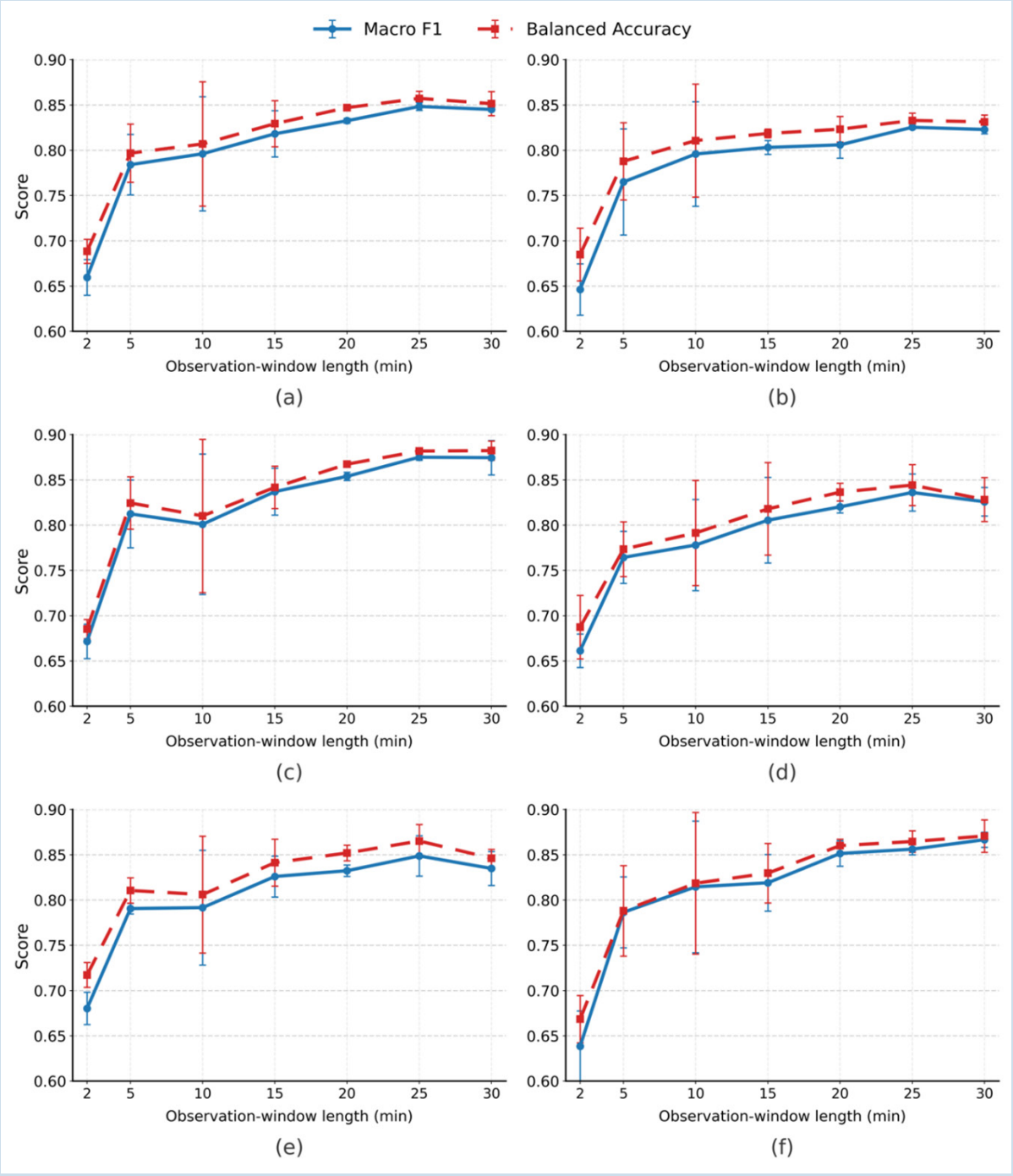


Figure 1. Classification performance across observation-window lengths and vessel forward speeds: (a) overall test set, (b) 0 kn, (c) 5 kn, (d) 10 kn, (e) 15 kn, (f) 20 kn. Markers indicate mean values across three training runs, and error bars denote standard deviation.

Figure 1(a) shows the aggregate test-set performance across the evaluated observation-window lengths. Both macro-F1 and balanced accuracy followed a similar trend. The shortest window of 2 min produced the weakest performance, with a macro-F1 score of 0.6597 ± 0.0197 and balanced accuracy of 0.6885 ± 0.0133. Increasing the window length to 5 min led to a substantial improvement, raising the scores to 0.7841 ± 0.0335 and 0.7968 ± 0.0321, respectively.

Further improvements were observed for the 10-min and 15-min configurations, which achieved macro-F1 scores of 0.7961 ± 0.0630 and 0.8182 ± 0.0256, and balanced accuracies of 0.8070 ± 0.0687

and 0.8294 ± 0.0255, respectively. The 20-min configuration reached a macro-F1 score of 0.8326 ± 0.0027 and a balanced accuracy of 0.8471 ± 0.0032. The highest mean performance was obtained using the 25-min window, with a macro-F1 score of 0.8484 ± 0.0042 and a balanced accuracy of 0.8573 ± 0.0078. Extending the window to 30 min did not further improve the aggregate result, as both metrics slightly decreased to 0.8451 ± 0.0083 and 0.8515 ± 0.0096.

The speed-based analysis is shown in **Figure 1(b)–(f)**. Overall, the performance trends across individual vessel speeds were broadly consistent with the aggregate results. For most speed-specific evaluations, performance increased from the shortest windows toward the longer observation windows, with the 25-min configuration generally producing the strongest or near-strongest mean performance. At 5 knots, the 5-min configuration slightly outperformed the 10-min configuration, although the corresponding standard deviations overlap. At 20 knots, the 30-min configuration achieved slightly higher mean performance than the 25-min configuration. These differences are small relative to the observed variability and should therefore be interpreted cautiously.

Overall, both the aggregate and speed-based results indicate that increasing the observation-window length improves classification performance up to the longer-window range, while the gain becomes limited between the 25-min and 30-min configurations.

The results are additionally summarised in **Table 2**.

Table 2. Classification performance across observation-window lengths for each vessel forward speed and overall, reported as macro-F1 and balanced accuracy (mean ± standard deviation).

Window [min]	Speed [kn]	Macro F1	Balanced accuracy
2	**Overall**	**0.6597 ± 0.0197**	**0.6885 ± 0.0133**
	0	0.6463 ± 0.0283	0.6849 ± 0.0291
	5	0.6717 ± 0.0189	0.6853 ± 0.0106
	10	0.6614 ± 0.0185	0.6874 ± 0.0350
	15	0.6803 ± 0.0179	0.7173 ± 0.0137
	20	0.6385 ± 0.0391	0.6685 ± 0.0261
5	**Overall**	**0.7841 ± 0.0335**	**0.7968 ± 0.0321**
	0	0.7650 ± 0.0586	0.7879 ± 0.0426
	5	0.8124 ± 0.0374	0.8245 ± 0.0289
	10	0.7644 ± 0.0287	0.7735 ± 0.0302
	15	0.7906 ± 0.0060	0.8106 ± 0.0139
	20	0.7865 ± 0.0392	0.7881 ± 0.0500
10	**Overall**	**0.7961 ± 0.0630**	**0.8070 ± 0.0687**
	0	0.7959 ± 0.0578	0.8107 ± 0.0624
	5	0.8010 ± 0.0776	0.8102 ± 0.0847
	10	0.7781 ± 0.0502	0.7914 ± 0.0581
	15	0.7916 ± 0.0634	0.8060 ± 0.0644
	20	0.8146 ± 0.0727	0.8186 ± 0.0782

Window [min]	Speed [kn]	Macro F1	Balanced accuracy
15	**Overall**	**0.8182 ± 0.0256**	**0.8294 ± 0.0255**
	0	0.8032 ± 0.0076	0.8186 ± 0.0047
	5	0.8370 ± 0.0258	0.8417 ± 0.0234
	10	0.8055 ± 0.0471	0.8180 ± 0.0511
	15	0.8260 ± 0.0226	0.8413 ± 0.0258
	20	0.8191 ± 0.0313	0.8297 ± 0.0329
20	**Overall**	**0.8326 ± 0.0027**	**0.8471 ± 0.0032**
	0	0.8060 ± 0.0147	0.8233 ± 0.0142
	5	0.8539 ± 0.0044	0.8673 ± 0.0002
	10	0.8202 ± 0.0067	0.8365 ± 0.0098
	15	0.8324 ± 0.0063	0.8520 ± 0.0086
	20	0.8514 ± 0.0141	0.8601 ± 0.0070
25	**Overall**	**0.8484 ± 0.0042**	**0.8573 ± 0.0078**
	0	0.8254 ± 0.0020	0.8330 ± 0.0080
	5	0.8751 ± 0.0034	0.8818 ± 0.0025
	10	0.8361 ± 0.0204	0.8442 ± 0.0226
	15	0.8488 ± 0.0223	0.8652 ± 0.0182
	20	0.8562 ± 0.0062	0.8646 ± 0.0120
30	**Overall**	**0.8451 ± 0.0020**	**0.8515 ± 0.0133**
	0	0.8229 ± 0.0047	0.8314 ± 0.0076
	5	0.8745 ± 0.0190	0.8823 ± 0.0107
	10	0.8259 ± 0.0158	0.8283 ± 0.0243
	15	0.8349 ± 0.0187	0.8462 ± 0.0098
	20	0.8666 ± 0.0083	0.8707 ± 0.0179

5 DISCUSSION

The observed results indicate that the analysed attention-based sea-state classification approach benefits from longer observation windows when using fixed 6DOF ship-motion inputs. This improvement can be attributed to the fact that longer observation intervals provide a more representative description of vessel-response dynamics, allowing the model to capture temporal patterns that are not sufficiently expressed in shorter windows. Very short observation windows appear to contain insufficient information for stable discrimination between sea-state classes, particularly between adjacent classes, which helps explain their lower classification performance. These misclassifications are illustrated by the confusion matrix shown in **Figure 2** for the 2-min observation window.

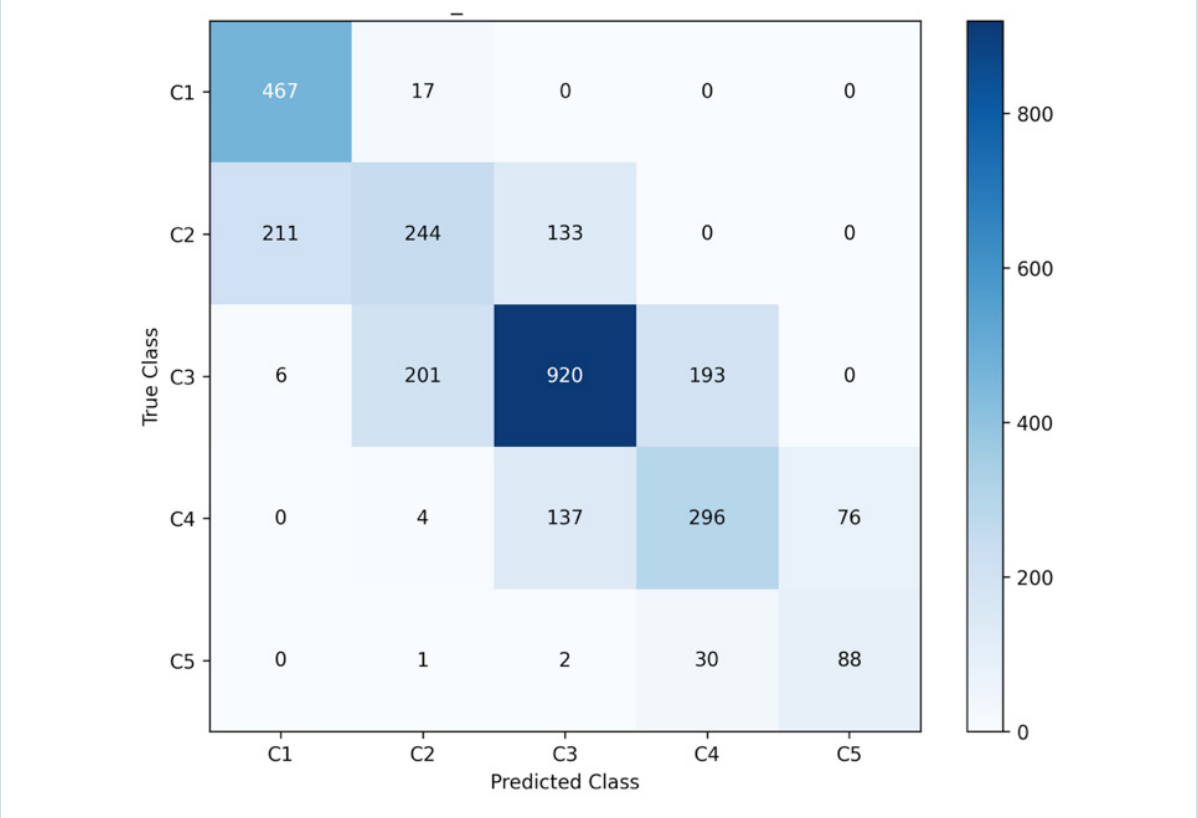


Figure 2. Confusion matrix for the 2-min observation window. Cells adjacent to the diagonal correspond to misclassifications between neighbouring sea-state classes.

The speed-based analysis further supports this interpretation, as broadly similar trends were observed across the considered vessel forward speeds. In most speed-specific evaluations, classification performance improved from the shortest windows toward the longer observation-window range, with the 25-min configuration generally achieving the strongest or near-strongest mean performance. This indicates that the benefit of increased temporal context is not limited to a single operating speed, but is generally consistent across the simulated speed conditions.

From an accuracy-oriented perspective, the 25-min configuration achieved the highest mean aggregate performance. However, this apparent optimum is specific to the present simulation setup and may shift when the method is applied to real-world data and operating conditions. At the same time, the absence of further improvement for the 30-min configuration suggests that the useful information content begins to saturate in the 20–30-min range. Beyond this range, additional motion history may contribute only marginally to the classification decision while increasing the observation delay. The speed-based results show that the 30-min window slightly exceeded the 25-min window at the highest investigated speed, but this difference was small and should not be interpreted as evidence of a generally superior 30-min configuration.

For near-real-time or operationally responsive implementation, the 10-min window represents a relevant compromise between classification performance and latency. Although it does not achieve the highest score, it requires substantially less observation time than the longest windows while maintaining considerably better performance than the shortest configurations. The 5-min window may be useful when a shorter observation history is prioritised, but it comes with a more pronounced performance cost. In contrast, observation windows of 20 min and longer provide stronger classification reliability and may be preferable when accuracy and robustness are prioritised over response time.

The findings should be interpreted within the context of the adopted simulation setup. The analysis is based on simulated data, a single ship model, and wave conditions generated using the JONSWAP spectrum, which may limit generalizability. In addition, the shorter inputs were generated using a prefix-based extraction strategy, where only the initial *L* minutes of each 30-min record were retained. This enabled a controlled comparison across window lengths, but it does not fully represent sliding or adaptive windowing strategies that may be used in practical onboard systems. Future work should therefore validate the approach using real-world onboard measurements and examine sliding, overlapping, or adaptive observation windows across different vessel types and operating conditions.

6 CONCLUSION

This paper investigated the influence of observation-window length on attention-based sea-state classification from simulated 6DOF vessel-motion responses. By keeping the input representation fixed to the full 6DOF motion response and varying only the temporal duration of the input signal, the study isolated the effect of available temporal context on classification performance.

The results show that classification performance generally improves as the observation window increases. The 2-min configuration produced the lowest performance, while the highest mean macro-F1 score and balanced accuracy were obtained using the 25-min window. The 30-min configuration did not further improve the aggregate test-set performance, suggesting that the benefit of additional temporal context saturates in the 20–30-min range. The speed-based analysis showed broadly consistent trends across vessel forward speeds, with the 25-min window typically providing the strongest or near-strongest performance. At the highest investigated speed, however, the 30-min configuration slightly exceeded the 25-min result, but this difference was small and should be interpreted cautiously.

From an operational perspective, the findings confirm that observation-window length is an important design parameter in ship-motion-based sea-state classification. Longer windows are preferable when classification reliability is prioritised, whereas intermediate windows, such as 10 min, may offer a practical compromise when lower observation latency is required. Future work should validate these findings using full-scale onboard measurements, additional vessel types, and broader operating conditions. Further research should also examine sliding, overlapping, and adaptive windowing strategies.

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I. Artificial Intelligence and Data-Driven Transport Systems

A Multi-Layer Validation Framework for AIS-Derived Mooring Episodes in Port Environments

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ABSTRACT

Automatic Identification System (AIS) data are widely used in maritime traffic analysis, vessel monitoring, and safety-related studies, supported by international AIS performance and technical standards. Recent AIS research has addressed trajectory preprocessing, anomaly handling, route extraction, and maritime traffic analytics, while recognising persistent challenges related to temporal continuity, spatial consistency, and data quality. Previous work on berthed vessels showed that AIS-Derived positions may meet maritime positioning requirements while still exhibiting greater variability than GNSS-based (Global Navigation Satellite System) reference solutions. However, AIS messages recorded as moored vessel conditions remain less frequently analysed as structured spatio-temporal units to assess reported positional stability. This paper presents a multi-layer validation framework for mooring episode analysis in port environments, based on AIS data. The framework was applied to an analytical dataset comprising 101,957 AIS records from 64 MMSIs (Maritime Mobile Service Identity), from which 126 retained mooring episodes were identified. The study used AIS data, covering the Port of Naples (Italy) from 24 May to 14 June 2021. Episodes were extracted using navigational status, speed-over-ground below 0.3 kn, a minimum duration of 12 h, and a maximum gap percentage of 5%. As this is a first methodological prototype, the detailed presentation is limited to three significant and contrasting episodes, selected as the mathematically most stable case, a representative stable case, and the most unstable case using a composite instability score derived from standardised spatial indicators. The proposed framework links temporal filtering, spatial consistency assessment, episode-level profiling, and harbour-context interpretation into a systematic and reproducible procedure for identifying and comparing patterns of reported positional stability. Observed AIS-Derived variability should not be regarded as direct evidence of GNSS error or signal degradation. The proposed methodology provides a reproducible basis for evaluating AIS-Derived mooring behaviour and supports future integration with georeferenced harbour infrastructure for quantitative berth-validation applications

Keywords: AIS; mooring episode; multi-layer validation; positional stability; port environment; spatial dispersion; maritime data analysis; harbour

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION AND BACKGROUND

The Automatic Identification System (AIS) is a standardised maritime communication system that enables the exchange of navigational, voyage-related, and vessel-identification information between vessels and shore stations. Originally developed to support navigational safety and traffic monitoring, AIS data are now widely employed in maritime research applications including traffic-density estimation, route extraction, trajectory analysis, anomaly detection, environmental assessment, and maritime analytics [1–4]. The growing availability of historical AIS archives has expanded opportunities for data-driven investigations of vessel behaviour in coastal and port environments. While AIS research has traditionally focused on vessel movements and route reconstruction, port environments provide a distinct analytical setting in which vessels may remain stationary or operate at very low speeds for prolonged periods. Consequently, AIS data have increasingly been used to investigate vessel activity and operational patterns within ports, demonstrating their value beyond traditional navigation and traffic-monitoring applications [5].

The reliability of AIS-based analyses, however, depends strongly on the quality and characteristics of the underlying positional information. Previous studies have identified a range of AIS data-quality issues, including missing observations, duplicated records, MMSI (Maritime Mobile Service Identity) inconsistencies, abnormal trajectory points, and other spatio-temporal irregularities capable of influencing behavioural analyses and navigation-risk assessments [6]. Similarly, investigations of AIS positional accuracy have identified measurable discrepancies between AIS-reported positions and independent radar observations [7], while comparisons with RTK-GPS measurements have demonstrated positional errors associated with AIS transmission and timing effects [8]. These findings emphasise that AIS-reported positions should not be interpreted uncritically as direct representations of vessel behaviour and highlight the importance of understanding positional reporting characteristics when AIS data are used for detailed operational analyses. Such considerations become particularly relevant for stationary or slowly moving vessels. Unlike navigational trajectories, where vessel motion dominates observed positional changes, vessels that remain berthed or moored are expected to exhibit limited physical movement. Nevertheless, AIS observations collected during such periods may still display positional dispersion, temporal irregularity, and coordinate repetition arising from reporting characteristics, positioning uncertainty, local environmental influences, equipment configuration, or combinations of above.

Previous investigations of berthed vessels in the Port of Copenhagen [9] indicated that AIS-Derived positions of operationally stationary vessels may exhibit different temporal and spatial characteristics despite being collected within the same harbour environment. Variability was observed in positioning behaviour and positioning deviations, suggesting that AIS-Derived positional behaviour cannot always be interpreted solely in terms of vessel motion. These observations highlighted the need for more systematic approaches to characterising and comparing positional behaviour during mooring conditions. Despite the growing availability of AIS data and extensive research on trajectory preprocessing, route extraction, and movement-based behavioural analysis, relatively little attention has been devoted to the systematic investigation of AIS-Derived mooring behaviour. Existing methodologies primarily focus on individual AIS messages, vessel trajectories, or vessel-level summaries, whereas prolonged mooring periods are rarely treated as independent spatio-temporal analytical units. As a result, temporal continuity, positional consistency, spatial dispersion, and reporting variability often remain masked when observations are analysed individually or aggregated over broader operational periods. Consequently, reproducible methodologies are needed for extracting, validating, and comparing AIS-Derived mooring episodes as coherent analytical entities.

To address this gap, this study proposes a multi-layer validation framework for the analysis of AIS-Derived mooring episodes in port environments. Using AIS observations collected in the Port of Naples [10, 11], the methodology transforms AIS messages into validated AIS-Derived mooring episodes

and evaluates their reported positional stability through a sequence of temporal and spatial assessment procedures. The framework combines continuity-based validation, episode-level spatial profiling, and a composite instability ranking to support systematic comparison of mooring behaviour. The approach is demonstrated through contrasting case analyses comprising a mathematical optimum, a representative stable episode, and an episode exhibiting pronounced spatial instability.

2 DATA AND STUDY DESIGN

2.1 AIS dataset

The study used historical AIS observations collected within the Port of Naples, Italy, between 24 May and 14 June 2021. The original dataset provided by Spire Maritime contained 772,404 AIS messages. The processed dataset comprised 28 AIS-related variables, including vessel identity, navigational status, timestamps, speed, course, heading, and geographic position. To ensure consistency of positional analysis, only AIS position-report messages (types 1, 2, and 3) were used during mooring episode extraction. Vessels whose overall observation span was shorter than 12 h were excluded from further consideration. Following duplicate removal and MMSI-level filtering, the analytical dataset contained 237,234 position reports representing 149 single vessels. The 22-day observation period includes vessels exhibiting a broad range of mooring durations and reported positional behaviours. The final retained population used for episode-level analysis comprised 64 unique vessels. Cargo vessels represented the largest category (31 vessels; 48.4%), followed by passenger vessels (12; 18.8%) and tankers (12; 18.8%). Tugboats accounted for 5 vessels (7.8%), while other vessel categories comprised 4 vessels (6.2%) including miscellaneous craft, pleasure vessels, and vessels without available ship-type information. The retained population therefore reflects a diverse operational mix typical of a major commercial port environment.

2.2 Analytical scope

The objective of this study was not to evaluate individual AIS observations but rather to analyse AIS-Derived mooring episodes as coherent spatio-temporal units. An AIS-Derived mooring episode is defined as a continuous interval during which a vessel reports AIS navigational status code 5 (moored), satisfies the adopted speed threshold (< 0.3 kn), and fulfils the duration and continuity criteria of the framework. The term AIS-Derived mooring episode is used because the analytical unit represents a temporally coherent interval of reported mooring behaviour satisfying predefined navigational status, speed, duration, and continuity criteria. Similar to the use of behavioural episodes in mobility and trajectory analysis, the episode is treated as a complete spatio-temporal entity rather than a collection of individual observations. The term refers exclusively to AIS navigational status code 5 (moored) and does not include anchoring or any other navigational statuses. Treating each episode as an independent analytical entity enables comparison of reported positional stability between vessels and mooring periods. Application of the temporal filtering and continuity procedures yielded 175 candidate mooring episodes. Subsequent quality-control assessment based on temporal continuity reduced the population to 126 retained episodes satisfying the adopted gap-tolerance criteria. These retained episodes formed the analytical population used for spatial consistency assessment, instability ranking, and contrasting-case selection. Together, the retained episodes comprise 101,957 AIS observations originating from 64 distinct MMSI identifiers. Detailed interpretation focuses on a small number of contrasting cases selected to illustrate different manifestations of reported positional behaviour.

2.3 Workflow and case selection

The study follows a hierarchical workflow in which raw AIS observations are transformed into validated mooring episodes, characterised through spatial-dispersion metrics, and ranked according to a composite instability score. The ranking provides both a population-level overview of retained episodes and a basis for selecting contrasting cases for detailed examination. In this study, three reference episodes are considered: (i) the mathematical optimum identified by the composite instability score, (ii) a representative stable episode selected from highly ranked low-instability episodes using supplementary coordinate-diversity diagnostics, and (iii) the most unstable retained episode. Together, these cases represent the lower bound, a typical stable case, and the upper bound of reported positional behaviour observed within the retained population. These cases illustrate different manifestations of AIS-Derived positional behaviour and demonstrate the interpretive value of the proposed framework. The overall study design therefore combines population-level ranking with targeted case-based interpretation, providing a reproducible framework for evaluating AIS-Derived positional stability in port environments.

3 METHODOLOGY: MULTI-LAYER VALIDATION FRAMEWORK

3.1 Overview of the framework

The proposed methodology follows a multi-layer validation workflow (**Figure 1**) designed to transform AIS observations into validated AIS-Derived mooring episodes and evaluate their reported positional stability through successive temporal and spatial assessment procedures. The analysis proceeds through a hierarchical sequence of processing and validation steps. As a preprocessing phase, AIS observations are first subjected to data cleaning and temporal filtering procedures. Retained AIS-Derived mooring episodes are then evaluated using spatial-dispersion indicators.

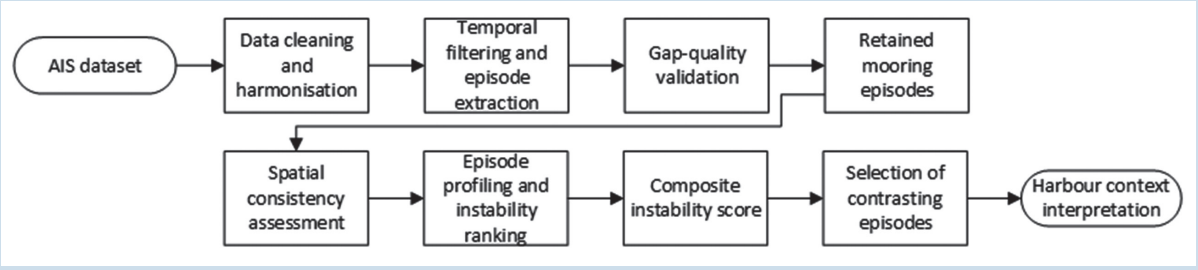


Figure 1. Multi-layer validation framework for AIS-derived mooring episode analysis. Made by the authors.

These indicators are standardised and integrated into a composite instability score, which is used to rank episodes by positional stability. Finally, selected episodes are examined within their harbour context to support interpretation of observed spatial behaviour.

3.2 Layer 1: Temporal filtering

The AIS dataset was cleaned and harmonised through message-type filtering, coordinate correction, metadata harmonisation, timestamp standardisation, and type normalisation. Only AIS position-report messages (types 1, 2, and 3) with navigational status parameter = 5 (moored) were retained for analysis, while duplicate observations recorded within the same minute were removed to minimise reporting redundancy while preserving the temporal structure of individual vessel tracks. AIS-Derived mooring episodes were identified using the criteria presented in **Table 1**.

Table 1. Mooring episode extraction criteria.

Criterion	Value	Purpose
Navigational status	Moored	Initial operational condition
Speed Over Ground (SOG)	< 0.3 kn	Exclusion of actual movement
Minimum duration	≥ 12 h	Retention of operationally meaningful mooring episodes
Gap percentage	≤ 5%	Exclusion of fragmented episodes

Source: Made by the authors

To avoid artificial fragmentation of otherwise continuous episodes, isolated non-moored observations occurring between consecutive moored observations were corrected using a simple spike-removal procedure before consecutive moored observations were aggregated into individual AIS-Derived mooring episodes.

3.3 Layer 2: Temporal continuity and spatial consistency assessment

It is well recognised that AIS-Derived episode analysis is sensitive to irregular transmission intervals and missing observations. Temporal continuity was therefore assessed using a 12 min gap-tolerance threshold. This value corresponds approximately to four nominal AIS reporting intervals for moored vessels and was adopted as a pragmatic continuity criterion intended to prevent artificial fragmentation of otherwise continuous mooring episodes caused by a small number of missed transmissions. Intervals exceeding this threshold were accumulated to calculate total gap duration, maximum gap duration, and a gap-percentage metric expressing the proportion of episode duration affected by interruptions. The 5% continuity criterion was adopted as a pragmatic quality-control threshold. It retained 126 episodes while excluding episodes exhibiting substantial temporal fragmentation. The criterion was intended to balance temporal continuity and population size rather than to represent an optimal or universal threshold. Application of the temporal continuity criterion reduced the dataset to 126 retained AIS-Derived mooring episodes comprising 101,957 AIS observations. These episodes constitute the analytical population examined in the remainder of the study. For each retained episode, geographic coordinates were projected into the UTM 33N coordinate reference system to enable metric-based spatial analysis. A reference position was subsequently defined using the median projected coordinates of all observations belonging to the episode. The positional behaviour of each episode was then characterised by calculating the radial deviation of individual AIS observations from this reference position. Radial deviation was defined as the Euclidean distance between an AIS-reported position and the corresponding episode reference position. The resulting deviation series was summarised using a set of spatial-dispersion metrics including mean radial deviation, median radial deviation, 95th-percentile radial deviation (P95), 99th-percentile radial deviation (P99), and maximum radial deviation. Together, these indicators describe both the typical positional variability of a moored vessel and the magnitude of infrequent larger excursions from the dominant reported position.

3.4 Layer 3: Episode-level profiling and composite instability score

To enable objective comparison among retained mooring episodes, five spatial-dispersion indicators were standardised using z-score transformation and combined into a composite instability score: mean radial deviation, median radial deviation, P95 radial deviation, P99 radial deviation, and maximum radial deviation:

$$S_i = \frac{1}{k}\sum_{=1}^{k} z_{ij} \quad (1)$$

where (S_i) is the composite instability score of episodes (i), (k) denotes the number of spatial indicators included in the ranking procedure and (z_{ij}) represents the standardised value of indicator j for episode i. Lower values of S_i indicate lower reported positional instability and therefore greater episode stability. All indicators contributed equally to the composite instability score because each metric was standardised prior to aggregation. The resulting ranking therefore reflects overall positional dispersion rather than any single indicator. The composite instability score was used exclusively as a ranking tool to support systematic comparison of retained episodes and selection of contrasting cases. Episodes were ranked in ascending order of instability, with rank 1 corresponding to the most stable episode and the highest rank corresponding to the most unstable episode. Additional diagnostics were subsequently applied to highly ranked episodes to assess coordinate diversity, positional repetition, and reporting behaviour. These diagnostics supported interpretation of ranking outcomes and selection of representative examples but were not incorporated into the instability score itself.

3.5 Layer 4: Harbour-context interpretation

The final layer focuses on the interpretation of selected episodes within their operational harbour context. To facilitate detailed examination, the instability ranking was used to identify three contrasting cases: the mathematically most stable episode, a representative stable episode, and the most unstable retained episode. The representative stable episode was selected from the highly ranked low-instability subset using supplementary coordinate-diversity and positional-repetition diagnostics. Together, these cases illustrate different manifestations of AIS-Derived positional behaviour ranging from highly stable to strongly dispersed conditions. Interpretation is limited to AIS-Derived positional behaviour and should not be regarded as direct evidence of vessel motion, GNSS error, or harbour-operational anomalies. The resulting framework provides a transparent and reproducible workflow for transforming raw AIS observations into validated AIS-Derived mooring episodes and systematically evaluating their positional stability within port environments.

4 RESULTS

4.1 Retained AIS-Derived mooring episodes

Application of the validation framework progressively reduced the original AIS dataset to 126 retained AIS-Derived mooring episodes comprising 101,957 AIS observations from 64 vessels. The episodes formed the analytical population used for spatial assessment, instability ranking, and contrasting-case selection. Descriptive statistics of the retained population are presented in **Table 2**. The retained episodes exhibited considerable variability in duration, observation count, gap burden, and positional dispersion, providing a suitable basis for identifying contrasting patterns of reported positional stability.

Table 2. Descriptive statistics of retained mooring-episode metrics (n = 126)

Variable	Mean	Median	Minimum	Maximum
Episode duration (h)	61.38	20.51	12.0	527.96
AIS observations per episode	809.18	267.00	152.0	7081.0
Gap percentage (%)	0.5	0.00	0.00	4.4
Mean radial deviation (m)	2.88	2.40	0.1	13.82
Median radial deviation (m)	2.22	1.95	0.0	9.37
P95 radial deviation (m)	7.07	5.12	0.0	60.17
P99 radial deviation (m)	13.24	7.34	1.13	146.4
Maximum radial deviation (m)	25.24	12.08	1.69	659.17

Source: Made by the authors

4.2 Contrasting Episode Analysis

The selected episodes were not intended to represent the entire population individually but rather to illustrate contrasting manifestations of AIS-Derived positional behaviour identified through the episode-ranking procedure. Their principal characteristics are summarised in **Table 3**. The composite instability score was used to rank all retained episodes according to their reported positional stability. The passenger cruise vessel (MMSI 371861000, Episode 3) was identified as the mathematically most stable episode (instability rank 1), while the tugboat (MMSI 247120100, Episode 1) represented the most unstable retained episode (instability rank 126).

Table 3. Selected reference episodes

Metric	Mathematical optimum	Representative stable episode	Most unstable episode
Episode identification (EID)	371861000_3	236509000_1	247120100_1
Instability rank (lowest best)	1	18	126
Instability score	-0.88	-0.59	5.54
Duration (h)	66.13	30.19	490.22
Number of observations	845	410	6320
Gap percentage (%)	0.0	0.20	0.2
Mean radial deviation (m)	0.11	1.22	13.82
Median radial deviation (m)	0.00	1.12	9.15
P95 radial deviation (m)	1.40	2.56	35.10
P99 radial deviation (m)	1.85	3.35	93.41
Maximum radial deviation (m)	6.97	4.15	659.17

Source: Made by the authors

Subsequent diagnostics revealed that several highly ranked episodes exhibited exceptionally low coordinate diversity and extensive positional repetition. To provide a representative example of stable mooring behaviour, the highest-ranked episodes were further evaluated using supplementary diagnostics describing coordinate diversity, dominant-coordinate fraction, and consecutive-repeat fraction. MMSI 236509000 (Episode 1; instability rank 18) was selected as the representative stable episode because it combined a favourable instability ranking with substantial coordinate diversity and very low levels of positional repetition. Unlike the mathematically most stable episode, its stability was not associated with coordinate-collapse behaviour.

The dominant-coordinate fraction represents the proportion of observations occupying the most frequently reported coordinate pair within an episode, whereas the consecutive-repeat fraction represents the proportion of observations that repeat the immediately preceding coordinate pair. Although the mathematically most stable passenger cruise vessel episode (MMSI 371861000, Episode 3) achieved the lowest instability score, it contained only five unique coordinate pairs and exhibited a dominant-coordinate fraction of 0.938 together with a consecutive-repeat fraction of 0.957. In contrast, the representative stable episode (MMSI 236509000, Episode 1) contained 259 unique coordinate pairs, with corresponding dominant-coordinate and consecutive-repeat fractions of 0.017 and 0.032. These diagnostics indicate that the representative stable episode achieved low positional dispersion without reliance on repeated coordinate states. All metrics reported in **Table 3** were calculated using the complete retained episodes, including candidate outlier observations, to ensure consistency with the composite instability ranking. **Figure 2** illustrates the spatial behaviour of the three selected reference episodes and highlights substantial differences in footprint size, positional concentration, and spatial dispersion. It is organised according to the geographical locations of the selected episodes within the Port of Naples.

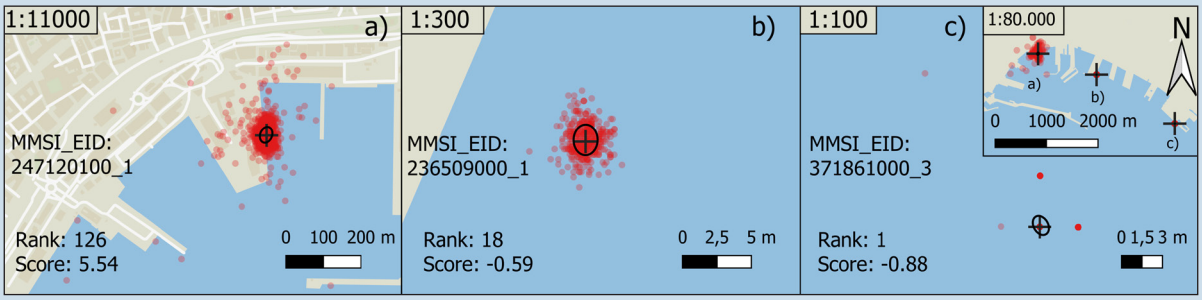


Figure 2. Spatial behaviour of the selected reference episodes. (a) Most unstable episode (MMSI 247120100_1), (b) representative stable episode (MMSI 236509000_1), and (c) mathematically most stable episode (MMSI 371861000_3). Made by the authors.

However, **Figure 3** presents the same episodes ordered according to stability characteristics to facilitate temporal comparison. In **Figure 2**, red points represent AIS-reported positions, black crosses denote episode reference positions, and ellipses indicate the dominant spatial footprint of each episode. Insets show the relative locations of the selected episodes within the Port of Naples with panels displayed at different spatial scales. The mathematically most stable episode (MMSI 371861000, Episode 3) exhibited an exceptionally compact footprint associated with a small number of repeatedly occupied coordinate states. In contrast, the representative stable episode (MMSI 236509000, Episode 1) displayed a compact but naturally dispersed point cloud, indicating low positional variability without pronounced coordinate repetition. The most unstable episode (MMSI 247120100, Episode 1) exhibited a dense central cluster together with numerous positional excursions extending well beyond the primary footprint, explaining its position at the bottom of the instability ranking.

Temporal examination of radial deviations revealed three distinct patterns of AIS-Derived positional behaviour (**Figure 3**). The mathematically most stable episode (MMSI 371861000, Episode 3) exhibited prolonged periods of highly repetitive positional reporting and only minor deviations from the reference position, consistent with the coordinate-collapse behaviour identified by the diversity diagnostics. In contrast, the representative stable episode (MMSI 236509000, Episode 1) displayed continuous low-amplitude fluctuations throughout the period, reflecting substantially greater coordinate diversity while remaining highly stable according to the instability ranking.

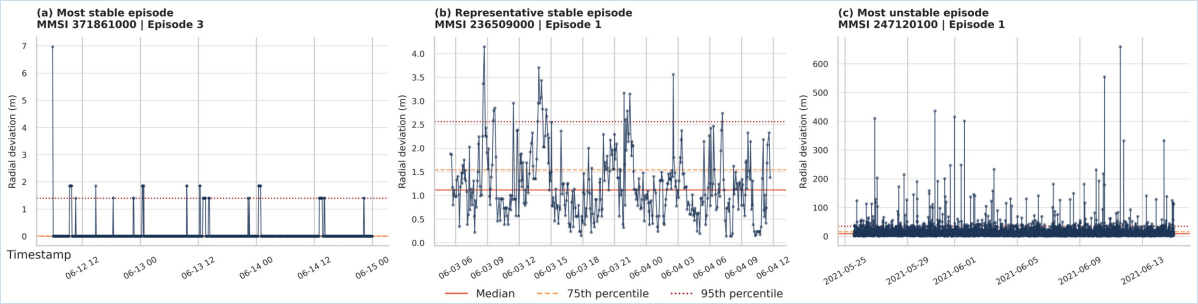


Figure 3. Radial deviation time series for the selected contrasting episodes. Made by the authors.

The most unstable episode (MMSI 247120100, Episode 1) was characterised by recurrent bursts of elevated deviations occurring throughout the 490-h observation period. Several excursions exceeded 400 m, with a maximum radial deviation approaching 660 m. Rather than a single isolated event, these excursions occurred repeatedly during the episode and therefore contributed substantially to the overall instability ranking.

4.3 Interpretation of the contrast

Comparison of the three reference episodes highlights both the usefulness and the limitations of instability-based ranking. Although the composite instability scores successfully differentiated episodes exhibiting markedly different positional characteristics, the results demonstrate that mathematical stability does not necessarily imply representative stable behaviour. The mathematically most stable episode (MMSI 371861000, Episode 3) achieved the lowest instability score but exhibited strongly quantised positional reporting and extensive coordinate repetition. In contrast, the representative stable episode (MMSI 236509000, Episode 1) combined low positional dispersion with substantially greater coordinate diversity, providing a more realistic example of stable mooring behaviour. At the opposite end, the most unstable episode (MMSI 247120100, Episode 1) illustrates the effects of recurrent large positional excursions on reported positional stability. Together, three selected episodes demonstrate the ability of the framework to distinguish between mathematical optimum, representative stability, and pronounced positional instability.

5 DISCUSSION

5.1 Methodological value of the framework

The proposed framework demonstrates that AIS-Derived mooring behaviour can be analysed systematically using a sequence of temporal, spatial, and diagnostic validation procedures. Rather than evaluating individual AIS messages in isolation, the framework treats AIS-Derived mooring episodes as coherent spatiotemporal entities, enabling temporal continuity, positional consistency,

and spatial variability to be assessed simultaneously. The multi-layer workflow proved valuable because no single indicator was sufficient to characterise reported mooring behaviour. Temporal continuity assessment ensured that only episodes with acceptable duration and data quality were retained, while spatial-dispersion metrics quantified positional variability. The composite instability score provided an objective mechanism for comparing retained episodes and identifying contrasting examples of reported positional stability.

5.2 Interpretation of stable and unstable episode behaviour

Application of the framework revealed that high positional stability can manifest through substantially different reporting behaviours. The mathematically most stable episode achieved the lowest instability score but was characterised by strongly quantised positional reporting and extensive coordinate repetition. In contrast, the representative stable episode combined low positional dispersion with substantially greater coordinate diversity and limited positional repetition, suggesting that numerical optimisation and representative stability are not necessarily equivalent.

This distinction represents an important methodological finding. Relying solely on aggregate instability metrics may favour episodes exhibiting coordinate-collapse behaviour, whereas supplementary diagnostics provide additional insight into the underlying reporting structure. At the opposite end of the ranking, the most unstable episode illustrates the effects of recurrent large positional excursions on reported positional stability. Together, the three reference episodes demonstrate the ability of the framework to distinguish between mathematical optimum, representative stability and pronounced positional instability.

5.3 Scope and limitations

The results should be interpreted as measurements of AIS-Derived positional behaviour rather than direct measurements of vessel position accuracy. The analysis relied exclusively on AIS observations and did not employ an independent geodetic reference capable of determining the true vessel location throughout each episode. Consequently, observed positional variability cannot be attributed unambiguously to GNSS error, multipath effects, AIS transmission characteristics, vessel movement, or other individual causal mechanisms. This distinction is particularly important because extremely compact positional distributions may reflect genuine positional consistency, coordinate quantisation, reporting behaviour, or combinations of these factors, while large positional excursions do not necessarily imply actual vessel movement. As demonstrated by the most unstable episode, substantial coordinate jumps may occur while AIS-reported navigational status and speed remain consistent with stationary-vessel conditions.

The framework was therefore designed to identify and characterise patterns of AIS-Derived positional behaviour rather than to determine their underlying cause. Its outputs should be interpreted as evidence of reported positional behaviour and not as definitive explanations of the physical or technical mechanisms responsible for the observed patterns.

6 CONCLUSION

This study presented a multi-layer framework for the extraction, validation, characterisation and ranking of AIS-Derived mooring episodes using AIS observations from the Port of Naples. Application of the framework yielded 126 retained AIS-Derived mooring episodes comprising 101,957 AIS observations from 64 vessels. Episode-level positional behaviour was quantified using radial-deviation metrics and a composite instability score, enabling systematic comparison of reported mooring stability.

The results demonstrated substantial variability in AIS-Derived positional behaviour during observed mooring conditions. The instability ranking successfully differentiated compact and spatially consistent episodes from episodes characterised by recurrent large positional excursions. Comparison of the selected reference episodes further showed that mathematical stability and representative stable behaviour are not necessarily equivalent. While the mathematically most stable episode exhibited highly quantised positional reporting, the representative stable episode combined a favourable instability ranking with substantially greater coordinate diversity and more realistic positional variability. This finding highlights the value of supplementing aggregate instability metrics with behavioural diagnostics when interpreting AIS-Derived position reports.

The proposed framework provides a reproducible methodology for screening large AIS datasets, identifying contrasting patterns of reported positional stability, and supporting subsequent investigations of vessel operations and AIS data quality. Future work should extend the analysis to multiple ports, vessel classes, and longer observation periods while examining the influence of AIS reporting characteristics and sensitivity assessment, GNSS positioning performance and environmental conditions on observed positional behaviour.

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I. Artificial Intelligence and Data-Driven Transport Systems

Review of Emerging Sensor Fusion Technologies Integrating Electro-Optical and Advanced Radar Systems in the Maintenance of National Security

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ABSTRACT

This paper analyses the contemporary development and application of sensor fusion technologies that integrate electro-optical and advanced radar systems in the maintenance of national security and the support of civil institutions. In conditions characterised by evolving and increasingly complex security threats, as well as the growing need for comprehensive monitoring of maritime, terrestrial, and aerial domains, the integration of advanced technologies has become essential for the development of effective situational awareness. Particular emphasis is placed on the use of electro-optical sensors in combination with advanced radar sensing technologies to enhance the precision and speed of threat detection, especially under challenging operational conditions and in environments with reduced visibility. The objective of this study is to provide an overview of the operational principles of newly developed systems and to analyse their effectiveness in improving surveillance and security infrastructures. Examples of such systems include architectures based on the Internet of Things (IoT) and 5G/6G connectivity, which enable the networking of all available assets and sensors within a given operational area such as vehicles, infrastructure, unmanned aerial systems (UAS), maritime platforms, and other monitoring devices into a unified operational picture accessible to multiple services and agencies in the field. These systems frequently operate on the principle of thermal signature detection, enabling efficient identification and tracking of vehicles, vessels, aircraft, and individuals for example in search and rescue (SAR) operations or border surveillance, as well as the detection of fires, smoke, and other anomalous events. The study will conduct a comparative analysis of existing technological solutions and examine practical case studies related to their implementation. Furthermore, the paper will conceptually assess the potential trajectories of their future technological advancement. In conclusion, advanced sensor fusion systems represent a significant advancement in the development of integrated situational awareness and in enhancing the efficiency of responses to security threats and incidents. They also provide opportunities for strengthening the resilience of national security systems through their integration into a comprehensive information awareness and decision-support framework.

Keywords: sensor fusion; national security; integrated systems; search and rescue

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

In the modern environment, characterized by constant evolution and increasing complexity of security threats, there is a growing need for comprehensive surveillance of maritime, land and air domains [1]. In order to develop effective situational awareness, necessary for maintaining national security and providing support to civil institutions, the integration of advanced technologies has become essential [1]. Therefore, a clear technological transition is visible from the use of individual, isolated sensors towards integrated multisensor architectures capable of generating a more comprehensive and reliable operational picture [2]. The foundation of such modern security architectures is the integration of advanced radar systems and electro-optical/infrared (EO/IR) sensors [1, 2]. Radars have traditionally been the most important sensor because they provide accurate information on the range, direction and speed of the target, while operating in complex weather conditions where visual confirmation is not possible [1, 2]. On the other hand, EO/IR sensors offer complementary information that enables better identification, classification and visual confirmation of targets based on thermal contours and high-resolution visual data [2]. Moreover, modern EO/IR systems are becoming increasingly important because they are completely passive, i.e. they do not emit signals, which makes them resistant to enemy radar absorption technologies and electronic jamming tactics [2, 3]. The combination of these sensors eliminates the so-called “blind spots”, significantly reduces the number of false alarms and successfully compensates for the individual limitations of each individual system [4, 5]. Since these networked sensors collect huge amounts of information, there is a need for complex computational processes to deal with data heterogeneity [1, 2]. The solution lies in sensor fusion, an integrated process that correlates and processes information from multiple sources and distributes it through a common command and control (C2) framework [2]. To speed up these processes and reduce the workload on human operators, multisensor systems designed for surveillance missions are increasingly integrating machine learning and artificial intelligence (AI) models that correlate data in real time and automatically classify targets [6]. The overall architecture additionally relies on the concepts of the Internet of Things (IoT) and advanced connectivity via 5G networks, enabling the networking of all available resources into a single operational picture [1]. The main objective of this paper is to analyse the contemporary development and application of sensor fusion technologies that integrate electro-optical and advanced radar systems for the purpose of maintaining national security [1]. The paper provides an overview of the operating principles of newly developed systems, conducts a comparative analysis of existing technological solutions, and examines practical aspects of their implementation in surveillance domains [1, 2]. Finally, the paper assesses potential directions for future technological development, with an emphasis on how advanced sensor fusion systems supported by artificial intelligence contribute to more precise detection, faster response to security threats, and strengthening the resilience of the overall security apparatus [1].

2 BACKGROUND

2.1 Advancement of electro-optical and electro-optical/infrared sensors

Electro-optical (EO) sensors, also often designated more specifically as electro-optical/infrared (EO/IR) sensors, are essentially a group of passive sensors that register electromagnetic (EM) waves emitted or reflected by their surroundings. Each sensor detects a designated electromagnetic band, as described in the **Table 1**. The only active component most commonly integrated into an EO sensor system is a laser range finder (LRF), which uses a very narrow beam, usually operating in the near-infrared (NIR) or short-wave infrared (SWIR) band. Today, these systems operate with RGB cameras and TIR/LWIR sensors as a minimum, but there is a significant shift towards holistic multispectral capabilities. Performance, together with operational capability and applicability, largely depends on two distinct areas [7]:

- Properties of the specific band of the EM spectrum in which the EO sensor operates. Lower-frequency sensors generally provide less information, i.e. lower resolution and poorer classification and identification capabilities, and vice versa. Nevertheless, some bands, although lower in frequency, carry unique information that other bands do not. For example, the heat information carried by TIR/LWIR is of the utmost importance for fire detection. Other bands provide important redundancy and robustness to the overall EO system, particularly in terms of resilience to poor visibility and adverse weather conditions.
- EO sensor system hardware and software design. The sensor hardware layer converts EM waves into a matrix of pixels with a certain resolution. Higher-resolution sensors are physically larger, thereby requiring larger gimbal systems, which is particularly important for all-weather operability, as well as more robust cooling systems, depending on the sensor type. On the other hand, the software layer conducts sensor fusion, both within a single EO system and between multiple cooperative systems operating on different platforms.

Development and international demand for EO systems in the maritime security environment are currently shifting largely towards the massive employment of cooperative UAVs and USVs as carrier platforms for EO sensor systems, with sufficient communication capabilities and resilience in contested EM environments. This, in turn, necessitates a reconsideration of data-fusion architectures [8].

Table 1. Comparison of EO bands

Name of the band	Wavelength	Advantages	Disadvantages
Thermal infrared (TIR), long wave infra red (LWIR)	14-7 μm	· Excellent at detecting man overboard (MOB) and fire at sea · Great whether and night resilience	· Low resolution · More expensive, bigger and heavier to carry
Medium wave infrared (MWIR)	5-3 μm	· Great whether and night resilience · Detection of high temperature leaks · Good for LRF	· Bigger and heavier due to cooling system · The most expensive
Near-infrared (NIR)/Short-wave infrared (SWIR)	1.7-0.7 μm	· Daylight detection · High resolution (HR) · Supplement visual spectrum camera · Good for LRF	· Low resilience to whether and low light condition
Visual band (RGB camera)	0.7-0.4 μm	· Daylight detection · High resolution (HR)	· Low resilience to whether and low light condition

Source: Made by the authors, backed by [9, 10]

2.2 Advanced radar sensors

Radar has traditionally been the most important onboard sensor, providing sufficiently accurate range, bearing, and speed information (2D radar), as well as altitude information (3D radar) at long ranges. It also provides resilience against electronic warfare and traditional drawbacks in the form of surface and weather clutter. Compared to EO systems, radar is essentially a single-band system. It is an active sensor, making energy consumption an important factor when considering the carrier platform. Radar provides early detection of large targets but often provides insufficient information for precise classification and identification [2].

Today, radar development is centred around more sensitive and resilient pulse radars. However, there is a shift from the traditional concept of long-range impulse radars designed primarily for the

detection of large targets with higher duty cycles and, ultimately, continuous-wave (CW) radars for the detection of medium to short-range low-flying, slow-flying, and small (LSS) targets. These radars use significantly less energy, are smaller in size, and are becoming increasingly affordable, although their higher frequencies up to millimetre wave band (as opposed to X and S traditional maritime surveillance bands) reduce range of detection and EM and whether resilience as can be seen in **Table 2**. Nevertheless, these emerging radar models are increasingly capable of being integrated onto autonomous platforms with limited space and electrical energy supply [2].

Table 2. Comparison of traditional and contemporary radar bands

Frequency bands	Frequency	Advantages	Disadvantages
X-band/S-band	8–12 GHz/2–4 GHz	· Robust whether resilience · Long detection range for big targets	· Large and heavy systems · Poor performance against LSS targets
Millimetre wave	30–300 GHz	· High resolution · Demand less energy consumption · Occupy less space	· Short range · Low whether resilience

Source: Made by the authors, backed by [1]

2.3 Data fusion

The described advancements in the fields of EO and radar technology have enabled the collection of large amounts of information about the operational environment and the creation of high-resolution situational awareness. However, the large amounts of heterogeneous data collected by different sensors have necessitated computational processes to overcome heterogeneity and the lack of synchronisation among sensors, as well as interoperability issues among different carrier platforms. These processes are collectively referred to as data fusion [1–3, 6, 11, 12].

This paper addresses the data fusion of different EO and radar sensors described above through the theoretical framework of data fusion architectures, fusion levels, techniques, and algorithms, with their respective advantages and disadvantages presented in **Table 3**. Four levels of data fusion are distinguished [1]:

- **Data level** – direct integration of raw, unprocessed data from individual sensors. This includes pixel-wise fusion of different EO images and radar imagery.
- **Feature level** – integration of previously processed features extracted from each sensor independently.
- **Decision level** – each sensor generates its own decision regarding the target, after which data fusion is used to generate a final decision.
- **Hybrid fusion** – a broad combination of the three aforementioned levels, applied interchangeably within customised fusion architectures.

Regarding data fusion techniques and algorithms, they can be divided into analytical-based methods, which use pre-programmed mathematical and statistical methods to synchronise temporal and heterogeneous data, and learning-based approaches, which employ machine learning (ML) algorithms to perform the same task. The type of sensor, the state of the environment in which the sensor operates, and the sensor's role within the architecture are factors that must be considered when designing a data fusion system [1, 11].

Table 3. Quantified comparison of data fusion levels

Data fusion level	Probability of data loss	Data accuracy	Computational costs	Data synchronisation	Communication Bandwidth	Fault tolerance and resilience
Data level	4	5	4	5	5	2
Feature level	3	4	3	4	3	3
Decision level	2	3	2	2	1	5
Hybrid fusion-	Depending on fusion strategy and data fusion system architecture; customised to optimise each system					

Source: Made by the authors, backed by [1, 6, 13]

The architecture of a data fusion system also largely depends on whether it fuses data from sensors on the same platform (multi-sensor fusion) or from sensors deployed across different platforms (multi-platform fusion), with the latter introducing an additional layer of data heterogeneity. This paper considers both cases, with numerous UAVs, USVs, and manned ships serving as carrier platforms for both EO and radar sensors. Therefore, the communication channels between these platforms must be properly designed [1, 7].

2.4 5G/6G connectivity and IoT

The Internet of Things (IoT) is a concept and a set of technological solutions that connect machines and sensors within a single network [14]. This concept was further enhanced with the introduction of 5G networks and technological solutions such as network slicing, which supports Enhanced Mobile Broadband (eMBB) for reliable and fast communication of massive amounts of data, massive Machine-Type Communications (mMTC) for reliable communication within dense sensor networks, and Ultra-Reliable Low-Latency Communications (URLLC) for extremely reliable communication of small amounts of data [15]. Strategically employing these aspects of 5G networks can enable massive sensor networks incorporating EO sensors, radars, edge computing, and data-fusion architectures that can be designed and scaled accordingly [16].

While 5G is already being used for maritime surveillance missions, although currently with a limited number of sensors and platforms, 6G is still under development and is expected to further reduce latency, widen communication channels, and even use communication signals for extremely precise, radar-like detection through Integrated Sensing and Communication (ISAC)[17]. However, both 5G and, even more so, 6G communications rely heavily on line-of-sight (LOS) communication channels and have limited resilience to weather conditions and sea-state conditions, which can further reduce the available communication range [18]. Moreover, network security, encryption, reliability, resilience, and centralisation have already been identified as weak points of 5G networks for military applications [19]. However, the use of reconfigurable intelligent surfaces (RIS) for smart signal reflection, potentially mounted on UAVs, could improve communication range and resilience. Therefore, further advancements in 5G and 6G maritime communications may depend on the development and integration of several specific technologies [19, 20].

3 METHODOLOGY

Literature review presented in the paper, includes four major technological components for integrated sensor systems that are: modern radar development, modern EO/IR development, data fusion architectures and advanced connectivity. To evaluate data fusion architectures, this paper adopts a

structured qualitative-to-quantitative evaluation methodology based on six core operational parameters: (1) Data loss probability, (2) Target accuracy, (3) Computational overhead, (4) Temporal synchronization requirements, (5) Communication bandwidth demands, and (6) System fault tolerance/resilience, as systematically analysed in **Table 3**. Both opportunities and drawbacks are in the results chapter formed into two distinct data fusion architecture systems for optimal usage in security contested environment and for the tasks of maritime surveillance detection, SAR and similar.

For the purpose of comparative analysis of modern integrated multisensory systems, a qualitative comparative methodology based on the analysis of publicly available technical and manufacturing data was applied with the aim to analyse key features of modern architectures that integrate various sensor technologies, data fusion, command and control (C2), artificial intelligence, and automation of the threat detection and assessment process. The sample of six modern multisensory systems from different defence equipment manufacturers was compared with respect to the way individual technological components are integrated. They were selected to encompass different approaches to the integration of radar, electro-optical/infrared (EO/IR), radio frequency, and other sensor capabilities within a common operational architecture.

The results are presented in the form of a comparative table, where the features of individual systems are described qualitatively, without forming an overall numerical result or ranking. Such an approach was chosen because the analysed systems differ in purpose, architecture, level of integration and operational concept, which is why a single numerical rating would not necessarily represent an objective measure of their overall value. **Table 4**, therefore, evaluates commercial multi-sensor architectures based on five baseline functional criteria: sensor payload diversity, fusion/C2 integration, AI capabilities, and primary mission profile. It serves primarily to identify common technological elements and differences in approaches to the integration of multisensory capabilities inside the security sensor marked and between market and concepts described in the scope of this paper. Moreover, key limitation of this study stems from its reliance on publicly available technical specifications and literature, as classified military performance parameters (such as exact radar cross-section detection thresholds, anti-jamming margins, and real-world processing latency) are restricted. Furthermore, performance metrics under extreme electronic warfare environments were evaluated conceptually rather than validated through field trials.

4 RESULTS AND DISCUSSION

While considering sensor network design, including data fusion architecture and communication capabilities for security and defence applications, particular attention must be given to increasing data accuracy, fault tolerance, redundancy, and EM resilience of networks in contested spectrum environments beyond commercial standards [19]. However, many factors are a function of the particular area of operation. Considering specifically the restrictions of 5G and 6G communications outside the LoS range, a multisensory platform such as this would perform optimally in a littoral area with dense maritime traffic and relatively moderate weather conditions, while still accounting for dense network traffic and possible deteriorating weather conditions. Distinct, encrypted, and separated network connections would, under these conditions, have to strike a compromise between the number of platforms connected and the network capacity allocated to each platform. This, in turn, depends on the sensor type and the amount of data processing performed on the platform itself (edge computing) and at the centralised manned ship. The latter will generate a need for wide communication channels.

Since each platform carrier will carry multiple different EO and/or radar sensors, the use of edge computing will prompt the need for data- or feature-level multisensor fusion, i.e. a high processing load on the platform carrier. The centralised mothership would then perform feature- or decision-level multi-platform data fusion to maximise fault tolerance [1].

In such a constellation, USVs would be optimal sensor carrier platforms, offering sufficient space, energy capacity, and persistence, with UAVs serving as primary communication links using passive RIS technology. Such an approach would minimise network congestion and provide medium to high data reliability and fault tolerance, depending on the data fusion level.

A secondary architecture option includes data-level multi-platform fusion among UASs serving as sensor carrier platforms. This would require significantly more network resources but provide additional resilience and reliability. Processing would be facilitated by first combining data from the same sensor types to reduce data heterogeneity and then creating feature-level fusion between the corresponding features of each sensor type. In this way, the impact of losing a single platform would be minimised and overall reliability maximised, at the cost of increased network load.

Sensor type selection is also important, since a low-resolution NIR sensor consumes less network bandwidth than an HR RGB camera and is significantly more resilient. Embedded data fusion algorithms should implement learning capabilities wherever possible. However, it is important to test each individual layer and sensor algorithm, particularly given the lack of previously conducted experiments.

All in all, using mMTC and eMBB for high-rate data traffic and URLLC for system command and control (C2) could enable smart iteration between these architectures to optimise system effectiveness [15]. This could involve heavy network loading under stable weather conditions to cover larger areas, particularly with the increased capacity expected from 6G. Conversely, the first architecture could reduce network congestion and provide reliable communication and efficient surveillance over smaller areas under poor weather conditions. Prediction and management of these, and potentially additional, iterations of system architecture will be crucial with emerging AI systems for network prediction and management already being developed for commercial purposes as part of 6G technologies [20]. Furthermore, weather and sea sensors located on the coast or mounted on buoys could potentially send critical information to the network management centre through the same IoT network technologies [21].

Table 4 presents a comparative overview of six contemporary integrated multisensor systems developed by different defence equipment manufacturers. The selected systems were chosen to represent current approaches to integrating heterogeneous sensors within a common operational architecture, with a particular emphasis on the combination of radar, electro-optical/infrared (EO/IR) sensors, additional sensor capabilities, sensor fusion, and command and control (C2). The comparison is based on five main characteristics: the composition of the integrated radar and EO/IR sensor package, the sensor fusion and C2 architecture, the application of artificial intelligence (AI) and automation, and the primary operational role of each system. These criteria were selected in accordance with the technological aspects discussed in the theoretical part of the paper. Radar provides information on range, direction, velocity and, in the case of three-dimensional systems, altitude, while EO/IR sensors provide complementary information that can improve target identification, classification and visual confirmation [1, 2]. The combination of these sensor types can therefore compensate for the limitations of individual sensors and contribute to improved situational awareness. The integration of radar and EO/IR sensors represents only one component of modern multisensor architectures. Modern systems increasingly include additional capabilities such as radio frequency sensing, electronic support measures (ESM), identification systems and dedicated effectors. The resulting architectures require data fusion processes capable of addressing heterogeneous data, synchronization and interoperability between different sensors and carriers [1, 6, 11]. In this context, sensor fusion allows for the correlation and processing of information obtained from multiple sources into a more coherent view of the operational environment. The selected systems illustrate several practical approaches to this concept.

Table 4. Comparison of commercially available systems

Integrated Multisensor System	Radar + EO/IR Sensors	Sensor Fusion / C2	AI / Automation	Primary Application
Rheinmetall Skynex	X-TAR3D radar + Multi-Sensor Unit / EO sensor	Skymaster C2; automatic track generation and networking of sensors/effectors	Automated detection, classification and effector assignment	Networked ground/ship-based air defence and C-UAS
Leonardo Falcon Shield	Configurable AESA radar + NERIO-ULR EO/IR	AI-enabled multisensor fusion; integrated C2; RF/ESM and EW integration	AI/deep-learning detection, classification and identification	Integrated air defence, C-UAS and multi-domain surveillance
Elbit Systems ReDrone	DAiR 3D tactical radar + COAPS-L EO/IR	Unified C2; integration of SIGINT and electronic attack	AI/ML video analytics and automated threat processing	C-UAS, airspace security and tactical surveillance
HENSOLDT Xpeller	SPEXER radar family + NightOwl M EO/IR	Multisensor fusion; modular open architecture; C2	AI-assisted image analysis and automated classification	C-UAS, critical infrastructure and area protection
Rafael Drone Dome	360° C-UAS radar + day/night EO/IR	Integrated C2; RF detection/DF; electronic and optional hard-kill effects	Automated detection, tracking and threat assessment	C-UAS, military and critical-infrastructure protection
IAI/ELTA Drone Guard Gen 5	ELTA 3D AESA radar + EO sensors	Unified C2; COMINT/COMJAM and electronic attack	AI-based detection, classification and threat analysis	C-UAS, homeland security and military applications

Source: Made by the authors, backed by [22–27]

Additional consideration is the increasing role of AI and automation in multisensor systems. Modern architectures increasingly support automated threat detection, acquisition, tracking, classification and assessment, reducing the processing burden associated with large amounts of heterogeneous sensor data. Such capabilities are particularly relevant in environments where multiple low-signature or fast-moving targets may need to be processed simultaneously. The use of learning-based approaches is also in line with the broader development of data fusion techniques discussed in the paper, in which machine learning methods are increasingly considered alongside analytical approaches for processing heterogeneous sensor information [1, 6]. The six systems presented in **Table 3** should therefore not be interpreted as a ranking of individual products. Instead, they represent a qualitative sample of contemporary multisensor architectures from different manufacturers and demonstrate the technological shift from isolated sensor operation to integrated systems in which sensors, data fusion, automation, and management and control are increasingly interconnected. Their comparison provides a practical technological perspective that complements the theoretical discussion of data fusion levels, multisensor architectures, and communication requirements presented in the previous sections [1, 6, 11].

5 CONCLUSION

To conclude, the aforementioned conducted research firstly analyses the sensor specifications of electro-optical and radar technologies currently in use regarding their configuration properties such as bandwidth and its relation to the performance and operational range of specific sensors as well as their data computational features and adaptability to efficient mounting on specific platforms. Furthermore, paper analyses various forms of data fusion and ranks them according to specific performances of each type or layer of data fusion. Moreover, various data fusion techniques produced by various companies and users are compared considering the specific used sensors, adaptability to command-and-control environment, integration of data, as well as practical usage for each one of them. The purpose of comparison is a synthesis of the common features, as well as common drawbacks of each of these platforms, rather than ranking them. What they all have in common is various adaptabilities to command-and-control environment, processing of large quantities of heterogeneous information with various degrees of usage of up-to-date technologies such as artificial intelligence in doing so. In addition, they all possess specific features designed to combat and contrast modern problematics of electronic warfare, including electromagnetic resilience, RF detection systems and abilities to act in offensive ways using electromagnetic systems for protection. Their common drawback, however, is the fact that enormous amounts of data have to be processed, transported through communication systems, which are requiring broader bandwidths. High frequency communication systems lack the possibility of being transmitted beyond line of sight. When considering an isolated data exchange system, such as the one used for military purposes, which also entails data encryption and protection, the communication with such systems becomes a hardship. Possible ways to combat this include the higher level of data processing on platforms themselves (edge computing), which implies larger platforms, or transmitting of raw data to a mothership which is then being processed. Other forms of communication architecture adaptable to a military environment include usage of USVs as primary data collecting platforms and UAVs a secondary relays increasing the range beyond line of sight, however this is to be evaluated and discussed in future research. On top of that, comprehensive future research will focus on quantitative field validation and simulations under simulated jamming conditions in the form of a case study for each described concept.

Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, analysis, interpretation, and conclusions were developed and verified by the author(s), who remain fully responsible for the content.

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II. Navigation, Safety and Human-Centred Transport Systems

Is Accuracy not Enough? Elevation Mask Angle Effects on GPS L1 Solution Availability in Maritime Positioning

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ABSTRACT

Global Navigation Satellite Systems (GNSS) are widely used as the primary Electronic Position Fixing System (EPFS) in maritime navigation. Besides positioning accuracy, their operational value depends on the continuous availability of valid positioning solutions. This paper assesses single-frequency GPS L1 positioning performance under elevation mask angle variation using four datasets from three coastal or near-coastal reference stations. The data were processed using a consistent RINEX-based RTKLIB single point positioning strategy, with elevation mask angles from 0° to 45° tested in 5° increments. Performance was evaluated through horizontal and three-dimensional positioning error, satellite geometry, number of valid satellites, and solution availability. Operational acceptability was assessed using IMO-based criteria combining horizontal accuracy and availability. The results show that positioning accuracy remains acceptable across a broad range of configurations, while solution availability and compliance show clear threshold-type behaviour. Stable compliance was observed between 5° and 20°, 25° represented a transitional regime, and mask angles of 30° and above resulted in systematic non-compliance. The findings show that accuracy-only assessment is insufficient for maritime GNSS usability. Elevation mask angle selection should be treated as a trade-off between excluding low-elevation observations and preserving sufficient satellite geometry for continuous positioning. In the context of sustainable maritime transport, the study supports safer and more reliable digital navigation through improved operational interpretation of GNSS performance.

Keywords: maritime navigation; satellite positioning; positioning performance assessment; solution availability; dilution of precision; elevation mask angle

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FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION AND BACKGROUND

In contemporary maritime bridge operations, the GNSS-derived position is not only a numerical output, but a continuous input to electronic navigation systems, route monitoring, situational awareness, and decision-making (Bowditch, 2019). For that reason, positioning performance cannot be judged only by accuracy. A solution must also be available continuously enough to support operational use. Maritime positioning requirements are defined within the International Maritime Organization (IMO) framework. Resolution A.915(22) specifies performance requirements for GNSS use, while A.1046(27) defines the Worldwide Radionavigation System and includes positioning accuracy and signal availability requirements for different navigation areas (IMO, 2001, 2011). These requirements are used here as operational reference thresholds. Since the analysis focuses on horizontal positioning error and solution availability, **Table 1** summarises only the IMO criteria directly used for the interpretation of results.

The elevation mask angle (MA) defines the minimum satellite elevation accepted in the positioning solution. Its effect is twofold. Low-elevation observations are more exposed to multipath, atmospheric effects, and signal instability, while higher mask angles reduce the number of usable satellites and may weaken satellite geometry. This is reflected in Dilution of Precision (DOP), which describes the effect of satellite geometry on the positioning solution (Kaplan & Hegarty, 2006). Earlier studies have shown that satellite geometry, satellite loss, and elevation-dependent observation quality affect GNSS positioning performance (Kos et al., 2012; Won et al., 2012; Anđić & Đurović, 2022).

Table 1. IMO positioning performance requirements used as operational reference criteria

IMO framework	Navigation context	Positioning accuracy requirement	Availability requirement	Use in this study
A.1046(27)	Ocean waters	HE ≤ 100 m, P = 95%	99.8%	General reference for ocean navigation performance
	Harbour/ approaches/ coastal	HE ≤ 10 m, P = 95%	99.8%	Primary operational benchmark for coastal/ restricted-waters

HE – horizontal error; P – probability

Source: Adapted from IMO A.1046(27).

In maritime applications, this trade-off has direct operational relevance. Previous work on GNSS performance in relation to maritime requirements has often focused mainly on positioning accuracy, while solution availability has received less explicit attention (Kos et al., 2019; Zalewski et al., 2022). This study assesses the effect of elevation mask angle variation on single-frequency GPS L1 positioning performance and evaluates operational acceptability using IMO-based accuracy and availability criteria. The remainder of the paper is organised as follows. Section 2 describes the data and processing method. Section 3 presents the positioning performance and compliance results. Section 4 discusses the operational implications and limitations. Section 5 concludes the paper.

2 DATA AND METHODS

The methodology was designed to isolate the effect of elevation mask angle on GPS L1 positioning performance and evaluate its consistency across multiple datasets.

2.1 GNSS data sources and dataset design

GNSS observations were obtained from continuously operating reference stations within the EUREF Permanent Network (EPN) and the Croatian Positioning System (CROPOS) (EUREF, 2026; SGA, 2026). Both networks provide GNSS data in the standard Receiver Independent Exchange Format, ensuring consistency and reliability of the analysed positioning solutions (IGS, 2015). Three coastal, mid-latitude reference stations were selected: Zadar (EUREF) and Mali Lošinj (CROPOS) in Croatia, and Ciboure (EUREF) in France (**Figure 1** and **Table 2**).

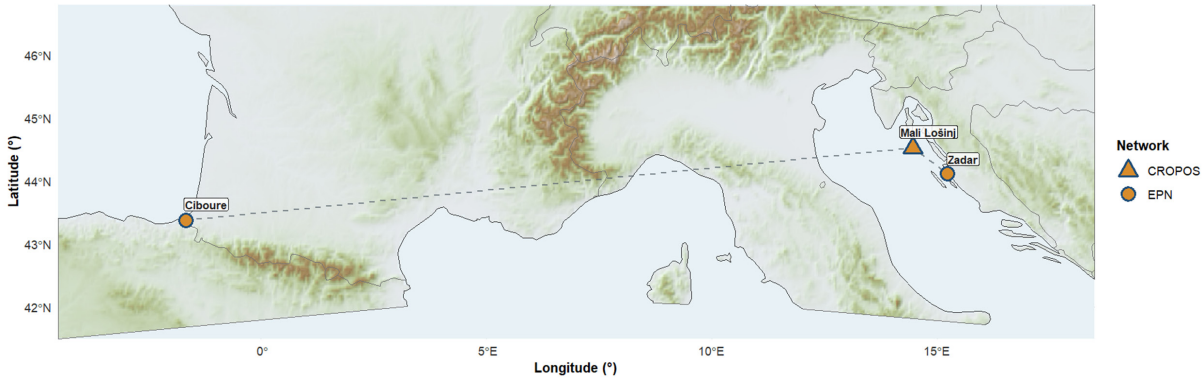


Figure 1. Geographic distribution of the selected reference stations.

Table 2. Features of selected reference stations

Station	Network	Country	Latitude (°)	Longitude (°)	Approx. height (m)
Zadar (ZADA)	EPN	Croatia	44.1190	15.2310	64.3
Mali Lošinj (MALI)	CROPOS	Croatia	44.5330	14.4670	62.5
Ciboure (SCOA)	EPN	France	43.3830	-1.6670	60.2

ZADA DOY 148/2021 was used for the initial exploratory processing and identification of the main response pattern. For graphical presentation in the results section, the MALI dataset was selected as a representative diagnostic example because it clearly illustrates the behaviour observed across the wider set of processed solutions. The relationship between elevation mask angle and positioning performance was analysed, allowing identification of key behavioural patterns, including the dependence of positioning performance on solution availability and satellite geometry. Datasets 2 to 4 (ZADA, MALI, SCOA) were subsequently used to assess temporal and spatial consistency, referring to DOY 148/2025. This enabled assessment of temporal and spatial consistency under comparable, nominal observation conditions, reducing risks of dataset-specific conclusions.

2.2 Processing strategy and elevation mask angle configuration

The processing workflow is shown in **Figure 2**. GNSS data were processed using the open-source RTKLIB package in Single Point Positioning (SPP) mode (Takasu, 2009). The analysis was based on single-frequency GPS L1 observations and broadcast ephemerides. Standard ionospheric and tropospheric correction models were applied. Positioning solutions were computed at a sampling interval of 60 s.

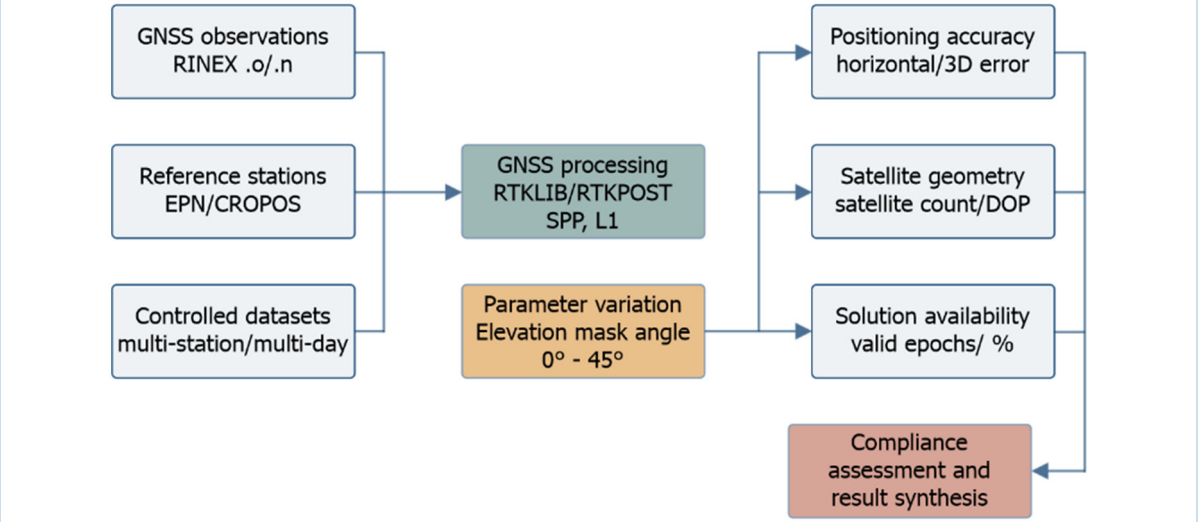


Figure 2. Methodological workflow from RINEX data acquisition to positioning performance assessment and compliance evaluation.

The elevation mask angle was varied systematically, with values of 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45°. No additional GDOP/innovation rejection filter was applied to the primary positioning outputs (Takasu, 2013). Such filtering would reduce extreme errors, but also solution availability. Standard observation files containing pseudorange measurements were used in combination with broadcast navigation files. The resulting positioning solutions were subsequently analysed in the R programming environment (R Core Team, 2023). The analysis included the computation of positioning errors, satellite geometry indicators, and solution availability metrics, together with aggregation of epoch-level results.

2.3 Performance metrics and IMO-based assessment

Positioning accuracy was assessed using horizontal and three-dimensional positioning error, computed with respect to known reference coordinates. Satellite geometry was characterised using the number of valid satellites used in solution estimation and DOP indicators, providing a measure of the geometric strength of the satellite configuration (Kaplan & Hegarty, 2006). Solution availability was expressed as the percentage of valid positioning epochs relative to the total number of expected epochs. Accuracy and solution availability are treated here as distinct, but not independent, performance dimensions. Accuracy characterises the quality of the position estimate conditional on a valid solution being available, whereas solution availability characterises the continuity with which such valid solutions can be obtained. The derived performance metrics were subsequently used for IMO-based compliance assessment and interpretation of positioning performance behaviour.

In this study, availability is interpreted as processing-derived solution availability rather than direct signal-in-space availability. As presented in **Table 1**, the assessment focuses on positioning accuracy and solution availability. Although IMO A.1046(27) distinguishes between ocean navigation and navigation in harbour entrances, harbour approaches, and coastal waters, the present compliance assessment adopts the latter as the primary operational benchmark. This category provides the stricter and more discriminative accuracy requirement, namely a horizontal positioning error not greater than 10 m with 95 % probability, combined with solution availability exceeding 99.8 %. The ocean-navigation threshold of 100 m was considered as a regulatory context. Horizontal positioning error was assessed as the primary compliance variable, while three-dimensional positioning error was

retained as a supplementary indicator. Solution availability was expressed as the percentage of valid positioning epochs relative to the total number of expected epochs within the observation period. For each dataset and elevation mask angle configuration, compliance was assigned as a binary outcome. The binary compliance approach was informed by an earlier graduate thesis comparison of GPS positioning results with IMO A.1046(27), and is extended here through multi-station, multi-day assessment and combined accuracy-availability classification (Čović, 2025). A configuration was classified as compliant only when both accuracy and availability criteria were satisfied.

2.4 Cross-dataset consistency assessment

For each dataset and elevation mask angle configuration, positioning-derived and DOP-derived indicators were calculated and standardised using z-score transformation to account for differences in units and numerical ranges. Standardised indicator profiles were then compared across datasets using Pearson correlation coefficients. The resulting correlation matrix was used as an exploratory profile-shape similarity measure, indicating whether the analysed datasets followed comparable response patterns. The analysis was not treated as an inferential statistical test or as evidence of equality in absolute positioning performance.

3 RESULTS

Results are first presented for a representative diagnostic dataset, followed by a cross-dataset assessment of consistency across the wider solution set.

3.1 Overview of processed datasets and similarity assessment

The analysed datasets were used to assess whether the performance pattern observed in the representative diagnostic dataset was consistent across different observation days and stations. ZADA DOY 148/2021 supported the initial exploratory processing, while ZADA, MALI, and SCOA DOY 148/2025 were used to examine temporal and spatial consistency. **Figure 3** presents the Pearson correlation matrix of standardised positioning and DOP-derived indicator profiles across datasets.



Figure 3. Correlation matrix of standardised positioning and DOP-derived indicator profiles across datasets.

The generally high positive correlations indicate that the analysed datasets follow comparable response patterns. This supports the use of the selected representative dataset for detailed visual interpretation, while retaining the wider dataset collection as the basis for compliance assessment.

3.2 Positioning accuracy behaviour

The representative dataset (MALI) illustrates the main behaviour observed across the analysed datasets. **Figure 4** shows that error values remain relatively stable across lower mask angles, with a gradual increase at higher configurations, indicating that positioning accuracy is only moderately affected by elevation-dependent observation selection.

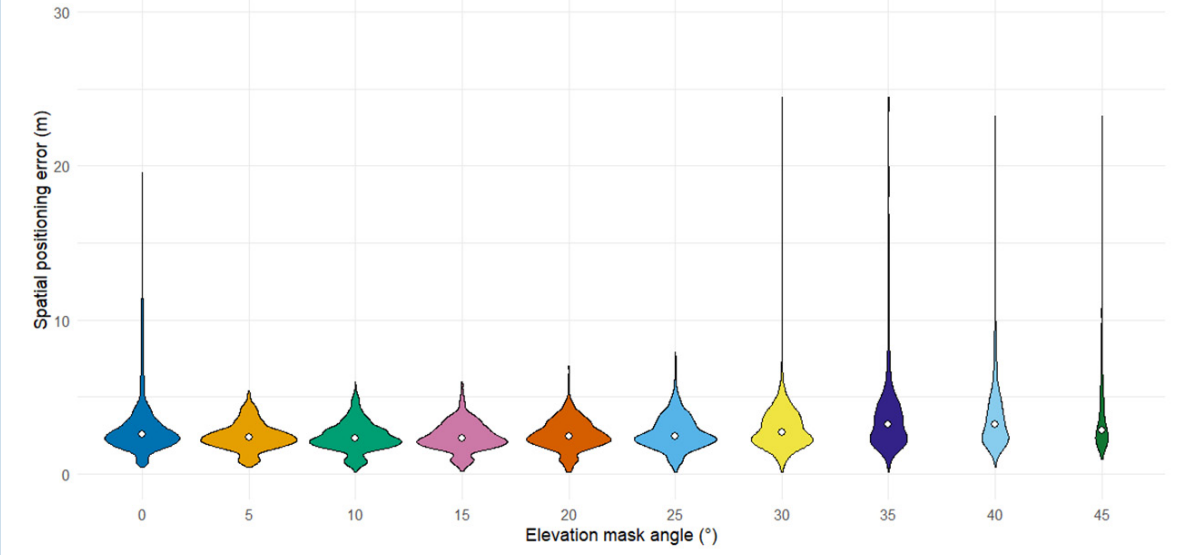


Figure 4. Distribution of three-dimensional positioning error as a function of elevation mask angle for the MALI dataset. The violin plot shows the spread and central tendency of positioning error across configurations.

The relationship between satellite geometry and positioning error is further illustrated in **Figure 5**, where 3D positioning error is shown as a function of GDOP.

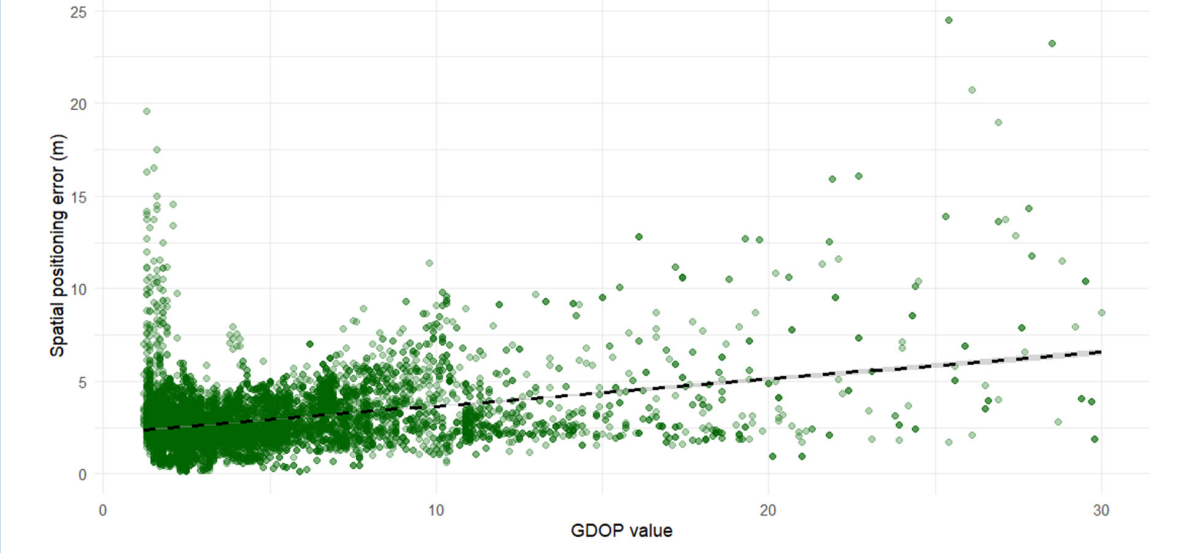


Figure 5. Three-dimensional positioning error as a function of GDOP. The results indicate a relationship between satellite geometry and positioning error, with increasing GDOP associated with higher error variability.

The results indicate a visible but limited increase in positioning error with deteriorating satellite geometry, while the majority of observations remain within a relatively narrow error band.

3.3 Solution availability behaviour

In contrast to positioning accuracy, solution availability exhibits significant and systematic elevation mask angle dependence. At lower mask angles, solutions are continuous, while increasing the mask angle leads to gaps and eventual fragmentation of the solution timeline (**Figure 6**).

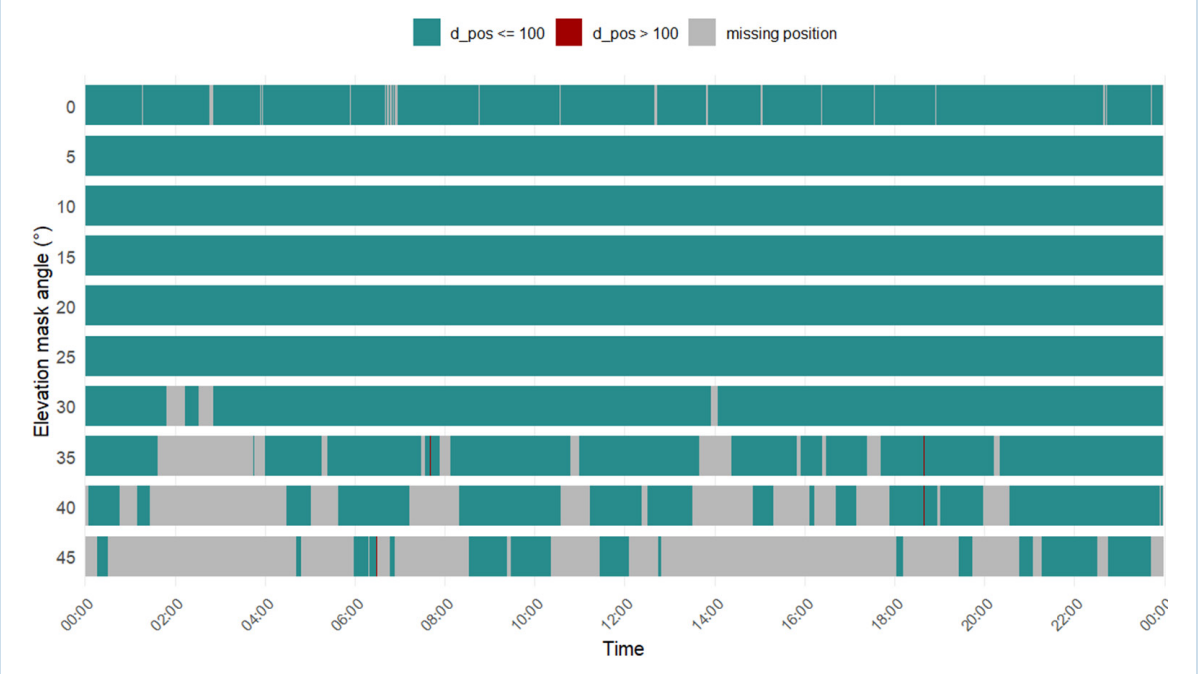


Figure 6. Temporal distribution of valid positioning solutions for different elevation mask angle configurations for the MALI dataset.

This behaviour is operationally important because intermittent valid solutions may remain accurate when available, but cannot support continuous navigation monitoring. The underlying mechanism is reflected in the satellite geometry indicators summarised in **Table 3**. Mean HDOP increases from 0.92 at 5° to 3.23 at 45°, while mean GDOP rises from 1.83 to 13.62. The degradation exhibits a non-linear pattern, with relatively stable geometry at lower mask angles followed by pronounced degradation beyond a critical range.

3.4 Compliance with IMO requirements

A consolidated compliance heatmap (**Figure 7**) illustrates the consistency of positioning performance and mask angle configurations, expressed as the proportion of compliant datasets for each configuration. The results reveal three distinct performance regimes. Full consistency is observed in the 5°–20° range, where all datasets satisfy the adopted positioning performance criteria. The 25° configuration represents a transitional regime, with partial compliance. Elevation mask angles of 30° and above are consistently associated with non-compliance.

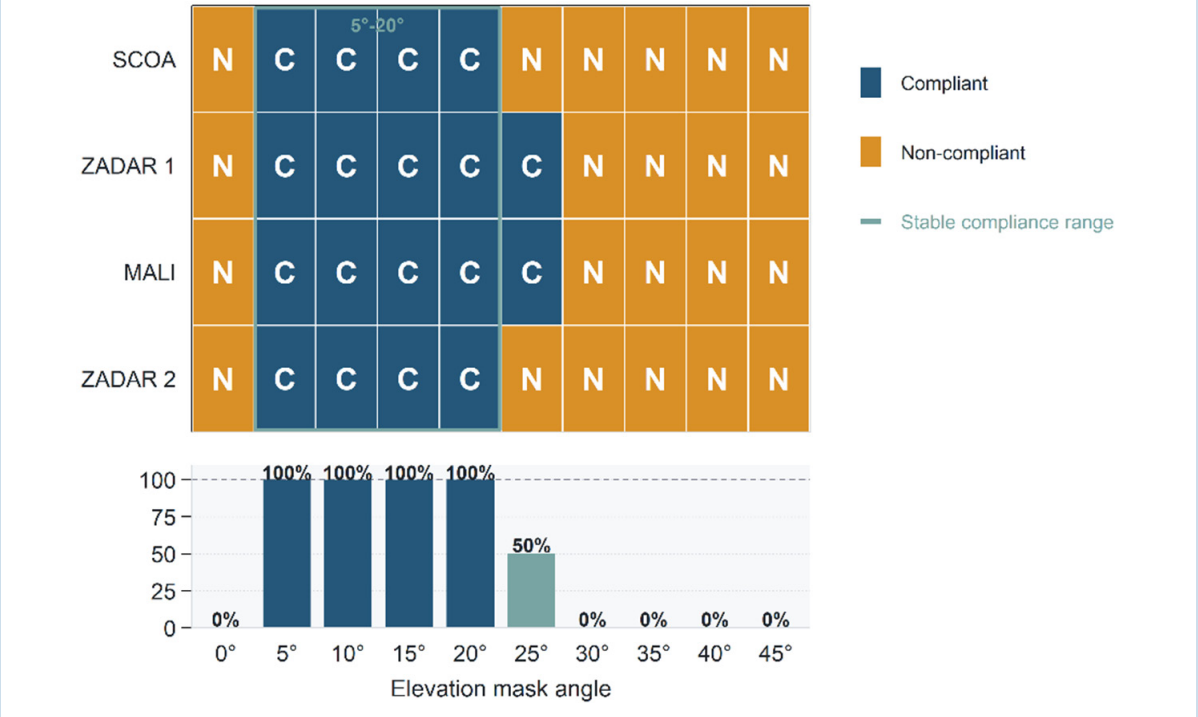


Figure 7. Binary compliance and inter-dataset consistency of GPS L1 positioning performance as a function of elevation mask angle. The upper panel shows compliance outcomes for individual datasets, while the lower panel summarises the proportion of compliant datasets for each configuration.

The same pattern was observed across both observation days and stations: temporal comparison at ZADA showed deviations limited to the transitional 25° configuration, while spatial comparison across ZADA, SCOA, and MALI confirmed that the compliance range is governed by elevation-dependent geometry and availability rather than by site-specific effects. **Table 3** summarises the aggregated GPS L1 positioning performance, and supports the identification of stable and non-compliant operating ranges.

Overall, positioning accuracy remains within acceptable limits across a wide range of configurations, while loss of compliance is primarily driven by reduced solution availability.

4 DISCUSSION

The results show a consistent elevation-mask-dependent GNSS performance pattern. Positioning accuracy remains relatively stable across a range of configurations, while solution availability degrades at higher mask angles. This reflects a trade-off between excluding low-elevation observations and preserving sufficient satellite geometry for continuous positioning. At higher mask angles, the loss of solution availability outweighs any potential benefit from improved signal conditions. The results are relevant for the configuration and assessment of GNSS positioning in maritime navigation. Under the analysed GPS L1 conditions, the 5°–20° range provided the best balance between measurement quality, satellite geometry, and solution availability. The key finding is that accuracy alone does not define usability. A configuration may produce accurate positions when a solution is available, but still be unsuitable if valid epochs become intermittent. Accordingly, accuracy and solution availability should not be interpreted as independent quantities, but as complementary performance dimensions: accuracy describes the quality of available position solutions, whereas availability describes whether such solutions are provided with sufficient continuity for operational use.

Table 3. Aggregated positioning performance indicators by elevation mask angle.

MA (°)	MHE (m)	SD HE (m)	Mean 3DE (m)	SD 3DE (m)	Mean Sat No.	Mean HDOP	Mean GDOP	A (%)	C (%)
0	1.93	1.07	3.89	2.56	10.2	0.87	1.69	91.98	0.00
5	1.62	0.57	2.70	1.04	9.6	0.92	1.83	100.00	100.00
10	1.58	0.56	2.49	0.99	8.6	1.03	2.17	100.00	100.00
15	1.56	0.57	2.53	1.04	7.5	1.20	2.72	100.00	100.00
20	1.61	0.62	2.68	1.15	6.7	1.44	3.44	99.98	100.00
25	1.73	1.01	3.01	1.62	5.9	1.90	4.67	99.41	50.00
30	1.92	1.24	3.65	2.38	5.3	2.39	6.49	93.73	0.00
35	2.21	1.82	4.61	3.60	4.8	2.84	8.74	78.97	0.00
40	2.43	1.86	5.62	4.20	4.5	3.08	11.02	56.71	0.00
45	2.53	1.80	6.61	4.63	4.3	3.23	13.62	28.86	0.00

Note: Availability and compliance values are aggregated across all datasets. Compliance denotes simultaneous fulfilment of the adopted horizontal accuracy and solution availability criteria. MHE = mean horizontal error; SD HE = standard deviation of horizontal error; 3DE = three-dimensional positioning error; A = solution availability; C = compliance

The proposed assessment links positioning error, satellite geometry, solution availability, and compliance with maritime performance criteria, and can support comparison of receiver settings, elevation-dependent filtering strategies, and degraded positioning scenarios. The study is limited to single-frequency GPS L1 positioning under nominal, open-sky conditions. The results should not be directly generalised to multi-frequency, multi-constellation, or receiver-integrated GNSS performance, nor to obstructed, interference-prone, or disturbed ionospheric environments. The identified mask-angle ranges should therefore be interpreted as case-specific empirical thresholds under the analysed conditions rather than as universal GNSS configuration recommendations. Solution availability was derived from RTKLIB positioning outputs and therefore represents processing-dependent availability of valid solutions. No additional GDOP or innovation rejection filter was applied, so short-duration extreme solutions caused by weak geometry were retained. Future work should extend the assessment to multi-constellation and multi-frequency processing, challenging operational environments, and controlled sensitivity analysis of processing filters.

5 CONCLUSIONS

This study investigated the influence of elevation mask angle on single-frequency GPS L1 positioning performance using multi-station, multi-day EUREF and CROPOS data. The results identify an operational elevation mask angle range within which both positioning accuracy and solution availability requirements are satisfied. Accuracy remained relatively stable across a wide range of configurations, while solution availability was the primary limiting factor. The same pattern was observed across different observation days and reference stations, indicating reproducible threshold behaviour under the analysed conditions. Against the adopted IMO-based criteria, the 5°–20° interval provided stable compliance, 25° represented a transitional configuration, and mask angles of 30° and above resulted in systematic non-compliance. The study shows that GNSS positioning performance in maritime applications should not be evaluated through accuracy alone. Availability of valid positioning solutions is essential for operational usability and safe maritime transport operations.

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Use of AI tools: AI-assisted tools were used for language, structural, and code refinement. All scientific analysis, interpretation, and conclusions were developed and verified by the authors, who remain fully responsible for the manuscript.

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II. Navigation, Safety and Human-Centred Transport Systems

Determining Actions for Collision Prevention between Ships in a Close-Quarters Situation Using Simulated Avoiding Strategies

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ABSTRACT

The International Regulations for Preventing Collisions at Sea (COLREGs) refer to the term close-quarters situation. As this term is not precisely defined, the authors analyse the interpretations and definitions of the term close-quarters situation by various authors or courts based on judicial processes and judgments. Most officers and Masters base their understanding of a close-quarters situation on their own experience. However, precisely because seafarers, maritime experts, and even court experts have different interpretations and definitions of a close-quarters situation, it leads to unintended consequences. This study accepts the proposed definition of a close-quarters situation as the minimum distance at which a collision can still be avoided by the action of only one vessel. Based on this definition, a series of navigational simulations was conducted using the navigational simulator Wärtsilä NTPRO 5000 to determine the minimum distances and times at which the stand-on vessel can still initiate effective avoiding action when the give-way vessel fails to comply with the COLREGs. A total of 168 simulations were performed using different scenario combinations of fine-form and full-form vessels, loading conditions, target vessel speeds, and course angles. The results of 168 simulations for the two ships shown in this paper demonstrate that the required distance and time at which a collision can still be avoided are mostly affected by vessel maneuvering characteristics, relative speed, and the angle of intersection, confirming previous findings on the importance of maneuvering performance in collision avoidance. The most critical situations were identified for course angles between 115° and 150°, where substantially greater distances and longer times were required to avoid collision. The findings provide practical guidance for navigators, Vessel Traffic Service (VTS) operators, and the development of autonomous collision avoidance systems by defining the operational limits within which effective avoiding action can still prevent a collision between vessels.

Keywords: close-quarters situation; COLREGs; action to avoid a collision; last opportunity to avoid collision; use of navigational simulator

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Collision avoidance at sea is a decision-making process in which the navigator takes timely and substantial action, in accordance with the COLREGs (1972), to ensure that vessels pass each other at a safe distance. Collision avoidance at sea requires the navigator to interpret the COLREGs in real time and use them as guidelines for that process. Over time, concerns have been raised regarding the ambiguous wording and interpretation of certain COLREGs terms and phrases. As a result, the rules are often interpreted inconsistently, with navigators relying on personal experience rather than uniform explanations and guidance, highlighting the need for clearer practical interpretation to improve safety of navigation. One of the terms that also requires clarification is the term *"close-quarters situation"* which is mentioned in Rules 8 and 19 of COLREGs.

The understanding of a close-quarters situation is largely based on the subjective judgment of navigators. Consequently, navigators worldwide apply different criteria and threshold values when determining the existence of such a situation, leading to inconsistent implementation of the COLREGs and potentially compromising safety of navigation. The lack of a universally accepted definition is also evident from different interpretations adopted by maritime experts, expert witnesses, and courts. In collision cases, their conclusions regarding the existence of a close-quarters situation have often been inconsistent and, at times, even contradictory, further emphasizing the ambiguity of the term. Therefore, one of the primary objectives of this research is to clarify the concept of a *close-quarters situation* by reviewing the existing interpretations and adopting a practical definition. The second objective is to determine the minimum distance at which the stand-on vessel can still avoid a collision by its own action when the give-way vessel fails to comply with the COLREGs using different ship models with different forms and manoeuvring characteristics in the navigational simulator.

The research is intentionally limited to defined ships and scenarios. The vessels and encounter geometries are realistic, but the simulations exclude wind, waves, current and shallow-water effects. These factors would alter drift, rate of turn and the required sea room. For that reason, the results should be treated as baseline values obtained under controlled deep-water conditions rather than universal limits.

2 MEANING OF A CLOSE-QUARTERS SITUATION

Collision avoidance at sea requires proper and timely action under the COLREGs so that ships at risk pass at a safe distance [19]. The limits for initiating a collision avoidance manoeuvre are different for different vessels and operating conditions. Action must therefore be taken early enough to preserve sufficient time and space for additional measures and are used as safety margins. Nevertheless, dense maritime traffic or non-compliance with the Rules may lead to unsafe passing distances, which are commonly termed as a close-quarters situation.

This term appears in Rule 8 (Action to avoid collision) and Rule 19 (Conduct of vessels in restricted visibility) but remains undefined despite attempts made at the 1972 conference. Cockcroft and Lameijer divide encounters between vessels in sight of one another into four stages: free manoeuvre, action required by the give-way vessel, action permitted by the stand-on vessel, and action required (**Figure 1**).

The authors define a close-quarters situation as the position when a collision can no longer be avoided solely by the action of the give-way vessel which is directed to keep out of the way of the other vessel, but also the stand-on vessel is required to take such action as will best aid to avoid collision [5]. The *Grepa–Verena* case further demonstrates the uncertainty of interpretation of the close-quarters situation term. Although no fixed distance applies, Cockcroft and Lameijer suggest the value of approximately 2–3 nautical miles in restricted visibility in the open sea and about 1 nautical mile when vessels are in sight of one another.

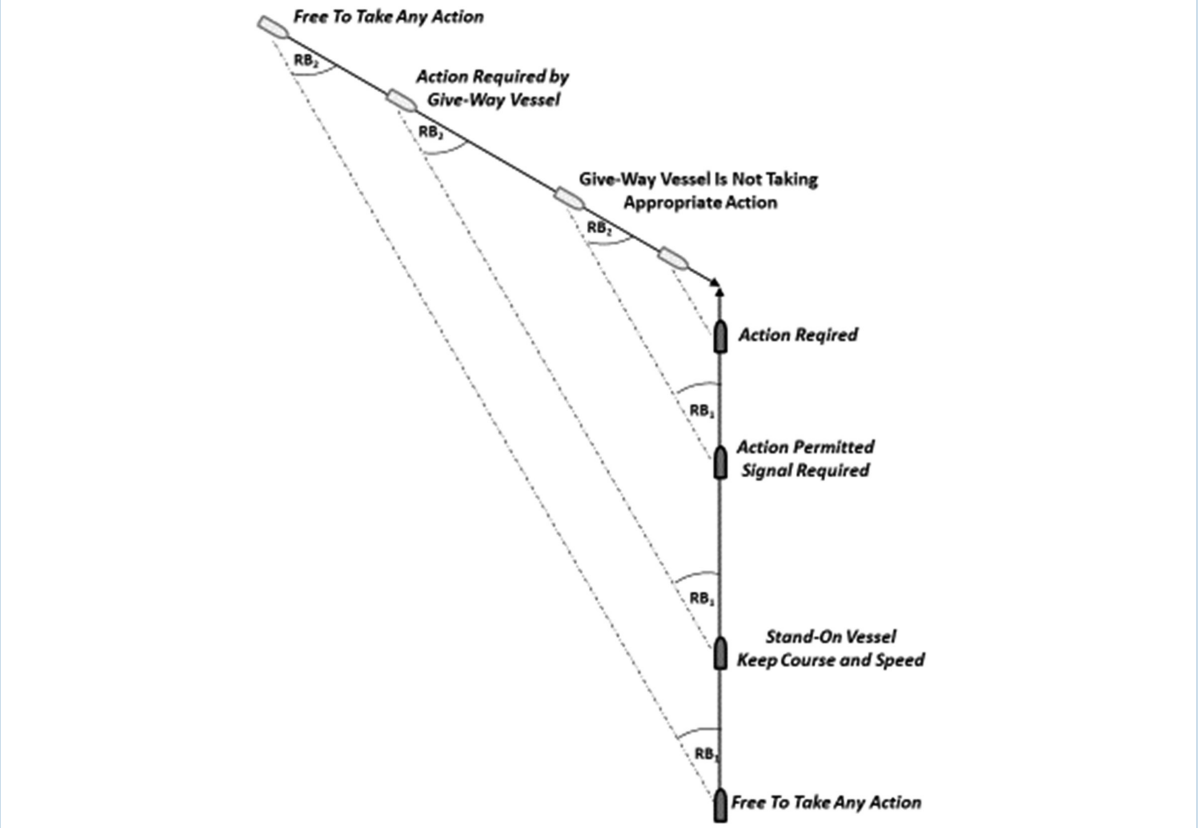


Figure 1. Four stages of collision risk [5]

He et al. similarly identify four stages of autonomous collision avoidance (ACA) and develop models for the first time-in-point of a close-quarters situation (FTCS) and first time-in-point of immediate danger (FTID) in open-sea and good weather conditions, placing both in the third stage [8]. Craig, reviewing U.S. and British court decisions, confirms that neither the Rules nor the courts establish a fixed distance [7]. One judicial definition includes situations in which vessels, while maintaining their courses and speeds, will not pass at a safe distance, although the term "safe distance" is also not defined in the Rules.

Cahill proposed the definition of a close-quarters situation when ships are in sight of one another: "We offer here a provisional definition of "close-quarters" as that area around a ship where a collision with an approaching vessel could not be avoided by the action of the approached vessel alone if the approaching vessel made a major, sudden and unexpected course change" [4]. Lloyd's *Da Ye* collision report notes that a close-quarters situation does not always involve risk of collision and that there is no clear boundary that separates the two concepts. In the *Maloja II* case, the English Admiralty Court emphasized that timely action is crucial to ensure that, whenever possible, vessels do not enter a close-quarters situation involving a risk of collision, where decisions must be made within a very short period of time and without sufficient time to determine the right decision. Mankabady similarly states that close-quarters situations arise when collision can no longer be avoided by a substantial manoeuvre of one vessel alone [13].

A British Merchant Navy Association article (1970) cited that, for large vessels, close-quarters distances may be measured in miles rather than yards. German Government letter 26/4/2 to the IMO (1981) stressed the importance of the navigator's awareness of the shape and size of the navigable waters. Sjekavica and Kacic describe close quarters as a condition in which vessels have very little time and manoeuvring space, while its assessment depends on relative speed, relative direction, distance, and surrounding circumstances [16].

Cornillou, examining navigational safety and VTS monitoring near Ushant for the French Government, linked close-quarters situations with near misses. Between 2008 and September 2013, 120 cases were analysed using closest point of approach (CPA) values of up to 0.5 nautical miles and time to closest point of approach (TCPA) values of up to 10 minutes [6]. Bakdi et al. used a risk identification methodology and four blocking areas to define a vessel safety domain, concluding that action by one vessel alone may be insufficient to eliminate collision risk [1].

2.1 Review on explanation of the term close-quarters situation

Based on the reviewed literature and the authors' understanding of the term close-quarters situation, it may be concluded that researchers mostly discuss the factors affecting it without proposing a clear definition. Since a close-quarters situation necessarily involves a particular distance between vessels, its definition should ultimately result in a numerical value expressed in metres, cables, or nautical miles. Although various influencing factors are identified in the literature, such value is not provided.

Other authors offer a more specific definition, describing a close-quarters situation as the distance at which collision can no longer be avoided by the action of one vessel alone, but both vessels must manoeuvre. While this interpretation may be acceptable from a legal perspective, it cannot be accepted for a navigator. It raises the question of why vessels were allowed to reach such a critical position. In most cases, this occurs because the give-way vessel failed to take proper and timely action.

Under Rule 17, the stand-on vessel is initially required to maintain her course and speed [9]. However, she may take action as soon as it becomes apparent that the give-way vessel is not taking appropriate action in compliance with Rules to avoid collision. Therefore, the stand-on vessel can intervene before a close-quarters situation fully develops and may prevent the encounter from becoming dangerous. A navigator is also expected to keep watch and act in accordance with the ordinary practice of seamen. Allowing a vessel to enter a situation in which collision can be avoided only with the combined action of both ships may therefore indicate that appropriate action was not taken early enough.

Rule 17(b) requires the stand-on vessel to act when the vessels are so close that collision cannot be avoided by the action of the give-way vessel alone [9]. Nevertheless, if it is already clear that the give-way vessel is not responding appropriately, waiting until this stage before taking action cannot be considered consistent with good seamanship and an ordinary practice of seamen. Had the give-way vessel acted in accordance with good seamanship, she would have manoeuvred in sufficient time and passed the other vessel at a safe distance [15].

For this reason, a more practical useful definition would describe a close-quarters situation as the minimum distance between vessels at which collision can still be avoided through appropriate action by only one vessel. Such action may not result in passing at a fully safe distance, but it would still prevent an actual collision. In maritime practice, an event of this kind is often described as a near miss.

Accepting this definition could make it easier to identify both the relative position of the vessels and the numerical distance at which a close-quarters situation begins. The most important factors would include the vessel's turning-circle characteristics, relative speeds, relative directions, and external forces such as wind, current, waves, and water depth, all of which may affect manoeuvrability [14].

3 SIMULATION PREPARATION AND METHOD

The simulations were designed to find the last point at which a ship could take collision avoiding action alone and pass the target ship at the closest point of approach of 100 m. This distance was selected as the worst-case passing margin under idealized conditions. It is not presented as a desirable operational clearance; rather, it represents a near-zero separation that still avoids hull contact, including hydrodynamic interaction effects. Similar last-line or critical-area concepts have been

discussed by Krata and Montewka. They defined the critical distance as the shortest distance at which the stand-on vessel can still successfully avoid a collision when the give-way vessel does not take any action. They compared this critical area with different ship-domain models [11,12]. Building on this concept, Szlapczynski et al. examined when the stand-on vessel should initiate an evasive manoeuvre, depending on the required separation represented by a decentralized elliptical domain [17]. Baldauf et al. argued that conventional CPA and TCPA alarms are insufficient because they do not provide an additional warning when the initial alarm is ignored. Therefore, they proposed the Last Line of Defence (LLoD), comparable to the Ultimate Action Alarm (UAA) used in airborne collision avoidance systems. The LLoD identifies the moment when the remaining collision-avoidance options approach a critical minimum, corresponding to the minimum distance at which one vessel can still independently prevent a collision [2, 3].

All trials were carried out on the TRANSAS NTPRO 5000 navigational simulator at the Faculty of Maritime Studies in Rijeka. The simulation area was set in deep water of 500 m to eliminate shallow-water effect. The simulation does not include wind, waves or current effect, while hydrodynamic interaction between the vessels was retained. At the start of each scenario, CPA was set to 0 m, meaning that collision would occur if no manoeuvre was made. The data outputs were the actual distance between the ships and the TCPA at the moment when the own ship began avoiding action.

Simplified flowchart of the simulation process is shown in **Figure 2**.

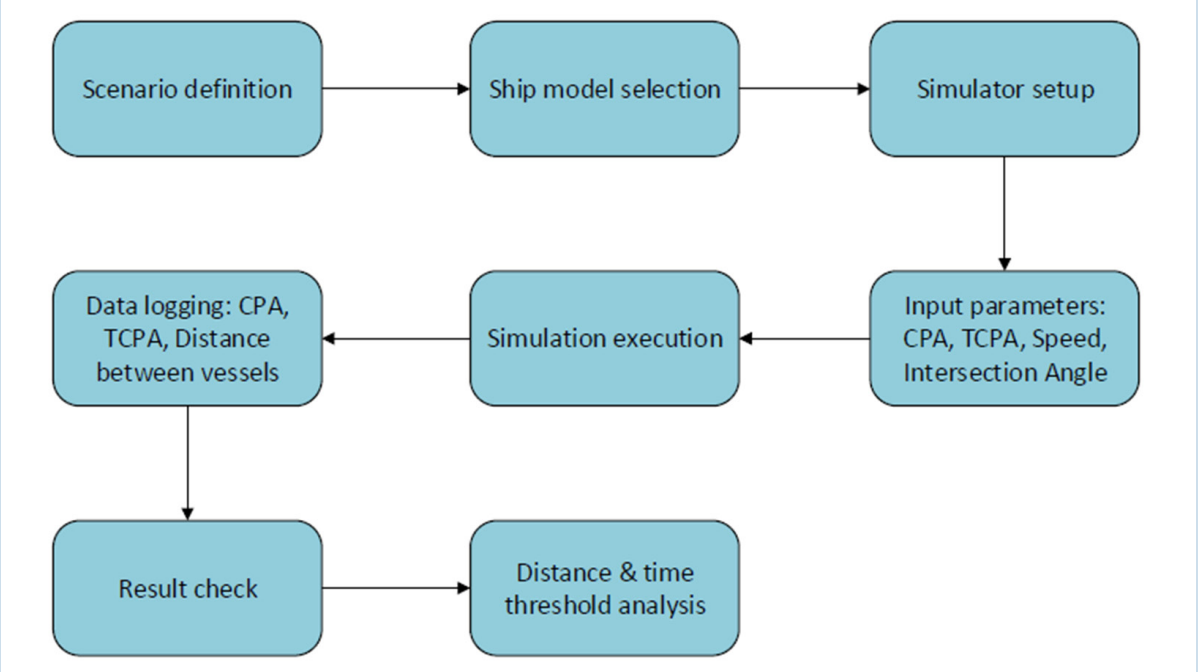


Figure 2. Simplified flowchart of the simulation process

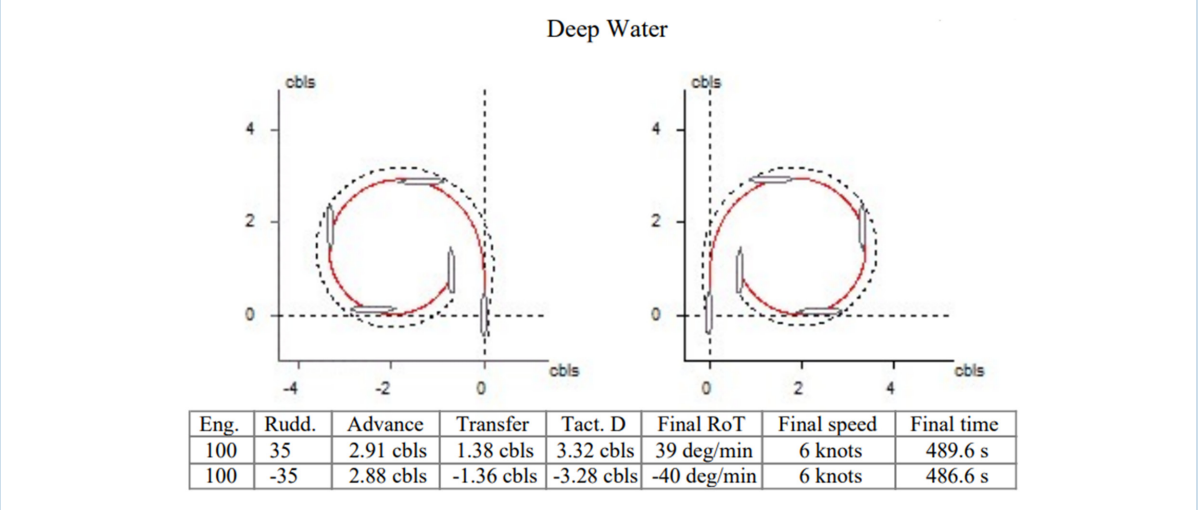
3.1 Ship Models

To keep the wide variety of ship types and manoeuvring characteristics, ships were grouped according to hull form. Vessels with a block coefficient (Cb) below 0.7 were treated as fine-form ships, and those above 0.7 as full-form ships. The condensed results in this paper focus on two own ships of comparable length: a fully loaded chemical tanker representing a full-form ship and a 2100 twenty-foot equivalent unit (TEU) container vessel representing a fine-form ship (**Table 1** and **Figures 3** and **4**).

Table 1. Type and size of own ships used in the selected simulations

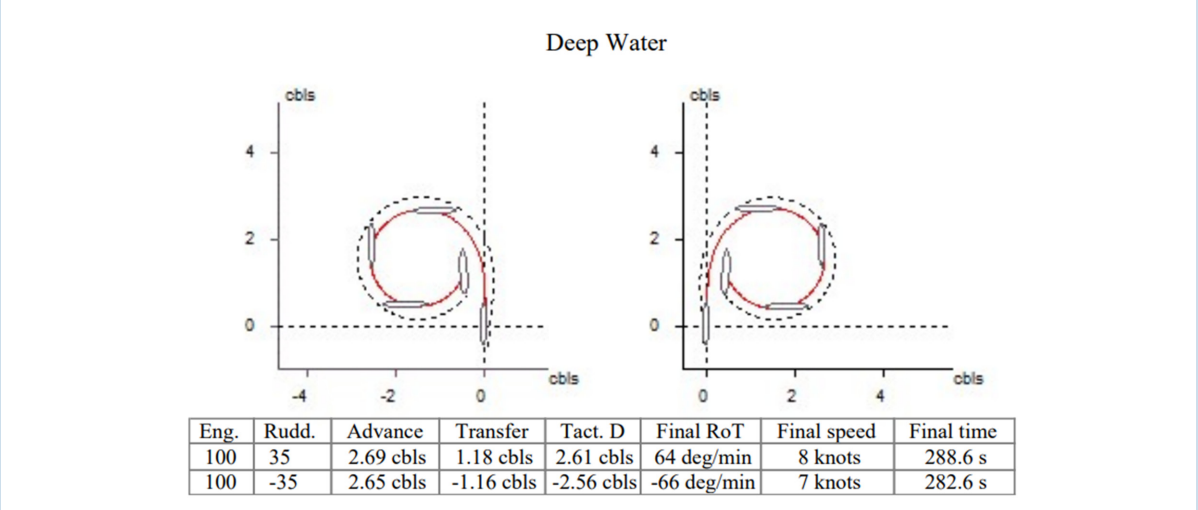
Ship type	Length overall (LOA) (m)	Breadth (B) (m)	Loading condition	Displacement (t)	Draft (T) (m)
Chemical tanker (Handysize)	182.55	27.34	Loaded	44,288	10.85
			Ballast	25,700	6.75
Container vessel (2100 TEU)	190.00	30.00	Loaded	32,910	8.50
			Ballast	23,911	6.50

Target ships were selected to represent different speeds and operational profiles: a Panamax bulk carrier at 14.8 kn and a container vessel at 25.4 kn. The first speed reflects common merchant vessel service speeds, while the second represents faster modern ship types. Own ship refers to the vessel that performs the avoiding manoeuvre, whereas target ship refers to the vessel being avoided which does not abide by the Rules.



Eng.	Rudd.	Advance	Transfer	Tact. D	Final RoT	Final speed	Final time
100	35	2.91 cbls	1.38 cbls	3.32 cbls	39 deg/min	6 knots	489.6 s
100	-35	2.88 cbls	-1.36 cbls	-3.28 cbls	-40 deg/min	6 knots	486.6 s

Figure 3. Turning circle of the full-form chemical tanker (own ship) using hard-to-port/starboard rudder [18]



Eng.	Rudd.	Advance	Transfer	Tact. D	Final RoT	Final speed	Final time
100	35	2.69 cbls	1.18 cbls	2.61 cbls	64 deg/min	8 knots	288.6 s
100	-35	2.65 cbls	-1.16 cbls	-2.56 cbls	-66 deg/min	7 knots	282.6 s

Figure 4. Turning circle of the fine-form container vessel (own ship) using hard-to-port/starboard rudder [18]

3.2 Scenario development

Own ship acted as the stand-on vessel in crossing situations, while the target ship represented the give-way vessel and did not manoeuvre. Avoidance was executed by hard-to-starboard rudder to pass at a distance of 100 meters from target vessel. This choice was made because course alteration is usually more effective than speed change for large displacement vessels, especially when immediate response is required. Maximum rudder deflection is not a routine action, but it is justified here because the study examines the last possible avoiding opportunity.

Head-on encounters were modelled with a course difference of 180°. Crossing encounters used intersection angles of 67.5°, 90°, 115°, 135°, 150° and 165°. The same initial principle applied in all scenarios: the vessels were placed on collision courses, own ship initiated a starboard alteration at different starting distances, and the minimum successful trial was the one in which the ships passed at a CPA of 100 m. **Figure 5** shows an excerpt from the navigational simulator at the moment when the own ship was passing at the closest point of approach of 100 m to the target ship and **Figure 6** shows schematic representation of the head-on simulation and crossing simulations.

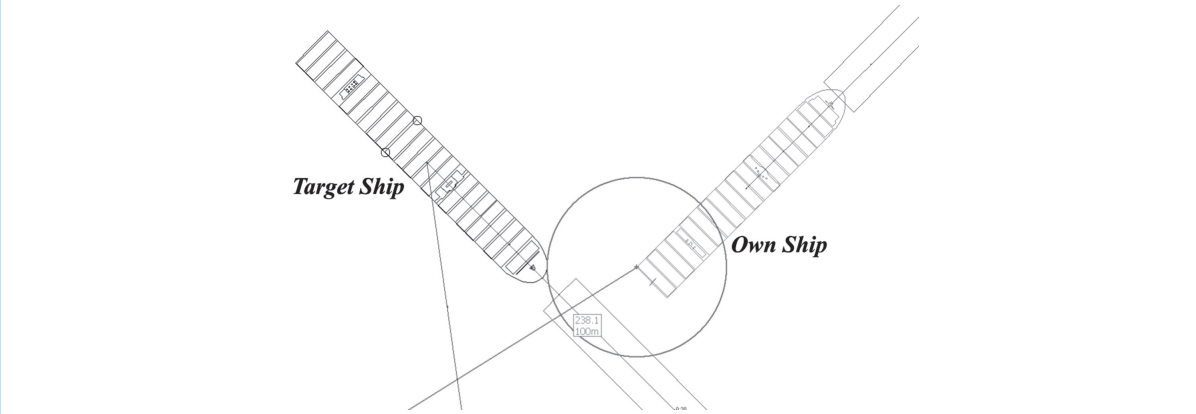


Figure 5. Ships passing at the closest point of approach of 100 m*

*The ship silhouettes are examples; they do not represent specific ships described in the scenario

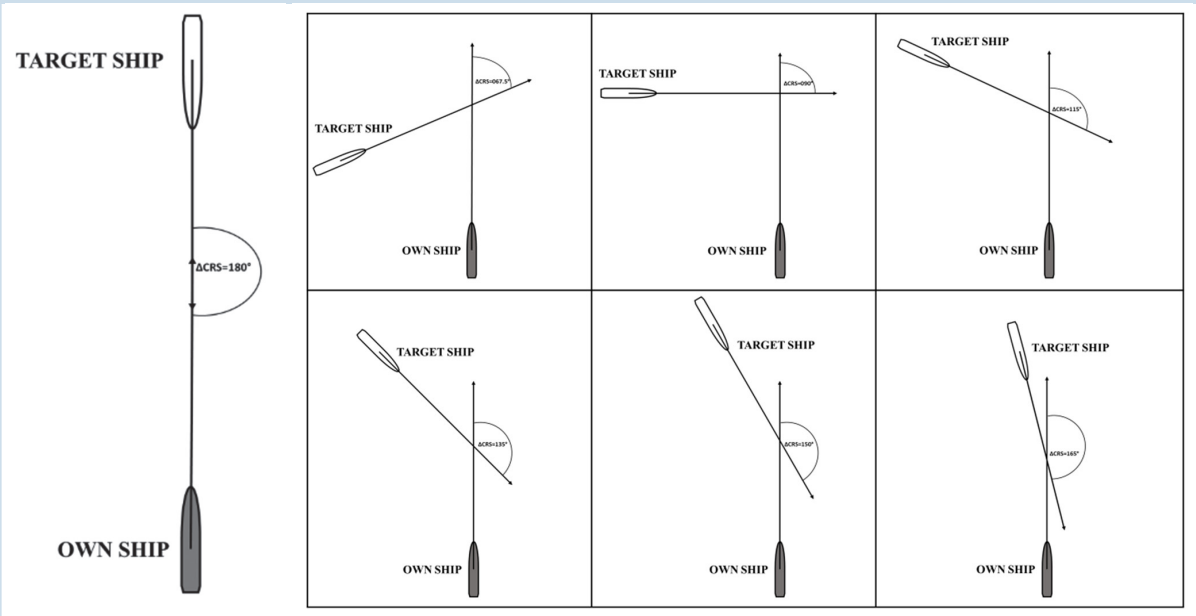


Figure 6. Schematic representation of the head-on simulation and crossing simulations

In total, 168 simulations were carried out by combining ship form, loading condition, target-ship speed, encounter geometry and vessel size. Because the complete set is extensive, the present version reports the fully loaded chemical tanker and the container vessel as the most direct comparison between full-form and fine-form behaviour.

4 RESEARCH RESULTS

Figures 7 and **8** show the minimum distances at which own ship had to begin altering course in order to avoid collision and maintain the 100 m passing criterion. For the loaded chemical tanker, the required starting distance in a crossing encounter at 67.5° was about 0.4 NM (Nautical Mile) against the slower target ship and about 0.6 NM against the faster target ship. When the intersection angle increased to roughly 115°-150°, the requirement rose to about 1.0 NM for the slower target and approximately 1.8 NM for the faster one. In head-on encounters the corresponding distances were approximately 0.7 NM and 1.1 NM.

The loaded container vessel required shorter distances because of its finer hull form and better turning response. At 67.5°, the minimum distance was about 0.4 NM for the slower target and 0.5 NM for the faster target. In the most demanding crossing range of 115°-150°, the distance increased to about 0.8 NM for the slower target and about 1.2 NM for the faster target. In head-on encounters, the container vessel began manoeuvring at approximately 0.6 NM against the slower target and 0.9 NM against the faster one.

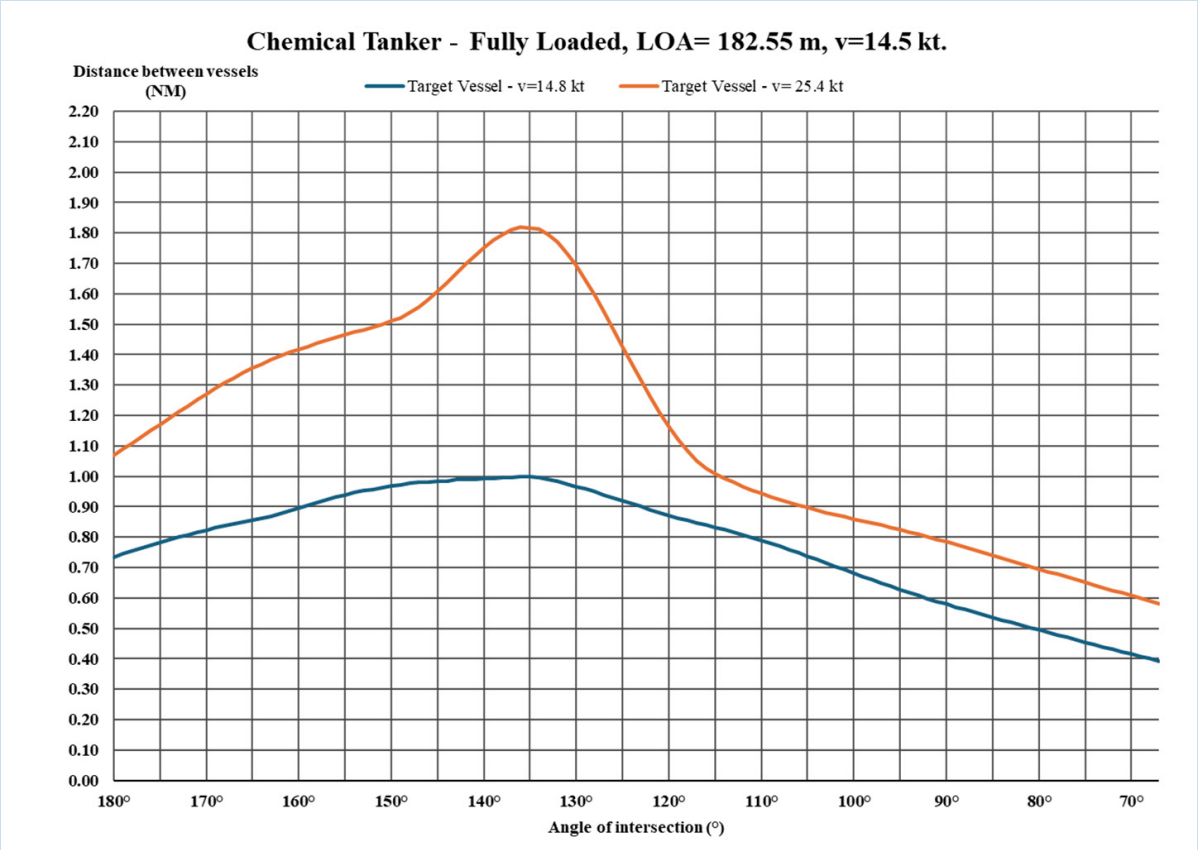


Figure 7. Chemical tanker avoiding-action distance as a function of intersection angle

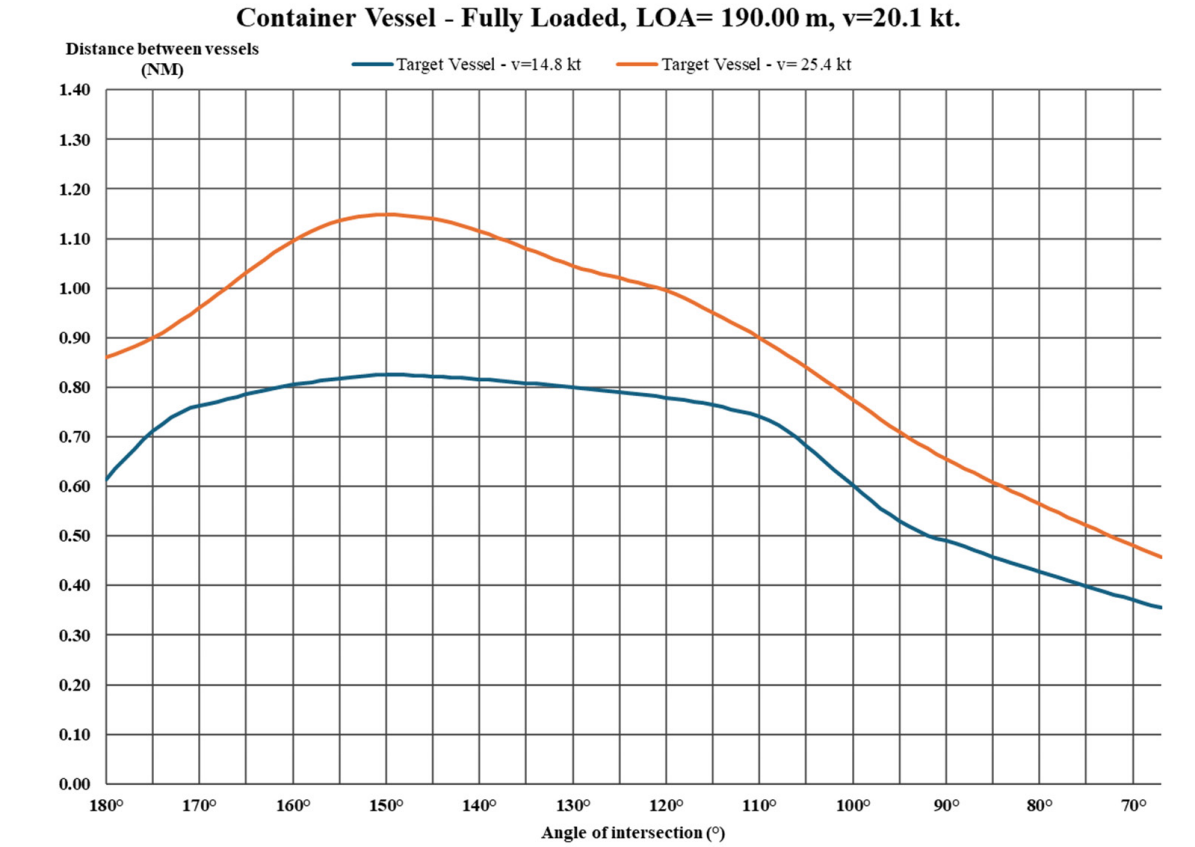


Figure 8. Container-vessel avoiding-action distance as a function of intersection angle

Figures 9 and **10** present the corresponding times. For the chemical tanker, the TCPA at the start of avoiding action was about 1.3 min against the slower target and 1.5 min against the faster target at 67.5°. The longest values occurred at approximately 120°-140°, reaching about 2.2 min against the slower target and 2.9 min against the faster target. In head-on encounters, the value was close to 1.5 min for slower target vessel and 1.6 min for faster target vessel.

For the container vessel, the time margins were smaller. At 67.5°, avoiding action began at about 1.0 min for both target speeds. The highest values, again near 120°-140°, were about 1.4 min for the slower target and 1.7 min for the faster target. In head-on encounters the TCPA was approximately 1.1 min. These results confirm that a full-form vessel may require substantially more time to produce the same minimum clearance, especially when the target ship is fast.

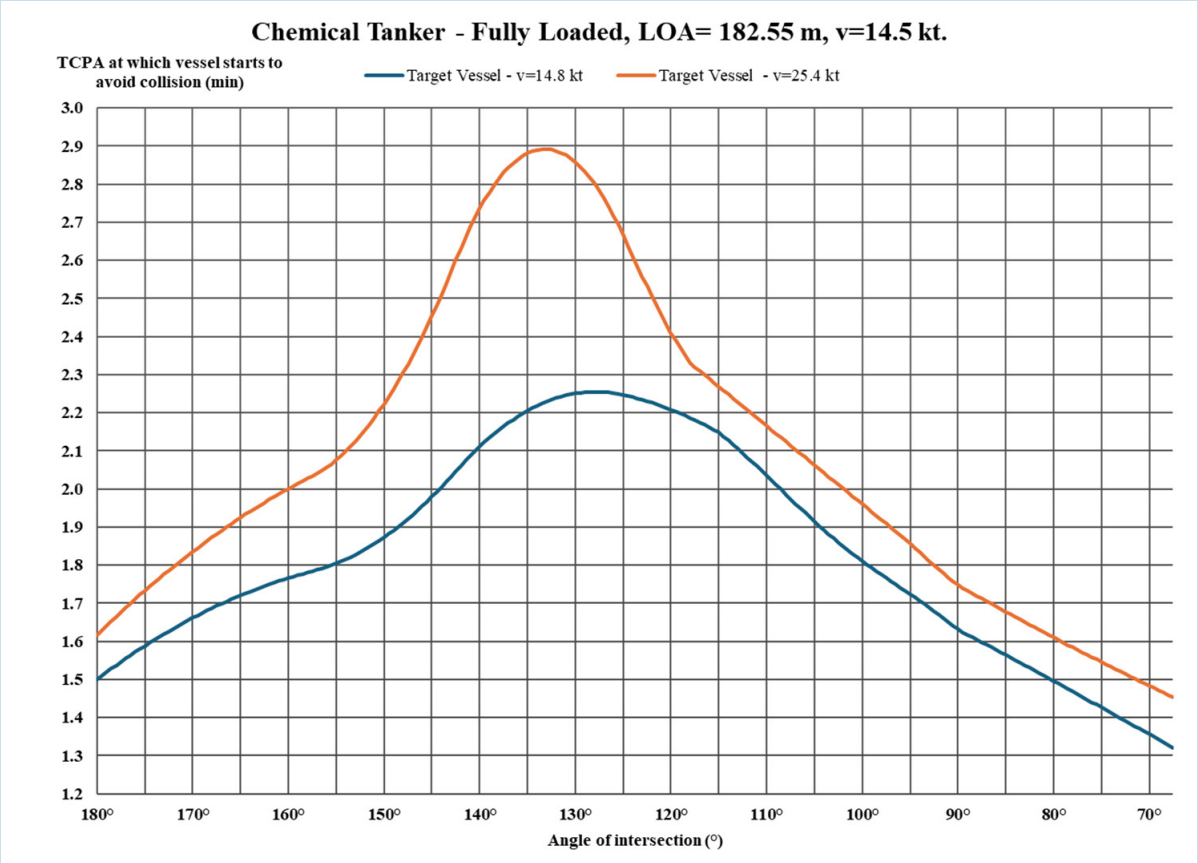


Figure 9. Chemical tanker TCPA at the start of avoiding action

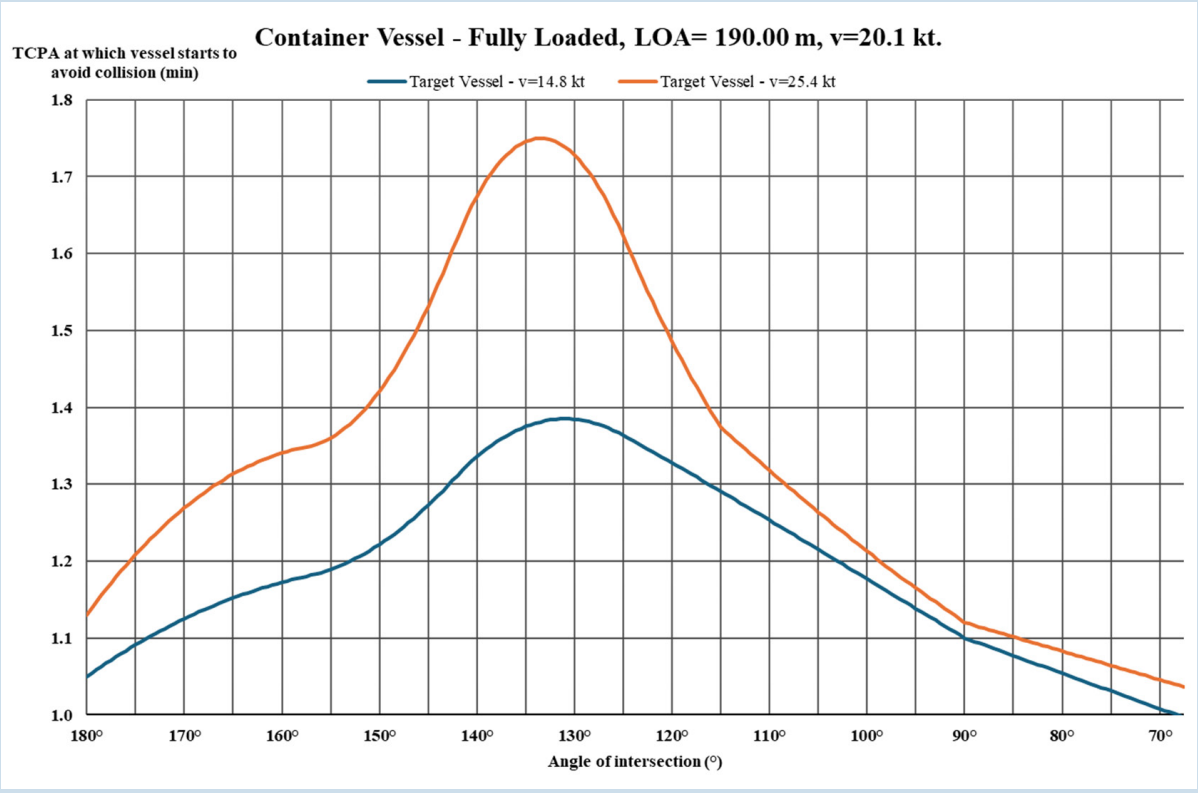


Figure 10. Container-vessel TCPA at the start of avoiding action

5 DISCUSSION

The simulations show that the last effective avoiding point cannot be expressed by a single distance that applies to all vessels. It changes with the own ship turning circle, hull form, speed loss during the turn, relative approach speed and intersection angle. Ships of similar length may therefore require different decision thresholds. In this study, the loaded chemical tanker needed around 60% more time than the loaded container vessel in the most critical crossing conditions because its rate of turn was lower and its drift and speed loss during the turn were greater.

The most unfavourable encounters were not the smallest-angle crossings but the range between about 115° and 150°. In this geometry, the stand-on vessel must move farthest from its original track if it wants to avoid passing ahead of the target vessel by a very small margin. For the chemical tanker meeting the fast target, the limiting distance reached approximately 1.8 NM. For the container vessel, the comparable value was about 1.2 NM. Whether action by the stand-on vessel at such distances is compliant with the COLREGs depends on the circumstances, including ship size and manoeuvring capability. For a large ship, an earlier alteration may be necessary to remain within the ordinary practice of seamen; for a smaller and more manoeuvrable vessel, the same early action might be judged differently.

The research also supports a cautious interpretation of Rule 17(c). In the crossing scenarios, own ship altered course to starboard, even where a port alteration could have reduced the required distance. Although Rule 17(c) does not create an absolute prohibition, a port alteration for a vessel on the own ship port side should remain a last-resort option. The simulations therefore deliberately followed the action that is more consistent with standard collision-avoidance practice.

A practical implication is that Automatic Radar Plotting Aid (ARPA) and future decision-support systems should not rely only on CPA and TCPA alarms [10]. Displaying the intersection angle and vessel-specific critical thresholds would help the officer assess when the stand-on vessel may still wait and when independent action becomes necessary. The same principle is relevant for VTS monitoring, remote operators and autonomous collision-avoidance systems. Future work should add radar-measurement uncertainty, antenna-reference effects, ship dimensions, shallow-water effect, current, wind and waves, because each of these factors can change the limiting distance and time.

6 CONCLUSIONS

This study reviewed the ambiguous use of close-quarters situation in maritime rules, case-based interpretation and professional literature, and proposed an operational definition suited to bridge practice: the minimum distance between ships at which collision can still be avoided by the action of one vessel alone. The definition does not describe an ideal passing distance; it identifies the last controllable boundary before physical contact becomes unavoidable if the other vessel does not contribute.

Simulator trials were then used to quantify that boundary for selected ship types and encounter geometries. Under the controlled conditions applied here, the limiting distance and TCPA depended primarily on hull form, turning capability, encounter angle and target-ship speed. The largest values occurred in crossing situations with intersection angles of approximately 115°-150°. In these cases, the loaded chemical tanker required notably greater distance and time than the loaded container vessel, which demonstrates why close-quarters thresholds must be linked to manoeuvring characteristics of a particular ship.

The results provide baseline values for bridge officers, VTS personnel and developers of automated collision-avoidance systems. They also show why a close-quarters situation should not be treated as a

fixed distance independent of the vessel and encounter. Further simulations that include environmental forces, shallow water, measurement inaccuracies and additional ship classes are required before the approach can be transformed into a broader operational standard.

Data Availability Statement: The raw data supporting the conclusions of the study are available from the authors on request.

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II. Navigation, Safety and Human-Centred Transport Systems

Human Readiness for the Digital Transformation of Maritime Navigation

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ABSTRACT

As maritime navigation becomes increasingly digitalised and automated, seafarers require new competencies to effectively operate, supervise and interact with advanced systems. Although the IHO S-100 framework, IMO e-Navigation and Sea Traffic Management have received considerable attention, fewer studies have examined how these developments are perceived by seafarers in everyday navigation. The experience gained from mandatory ECDIS implementation indicates that technological advances alone do not guarantee their effective use in practice, highlighting the importance of understanding seafarers' perceptions and educational needs before introducing new digital navigation concepts. Therefore, this study explores the human dimension of maritime digitalisation by investigating awareness, perceptions and educational needs related to emerging digital navigation technologies. Particular attention is given to knowledge of the S-100 framework, perceptions of the strategic priorities of the e-Navigation concept, cyber security awareness and attitudes towards future professional development. The study highlights existing knowledge gaps and identifies areas considered essential for the successful future navigation systems implementation. The findings suggest that maritime stakeholders broadly recognise the importance of digital transformation but simultaneously indicate a need for more systematic education and competency development. The successful implementation of digital navigation technologies will depend not only on technological advances but also on appropriate education, competency development and organisational support.

Keywords: maritime digitalisation; digital navigation and e-concepts; human factor; S-100; e-Navigation; sustainable navigation

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1 INTRODUCTION AND BACKGROUND

The maritime industry is undergoing a substantial digital transformation driven by rapid advances in information technologies, automation, communication systems and data integration [1]. Over the past two decades, maritime navigation has evolved from a process based primarily on the interpretation of information obtained from individual bridge systems to an increasingly interconnected digital environment in which data from multiple onboard and shore-based sources are integrated to support real-time situational awareness and navigational decision-making [1, 2]. Modern navigational bridges no longer operate as collections of independent systems. Nowadays they function as integrated information platforms that combine electronic navigational charts, radar, Automatic Identification System (AIS), Global Navigation Satellite Systems (GNSS), meteorological information, voyage planning tools and various decision-support applications into a unified operational environment [1, 3, 4]. Such developments are expected to improve navigational safety and operational efficiency by enhancing information availability and supporting real-time decision-making [4], while at the same time transforming bridge operations into a more complex environment that requires seafarers to develop additional competencies and interact effectively with increasingly sophisticated navigation systems [5, 6].

High-resolution hydrographic data, real-time environmental information, predictive analytics and automated decision-support tools are increasingly available [6]. These tools are gradually turning the navigator from an information processor into a supervisor of increasingly intelligent navigation systems. As a result, the navigator's role is shifting: instead of manually collecting and interpreting information, seafarers now evaluate, validate and manage recommendations generated by digital systems. This creates real opportunities to improve navigational performance, but it also introduces new challenges, including information overload, human-machine interaction issues, automation bias and cyber security risks.

One of the most significant developments in this transformation is the International Hydrographic Organization's (IHO) S-100 Universal Hydrographic Data Model. The current S-57 standard mainly supports Electronic Navigational Charts (ENCs). S-100, by contrast, offers a flexible architecture that can integrate several hydrographic and maritime information products within one digital environment, including S-101 Electronic Navigational Charts, S-102 bathymetric surface data, S-104 water level information and S-111 surface current information [7].

Parallel to S-100, the International Maritime Organization (IMO) has been promoting the e-Navigation concept as a strategy to harmonise the collection, integration, exchange and presentation of maritime information [8, 9]. The goal of e-Navigation is not to add more navigational equipment, but to optimise the interaction among existing technologies, navigators, and shore-based services, reducing human error and improving situational awareness [8]. The Sea Traffic Management (STM) concept aims to achieve a similar goal: a collaborative digital environment that enables continuous information exchange between ships, ports, and shore-based services [10].

This rapid expansion of interconnected navigation systems has made cyber security a critical operational concern. Modern ships increasingly rely on networked bridge systems, satellite communication and integrated information architectures, and each of these creates potential points of vulnerability [11]. Previous research shows that most maritime cyber incidents originate from human behaviour rather than purely technical shortcomings. This highlights the importance of situational awareness and trust in automated systems as essential prerequisites for safe operation [12].

The maritime industry has faced similar challenges before, during the introduction of Electronic Chart Display and Information Systems (ECDIS). ECDIS was one of the most significant technological advances in modern navigation. However, recent research shows that many navigational incidents were not caused by equipment failure, but by inadequate user competence, insufficient familiarisation, poor

understanding of system limitations and inappropriate reliance on automation [13, 14, 15]. This shows that successfully implementing new navigational technologies requires considerably more than regulatory approval and equipment installation. Continuous education, practical training and organisational support remain essential if the expected safety improvements are to be achieved.

A growing body of literature addresses individual aspects of maritime digitalisation, but fewer studies examine how seafarers actually perceive these developments in everyday practice [5]. Little is known about whether maritime stakeholders have sufficient knowledge of the S-100 framework, recognise the strategic priorities of e-Navigation, perceive cyber security as a significant operational challenge, or think additional education is necessary before these technologies are more widely implemented.

This knowledge gap is significant for two reasons. First, successful implementation of future navigational technologies ultimately depends on users who have the knowledge and confidence to operate increasingly complex digital systems. Second, identifying where awareness or preparedness is limited can help maritime administrations, training institutions and shipping companies design targeted educational programmes.

Accordingly, this study is based on a human-centred perspective on maritime digitalisation. It examines seafarers' and other maritime stakeholders' knowledge of the IHO S-100 framework, their perceptions of the strategic priorities of the IMO e-Navigation concept, their awareness of cyber security threats and their attitudes towards continuous professional development. The aim is to identify existing knowledge gaps and highlight areas essential for successfully implementing the next generation of digital navigation technologies.

2 METHODOLOGY

This study used a quantitative cross-sectional survey to investigate the awareness, perceptions and educational needs of maritime stakeholders regarding emerging digital navigation technologies. Instead of evaluating the technical performance of individual systems, the study examined how maritime professionals perceive selected aspects of the ongoing digital transformation and whether they consider themselves prepared for its implementation. **Figure 1** provides an overview of the research methodology.

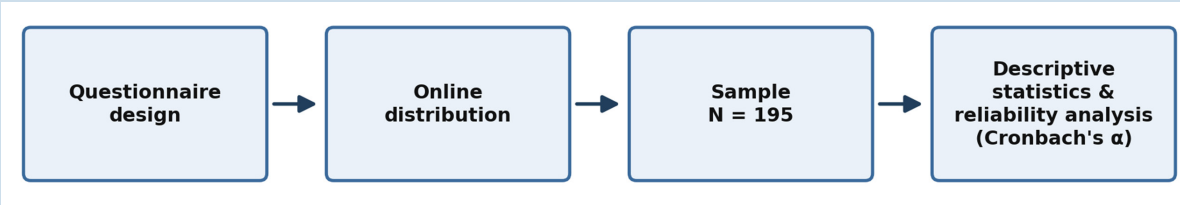


Figure 1. Overview of the research methodology (made by authors).

Data were collected using a structured online questionnaire. The questionnaire captured respondents' previous exposure to emerging navigation technologies, self-assessed knowledge of the IHO S-100 framework, perceptions of the IMO e-Navigation concept, awareness of cyber security threats and perceived need for continuous professional development. The questionnaire consisted of two sections. The first section collected demographic and professional information describing respondents' navigational background, including rank, age, sea service, ECDIS experience and vessel type. The second section investigated respondents' awareness and perceptions of emerging digital navigation technologies.

Respondents first indicated whether they had previously encountered selected emerging navigational technologies in their professional practice, including cloud-based navigation, automated route planning, weather route optimisation, fuel route optimisation and cyber security implementation. Self-assessed knowledge of the IHO S-100 framework was subsequently evaluated using a five-point Likert scale ranging from Very Poor (1) to Excellent (5). Respondents were then asked whether they believed that a better understanding of S-100 standards would benefit their future professional activities, using a five-point agreement scale ranging from Strongly disagree (1) to Strongly agree (5). The perceived importance of the five strategic priorities of the IMO e-Navigation concept was assessed using five independent statements addressing: user-friendly bridge design; standardised and automated ship reporting; improved reliability of navigation bridge equipment; graphical presentation of information received through communication equipment; and improved communication with Vessel Traffic Services. Each component was evaluated using a five-point importance scale ranging from Not Important (1) to Very Important (5). Respondents additionally assessed the severity of cyber security threats to modern digital navigation using a five-point scale from Insignificant (1) to Severe (5), and expressed their opinion regarding the necessity of continuous professional development to maintain competence in rapidly evolving digital navigation technologies using a five-point agreement scale. These five dimensions of digital navigation readiness, and their relationship to the study's overall construct, are illustrated in **Figure 2**.

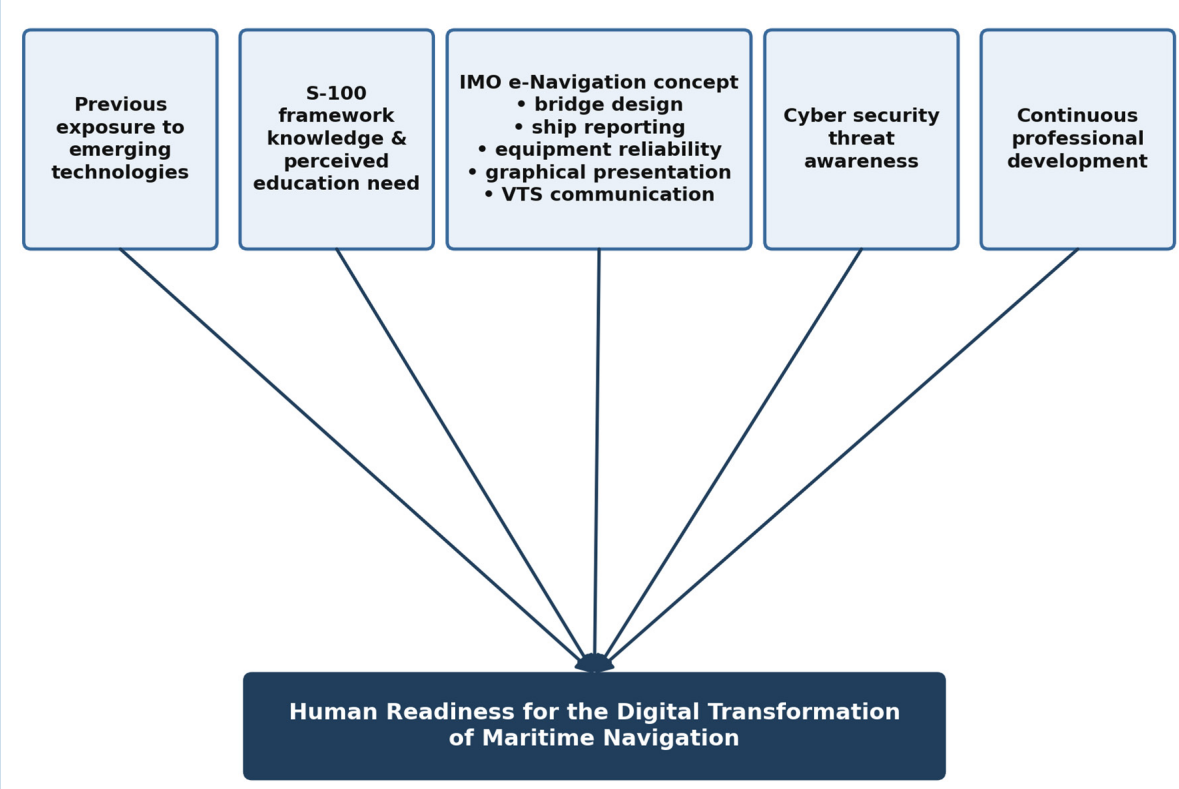


Figure 2. Conceptual framework of the study: dimensions of human readiness for the digital transformation of maritime navigation (made by authors).

All statistical analyses were performed using the R statistical computing environment. Descriptive statistics were calculated for all analysed variables, including the number of observations, arithmetic mean, standard deviation, median, minimum and maximum. Frequency distributions were calculated for categorical variables describing respondents' demographic characteristics and previous exposure

to emerging navigation technologies. The internal consistency of the five questionnaire items describing the IMO e-Navigation concept was evaluated using Cronbach's alpha coefficient [16]. Cronbach's alpha estimates the proportion of variance in a composite score that can be attributed to a common underlying construct, and is calculated as:

$$\alpha = (k / (k - 1)) \cdot (1 - \Sigma\sigma_i^2 / \sigma_t^2) \quad (1)$$

where k is the number of items (here, k = 5), σ_i^2 is the variance of the i-th item and σ_t^2 is the variance of the total score obtained by summing all items. Values of α range from 0 to 1, with values of 0.70 or higher generally considered acceptable for research purposes [17]. Cronbach's alpha was considered appropriate in this study because the five e-Navigation items were designed as parallel indicators of a single concept (the perceived importance of the IMO e-Navigation strategic priorities), were measured on the same five-point ordinal scale and were intended to be interpreted jointly. The remaining readiness indicators (S-100 knowledge, S-100 education need, cyber security threat perception and continuous professional development) were each measured with a single item and were therefore analysed individually, as internal consistency cannot be estimated for single-item measures. Differences between operational seafarers and supporting maritime stakeholders were examined using the Mann–Whitney U test, given the ordinal nature of the Likert-scale data, with statistical significance set at $p < 0.05$.

3 RESULTS

A total of 195 respondents participated in the survey. The sample included both operational seafarers and supporting maritime stakeholders involved in navigation-related activities. Operational personnel (n = 159; 81.5%) comprised Masters (n = 46; 23.6%), Staff Captains (n = 7; 3.6%), Chief Officers (n = 32; 16.4%), First Officers (n = 8; 4.1%), Second Officers (n = 30; 15.4%), Third Officers (n = 21; 10.8%), Safety Officers (n = 5; 2.6%) and Deck Cadets (n = 10; 5.1%). The supporting stakeholder group (n = 36; 18.5%) included maritime studies students (n = 12; 6.2%), former navigating officers currently not working at sea (n = 7; 3.6%), university professors (n = 7; 3.6%), ship management personnel such as superintendents and vessel operators (n = 4; 2.1%), ECDIS manufacturer representatives (n = 3; 1.5%), maritime pilots (n = 2; 1.0%) and a Port State Control officer (n = 1; 0.5%).

Respondents reported varying levels of previous exposure to emerging digital navigation technologies. Weather route optimisation was the most frequently encountered technology, reported by 111 respondents (56.9%), followed by fuel route optimisation (80 respondents; 41.0%) and cyber security implementation (69 respondents; 35.4%). Experience with automated route planning was reported by 44 respondents (22.6%), whereas 50 respondents (25.6%) indicated that they had not yet encountered any of the listed technologies in their professional practice. Overall, the results suggest that maritime stakeholders are considerably more familiar with optimisation technologies associated with voyage planning than with other emerging digital navigation concepts, indicating that the implementation of future digital navigation technologies remains at different stages of maturity across the maritime sector.

Respondents reported a relatively modest level of self-assessed knowledge of the IHO S-100 framework (M = 2.36, SD = 1.03), indicating that most participants considered their current understanding of the forthcoming hydrographic standard to be limited. In contrast, respondents expressed a strong need for additional education related to S-100 (M = 3.93, SD = 0.70), suggesting widespread recognition of the importance of future professional training. These findings indicate that awareness of the upcoming S-100 framework has not yet reached the level required for its forthcoming implementation despite a clear willingness among respondents to improve their knowledge.

All five strategic components of the IMO e-Navigation concept received relatively high importance ratings. User-friendly bridge design obtained the highest mean score (M = 4.17, SD = 0.88), followed by

equipment reliability (M = 4.09, SD = 0.84), standardised and automated ship reporting (M = 4.08, SD = 0.80), improved communication with Vessel Traffic Services (M = 3.88, SD = 0.99) and graphical presentation of information (M = 3.87, SD = 0.87). The consistently high ratings across all five components indicate broad support for the implementation of the IMO e-Navigation strategy and suggest that respondents recognise the importance of improving information integration and communication within future navigational systems. The five items describing the IMO e-Navigation concept demonstrated good internal consistency, with a Cronbach's alpha coefficient of 0.842, indicating that these variables reliably represent a common construct associated with perceptions of e-Navigation [17].

Respondents perceived cyber security as an important challenge for future digital navigation (M = 3.65, SD = 0.92). The highest agreement among all analysed variables was observed for continuous professional development (M = 4.24, SD = 0.80), demonstrating a strong consensus that ongoing education will be essential for maintaining competence in increasingly digitalised navigational environments. **Figure 3** summarises the mean ratings of all nine readiness indicators, ordered from highest to lowest agreement. Standard deviations ranged from 0.70 (S-100 education need) to 1.03 (S-100 framework knowledge). The lowest dispersion was observed for S-100 education need and continuous professional development, indicating a high level of consensus among respondents, whereas the greatest variability was found for S-100 framework knowledge, improved communication with Vessel Traffic Services (SD = 0.99) and cyber security threat perception (SD = 0.92), suggesting more heterogeneous levels of familiarity and risk perception across the sample. No statistically significant differences between operational seafarers (n = 159) and supporting stakeholders (n = 36) were found for any of the nine indicators (Mann–Whitney U test, all p ≥ 0.17), suggesting that the observed perceptions and knowledge gaps are shared across professional roles.

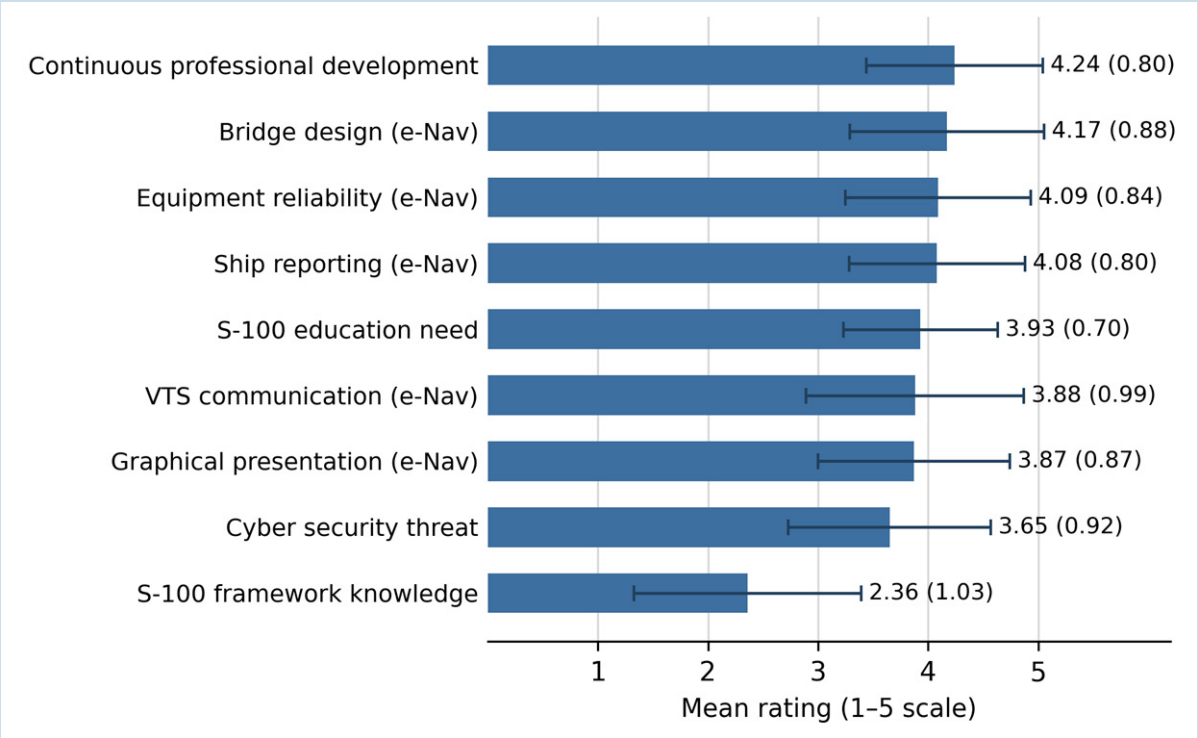


Figure 3. Mean ratings of the nine digital navigation readiness indicators on a five-point scale (N = 195). Bars represent mean values, and horizontal error bars indicate ± one standard deviation (SD); mean (SD) values are shown to the right of each bar. Indicators are ordered from highest to lowest mean rating; items marked "(e-Nav)" refer to the five strategic priorities of the IMO e-Navigation concept (made by authors).

4 DISCUSSION

The findings of this study offer a human-centred perspective on the awareness, perceptions and educational needs of maritime stakeholders in relation to emerging digital navigation technologies. The self-assessed knowledge of the S-100 framework (M = 2.36, SD = 1.03) was found to be low. This finding should be considered together with the strong demand for additional education (M = 3.93, SD = 0.70), which indicates that respondents were aware of their own limitations. Furthermore, this finding is in line with previous experience gained during the introduction of ECDIS, where the lack of adequate familiarisation and training, rather than the technology itself, was identified as a contributing factor to navigational difficulties [13-15]. Therefore, it can be concluded that the main challenge for maritime education and training institutions is not to generate demand for S-100-related training, but to ensure that this training is provided in a timely manner before the mandatory implementation of the framework [18].

The consistently high importance ratings assigned to all five components of the IMO e-Navigation concept, with user-friendly bridge design rated highest, align closely with the original rationale of the e-Navigation strategy, which prioritises harmonised information presentation and improved interaction between navigators and shore-based services over the introduction of additional equipment [8, 9]. This finding is consistent with previous research reporting generally positive seafarer perceptions of e-Navigation and S-100-related bridge developments [5]. However, this does not necessarily indicate operational readiness in the absence of adequate familiarisation.

Respondents also recognised cyber security as a relevant operational challenge (M = 3.65, SD = 0.92), although it was rated lower than continuous professional development. Previous research attributes a substantial proportion of maritime cyber security vulnerabilities to human behaviour and limited situational awareness, rather than to purely technical shortcomings [11, 12]. Therefore, the moderate ranking of cyber security observed in this study suggests that continued efforts to raise awareness are still needed, even though respondents' overall attitude was positive.

Taken together, these findings indicate that maritime stakeholders broadly recognise the strategic importance of digital navigation technologies. However, this positive attitude is accompanied by specific knowledge gaps, particularly regarding the S-100 framework. It should be noted that this gap between positive attitudes and more limited technical knowledge appears to be consistent with patterns already reported in the technology acceptance literature [19]. Consequently, positive attitudes towards digital navigation should not be taken as evidence of sufficient technical competence by themselves.

5 CONCLUSION

The maritime industry is entering a new phase of digital transformation. It is progressively implementing the IHO S-100 framework, the IMO e-Navigation strategy and increasingly interconnected navigational systems. The findings indicate that maritime stakeholders broadly recognise the strategic importance of these developments and strongly support continuous professional development. At the same time, self-assessed knowledge of the S-100 framework was found to be limited, although respondents identified a need for additional education.

These results suggest that future digital navigation technologies will not succeed through technological innovation alone. They will also depend on systematic investment in education, training and developing digital competencies among maritime professionals. Future research should extend these findings through larger, more internationally representative samples, and should further examine how perceived preparedness relates to actual, objectively assessed competence in using emerging digital navigation technologies.

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III. Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems

A Multi-Criteria Assessment of Green Strategies for Achieving IMO Net-Zero Transition Goals: A Review

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ABSTRACT

Although ports and ships play a central role in the global economy and international trade, they are also associated with significant environmental impacts [3]. With a projected annual growth rate of 2.1% over the coming years, the maritime industry is under pressure to reduce its emissions. In response, the IMO has developed a strategy targeting an achievement of net-zero emissions by 2050, relative to 2008 levels. In this context, the selection of appropriate green technologies in maritime transport constitutes a complex decision-making problem, as it requires the simultaneous consideration of environmental, economic, technical and social dimensions, as well as interests of multiple stakeholders [5, 9, 20, 21]. Due to this complexity, multi-criteria decision-making (MCDM) methods are increasingly being adopted as effective tools to support decision-making for the implementation of green technologies in ports and maritime transport. This paper provides a comprehensive review of the scientific literature on the application of MCDM methods in the selection of green technologies within the maritime sector. The results reveal prevailing research trends, strengths and limitations of existing methodologies, and key research gaps in addressing uncertainty and in practical implementation within real maritime environments. Furthermore, the findings indicate that existing studies tend to focus either on challenges at the port level or on those faced by ship operators, resulting in limited interoperability of approaches. This represents a challenge and an opportunity for future research.

Keywords: GHG emissions; ship; port; MCDM

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1 INTRODUCTION

Climate change and the escalating imperative to reduce greenhouse gas (GHG) emissions are placing the maritime sector at the forefront of one of the most profound systemic transformations in its history. Ports and shipping companies are increasingly compelled to reduce their carbon footprint, enhance energy efficiency, and transition toward cleaner energy sources to achieve compliance with the objectives of the IMO and Article 2 of the Paris Agreement adopted under the United Nations Framework Convention on Climate Change (UNFCCC), which establishes long-term strategic directions for mitigating the impacts of global warming [22].

As observed by [11] and [13], the Paris Agreement constitutes the first environmental agreement aimed at addressing global warming, with Article 2 highlighting the objective of limiting the increase in the global average temperature to below 2°C, while pursuing efforts to restrict the increase to 1.5°C for countries with adequate financial, technological, and infrastructural capacities. [16] further emphasise that effective alignment with the Paris Agreement necessitates the implementation of coordinated measures on both the shipping and port sides. Supporting this statement, [10] demonstrate that interventions made on a single subsystem of maritime transport are insufficient to fully address the decarbonisation challenge, given the pronounced infrastructural and financial interdependence between shipping companies and ports. Accordingly, the decarbonisation of maritime systems has emerged as a priority area of research, encompassing the integration of technological innovation, the strategic management of infrastructure, and the effective coordination of stakeholders within the maritime transport ecosystem.

The objective and purpose of this paper is to conduct a comprehensive analytical literature review of research in the field of maritime sector decarbonisation and to analyse how the existing literature addresses the assessment and selection of green strategies in ports and shipping to meet the IMO's GHG emissions reduction goals. Particular emphasis is placed on identifying prevailing research trends and challenges, the decision-making criteria and sub-criteria applied, and the multi-criteria methodological approaches used to assess green strategies. The analysis further examines whether existing studies integrate both maritime subsystems, ports and shipping, and whether they provide a basis for identifying green strategies that take into account their financial, technological, and infrastructural capacities. Based on these objectives, three research questions were formulated:

- RQ1: How does the existing literature on maritime decarbonisation address the assessment and selection of green strategies for achieving IMO net-zero GHG emission targets?
- RQ2: Which assessment criteria are considered in the literature, and to which maritime subsystem do they pertain?
- RQ3: Which multi-criteria methodological approaches are employed for the assessment and ranking of decarbonisation strategies in the maritime sector?

Accordingly, the review examines whether maritime decarbonisation is addressed holistically, considering both ports and shipping companies, and whether regulatory pressures encourage coordinated investment in green transition strategies.

2 METHODOLOGY

The analytical literature review was conducted in line with the PRISMA 2020 guidelines for systematic reviews. The method, presented in the form of a checklist, outlines the key stages of conducting systematic reviews within the healthcare domain, however, owing to its flexibility and advisory nature, it is readily applicable to broader research contexts [17]. In accordance with the PRISMA 2020 checklist, inclusion and exclusion search criteria were first established. In line with the research objectives, the

inclusion criteria were defined as studies that, irrespective of the methodological approach employed, address interventions aimed at mitigating GHG emissions by applying green technologies or assessment criteria. The exclusion criteria encompassed all studies that did not involve decision-making processes related to the selection of green technologies. To ensure the quality and reliability of the reviewed literature, non-peer-reviewed publications were excluded. Additionally, studies to which the authors did not have access or were not written in English were not considered. The literature search, conducted in accordance with the defined inclusion and exclusion criteria, was performed on 17th June 2026 using the Scopus database and the Scopus Advanced Search tool, employing Boolean operators. The search strategy was based on a query string incorporating the keywords: green, port, ship, techno*, strat* and decision. The terms technology and strategy were shortened to account for variations in word forms. Additional studies were identified through snowballing of relevant references. The search query string is presented in equation (1).

$$TITLE-ABS-KEY\,(green)\ AND\ (TITLE-ABS-KEY\,(port)\ OR\ TITLE-ABS-KEY\,(ship))\ AND\ (TITLE-ABS-KEY\,(techno*)\ OR\ TITLE-ABS-KEY\,(strat*))\ AND\ TITLE-ABS-KEY\,(decision) \quad (1)$$

The initial search yielded a total of 90 records. The collected studies were subsequently subjected to a four-stage selection process in accordance with the PRISMA framework performed by all three authors of this paper [17]. From the initial set of 90 records, 19 identified duplicates were removed, resulting in a total of 71 unique studies. Based on titles and basic metadata, 10 records were excluded due to insufficient relevance to the goals, either owing to the absence of an MCDM methodological framework or an unclear source. Consequently, 61 articles remained for further review. A detailed content screening subsequently led to the exclusion of 15 articles, which did not meaningfully address the identification of green technologies or the criteria for their selection. In total, 46 studies from the original sample of 90 were deemed to meet the inclusion criteria. The search and screening process is summarised in **Figure 1**.

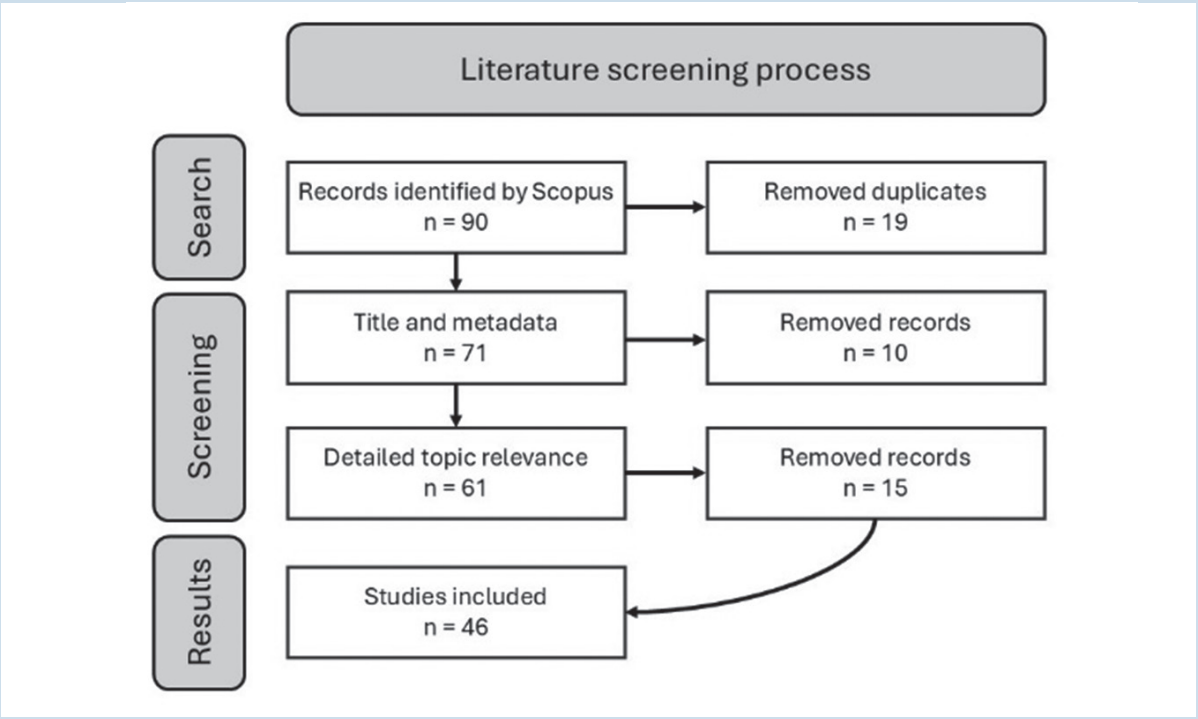


Figure 1. Literature screening process
Source: Made by authors

In the subsequent stage, and in accordance with PRISMA 2020, an analytical review of the selected studies was conducted, focusing on analysing which methodological approaches were employed, which criteria were assessed and the scope of criteria applicability to port and shipping systems in achieving the defined objectives.

3 RESULTS

The 46 selected studies were systematically classified according to the methodological approaches used to assess decision criteria and green technologies. The distribution of MCDM methods is shown in **Figure 2**.

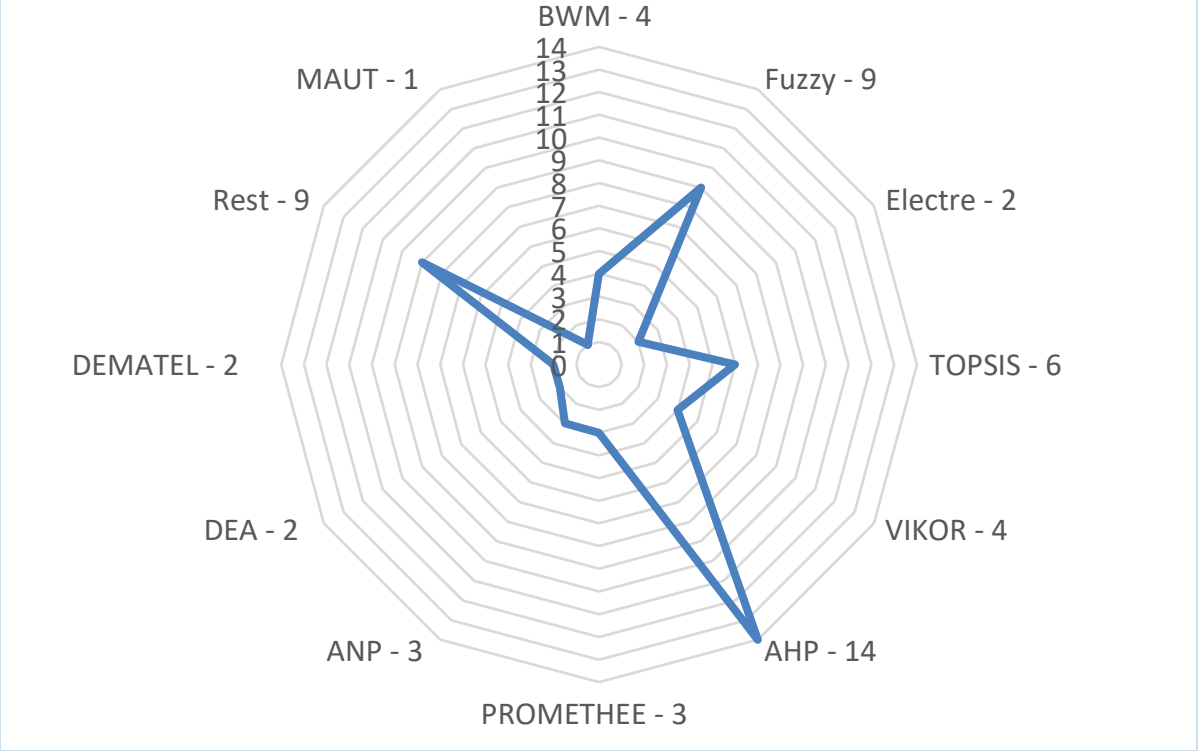


Figure 2. MCDM method frequency of use
Source: Made by authors

Figure 2 indicates an inclination among authors towards the adoption of Saaty's Analytic Hierarchy Process (AHP) approach to multi-criteria decision-making [18], the incorporation of fuzzy logic, and the use of the TOPSIS method, followed by other, less frequently applied methodologies. [14] justify the selection of the AHP approach on the grounds that it is widely employed in existing research, thereby enabling comparisons between decision-making approaches and facilitating the interpretation of results. The authors further note that the method is suitable for addressing problems involving multiple criteria within the process and support their choice by arguing that AHP effectively addresses the needs of decision-makers.

Authors of studies such as [1, 2], and [7] opted for the Fuzzy-AHP methodological approach. They explain that combining fuzzy logic with the AHP process enables the treatment of uncertainty and ambiguity in decision-making, emphasising that the subjectivity of decision-makers cannot be adequately expressed through the integer values required by classical AHP for weight calculation. The

incorporation of fuzzy logic into the decision-making process thus mathematically approximates human uncertainty, yielding more realistic results.

[15] approached the problem by combining several MCDM models, namely WSM and WPM methods which, according to [14], do not specify how to define the scale of evaluation for decision-making criteria. Nevertheless, the authors highlight the simplicity of calculating criterion values and the straightforward nature of pairwise comparisons as key advantages of these methods.

Six of the selected studies employed TOPSIS as the central methodological approach. According to [14], TOPSIS is particularly suitable for identifying alternatives that are closest to the ideal solution, although its applicability depends on the structure and objectives of the decision-making problem. Consequently, TOPSIS is not an optimal method for hierarchical ranking of criteria.

Each selected study in the review appropriately justified its choice of methodological approach in relation to its objectives. Some studies focused on assessing the suitability of implementing a specific green technology, while others addressed the issue of the zero-transition in a holistic manner, by examining the suitability of multiple green technologies. Accordingly, the studies differed in their definition and selection of evaluation criteria.

The authors of the collected works have adopted various approaches when defining assessment criteria or green technologies. [4, 6, 8], and [12] focused their research on the feasibility of implementing individual green technologies, such as liquefied natural gas, green hydrogen, green corridors, and the use of battery systems and electric motors for ship propulsion.

Most studies adopted a broader approach, assessing green technologies according to four main groups of criteria: environmental, economic, social, and technological. Although environmental performance is the primary objective of green technologies, their implementation also depends on investment and maintenance costs, social impacts, and the required technological capacity [19]. A comprehensive assessment should therefore consider all four dimensions.

The analysis further reveals a clear distinction between green strategies for ports and for ships. Of the 46 selected studies, 32 focused exclusively on port-related transition solutions, 12 on ship-related solutions, and only two on both subsystems. But even these two primarily addressed shore power supply during port stays, rather than an integrated decarbonisation solution across the whole maritime transport chain. This indicates that ports and ships are still predominantly addressed as separate subsystems.

4 CONCLUSIONS AND DISCUSSION

To justify the literature search methodology and ensure transparency, the authors would like to address the limitations exclusively using the Scopus database for literature search. Although Scopus is one of the largest multidisciplinary bibliographic databases and provides extensive coverage of peer-reviewed scientific publications, relying on a single database may have resulted in the omission of relevant studies indexed elsewhere, such as Web of Science, ScienceDirect, or discipline-specific databases. Consequently, some potentially relevant articles may not have been identified. However, to mitigate this limitation, a snowball sampling approach was employed by examining the reference lists of relevant publications, which enabled the identification and inclusion of additional studies, including those indexed in other databases. Nevertheless, Scopus was selected due to its broad coverage and indexing standards, while avoiding the inclusion of grey literature that is often retrieved through platforms such as Google Scholar. This approach was adopted to ensure that the review was based primarily on peer-reviewed and quality-controlled scientific sources.

Based on the analysis of the reviewed literature, it is possible to address the three proposed research questions, RQ1, RQ2, and RQ3. The selected studies examine the assessment and selection of green

technologies designed to support the objectives of the IMO and the Paris Agreement in achieving net-zero emissions in maritime systems. The authors conduct their analysis using social, economic, environmental, and technological criteria for the suitability of green technologies.

The literature demonstrates considerable interest in assessing green strategies for maritime decarbonisation, but most studies address ports and ships separately (RQ1). While many studies compare multiple technological alternatives using broad assessment frameworks, a smaller group evaluates individual green technologies. Consequently, maritime decarbonisation is generally addressed comprehensively within individual subsystems, but rarely from an integrated port-shipping perspective. The reviewed studies primarily apply four groups of assessment criteria: environmental, economic, social, and technological. However, their application varies according to the subsystem analysed. Of the 46 selected studies, 32 focus on ports, 12 on ships, and only two consider solutions applicable to both. This confirms a significant research gap in assessment frameworks that simultaneously consider the financial, technological, infrastructural, and environmental requirements of ports and shipping companies (RQ2). In evaluating the importance of criteria and the suitability of green technologies for the zero-emission transition, a variety of MCDM approaches are used to assess and rank green strategies. AHP is the most frequently applied method, either on its own or in combination with fuzzy logic. TOPSIS and other MCDM methods are also employed, reflecting the multidimensional nature of green technology selection and the need to incorporate heterogeneous decision criteria (RQ3). The principal finding of this review is therefore not the absence of green technologies or assessment methodologies, but the limited integration of port and shipping perspectives within a shared decision-making framework. Ports and shipping companies are technologically and infrastructurally interdependent, particularly in relation to alternative fuels, energy supply, and supporting infrastructure. Their transition strategies should therefore be evaluated in conjunction rather than as independent decisions. Among the most frequently referenced solutions are green hydrogen, 20, followed by yellow hydrogen, 18, liquefied natural gas (LNG), 7, and battery-powered propulsion systems for ships, 5. Green hydrogen is particularly relevant due to its potential to substantially reduce lifecycle GHG emissions when produced from renewable energy and supported by appropriate port and vessel infrastructure. To achieve net-zero emission targets, ports and shipping companies must reach a consensus regarding fuel selection and the corresponding adaptation of port and vessel infrastructure to ensure bunkering availability and enable global maritime transport. Such an approach would facilitate the elimination of greenhouse gas emissions in maritime systems and reduce dependence on fuel choices dictated by geopolitical circumstances and international relations. A key challenge for future research lies in identifying optimal solutions for the selection of green technologies that simultaneously consider both shipping and port contexts. [3] and [14] highlight the significant pressure imposed by the IMO and the Paris Agreement, although [14] adopt a more critical stance regarding the feasibility of the proposed timelines. They argue that achieving energy self-sufficiency for ports by 2030 is unrealistic, as full decarbonisation would require a fifteenfold increase in onshore electricity production. [3] extend the discussion to a global scale, emphasising that, without drastic measures, maritime transport could produce between 90% and 130% more emissions by 2050 compared to 2008 levels. They also point to geopolitical disparities, noting that developing countries are generally less supportive of market-based mechanisms for emission reduction due to insufficient financial resources to meet the substantial initial investments required for the implementation of green technologies. In addition to improving coordination between ports and shipping companies, future research should focus on developing integrated multi-criteria decision-making frameworks that support gradual emission reduction through financially and technologically feasible transition pathways. Such frameworks should jointly consider port and shipping requirements and integrate environmental, economic, social, technological, and infra-structural criteria to support the selection of both short-term transitional solutions and long-term net-zero technologies. More accessible technologies could serve as transitional solutions, while infrastructure should be designed to enable subsequent upgrades to cleaner technologies.

Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, analysis, interpretation, and conclusions were developed and verified by the authors, who remain fully responsible for the content.

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III. Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems

With the Wind at Our Backs: Implications of Wind-Assisted Propulsion Systems for Maritime Training and Navigational Safety

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ABSTRACT

Wind-assisted propulsion systems (WAPS) are considered promising technologies to improve energy efficiency and reduce greenhouse gas emissions in line with International Maritime Organization (IMO) decarbonisation and energy-efficiency initiatives, such as the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI). Technologies such as wing sails, rotor sails, suction sails and kite sails are emerging as commercially viable solutions. However, the operation of such systems presents operational, technical and navigational challenges that are not yet specifically addressed within the existing International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) framework. This paper presents a qualitative review of relevant IMO regulations and conventions, including EEDI, EEXI, Ship Energy Efficiency Management Plan (SEEMP), STCW and The International Regulations for Preventing Collisions at Sea (COLREGs) to analyse the implications of WAPS deployment for maritime training and navigational safety. It also discusses the main WAPS technologies and their influence on ship operation and manoeuvrability and reviews the ECDIS training scheme as a possible model for future WAPS competence development. The analysis identifies essential competence requirements for navigational, engineering and electro-technical officers, including knowledge of aerodynamic principles, automated control systems, maintenance procedures and emergency response. Furthermore, the forces generated by WAPS may affect leeway, manoeuvrability, stopping distances and collision-avoidance decisions, highlighting the need for further research on the practical application of COLREG provisions in certain operational scenarios. The paper proposes a role-based approach to WAPS training and supports the ongoing discussion on the safe integration of wind-assisted propulsion technologies into maritime operations, education and regulations.

Keywords: wind-assisted propulsion systems (WAPS); maritime education and training; STCW; COLREGs; ship handling

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1 INTRODUCTION AND REGULATORY CONTEXT BACKGROUND

The maritime industry is under increasing pressure to reduce greenhouse gas emissions and improve energy efficiency in accordance with the International Maritime Organization's (IMO) decarbonisation strategy. Among the technologies being adopted to support these objectives are Wind-Assisted Propulsion Systems (WAPS), including wing sails, rotor sails, suction sails and kite sails. By generating supplementary thrust from wind energy, these technologies can reduce engine load, fuel consumption and associated emissions, contributing to compliance with Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI) and Ship Energy Efficiency Management Plan (SEEMP) requirements [1-3].

The growing deployment of WAPS represents more than a technological response to decarbonisation requirements. Unlike many energy-efficiency technologies that operate largely in the background of ship operations, WAPS introduce aerodynamic forces that may influence ship handling, manoeuvrability and bridge operations. Depending on the installed technology, these effects may include increased leeway, altered turning behaviour, changes in stopping performance, restricted bridge visibility and additional demands associated with automated control systems [4-6]. Consequently, the safe and efficient operation of WAPS-equipped vessels depends not only on technical performance but also on the competence of the personnel responsible for navigation, machinery operation and system monitoring.

The development of competence requirements for emerging maritime technologies frequently lags their technical adoption. Recent IMO initiatives, including the Generic Interim Guidelines on Training for Seafarers on Ships Using Alternative Fuels and New Technologies, recognise the need for supplementary training frameworks while broader revisions of the STCW Convention remain under development [7]. Although STCW establishes general competence requirements for navigational, engineering and electro-technical personnel [8], the extent to which these provisions adequately address the operational implications of WAPS remains only partially explored in the literature [9].

A similar question arises in relation to navigational safety and the application of the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs). Vessels equipped with WAPS remain classified as power-driven vessels and continue to operate under the existing collision-avoidance framework [10]. However, additional aerodynamic forces may influence manoeuvrability, leeway, track-keeping performance and emergency response characteristics [5, 6]. As discussed in recent research on Maritime Autonomous Surface Ships (MASS), the principal challenge may not be whether regulations apply, but how they are interpreted and implemented in the presence of novel technologies [11].

A useful precedent for future WAPS competence development can be found in the introduction of the Electronic Chart Display and Information System (ECDIS). The integration of ECDIS into maritime operations was accompanied by the establishment of generic and type-specific training requirements, simulator-based learning and familiarisation procedures, providing a structured approach for incorporating new technology into shipboard operations while maintaining navigational safety [8, 12]. Similar principles may offer a practical model for future WAPS training and competence development.

While previous studies have examined WAPS competence requirements, simulator training needs and onboard operational challenges [4, 9, 13], the present study integrates these perspectives with navigational-safety considerations and existing STCW and COLREG frameworks to propose a role-based training approach.

This paper presents a qualitative review of relevant IMO regulations and conventions, including EEDI, EEXI, SEEMP, STCW and COLREGs, and examines the operational characteristics of contemporary WAPS technologies to analyse their implications for maritime training and navigational safety.

2 METHODOLOGY

This study adopts a qualitative approach combining regulatory review, technical analysis and comparison with existing maritime training practices. The analysis is based on three complementary components.

The first component draws upon the review of regulatory instruments presented in the previous section, including IMO energy-efficiency measures (EEDI, EEXI and SEEMP), STCW competence requirements and selected COLREG provisions. This review establishes the regulatory context within which WAPS are being adopted and identifies issues relevant to crew competence and navigational safety. These regulatory instruments were selected because they provide the international framework governing ship energy efficiency, crew competence and collision avoidance, which are the areas most directly affected by WAPS deployment.

The second component examines the operational characteristics of the principal WAPS technologies currently employed in commercial shipping, namely wing sails, rotor sails, suction sails and kite sails. Attention is given to operational characteristics that may influence ship handling, manoeuvrability, bridge operations and maintenance requirements. These technologies were selected because they represent the principal forms of WAPS currently employed in commercial shipping and are consistently represented in the technical reports and scientific literature reviewed in this study.

The third component considers the implementation of ECDIS training as a reference model for future WAPS competence development. Generic and type-specific training concepts, simulator-based learning and familiarisation requirements are evaluated as potential elements of a future WAPS training framework. The ECDIS training framework was selected because it provides an established example of introducing new technology through generic and type-specific training supported by simulator-based competence development.

The competence areas presented in **Tables 2–4** were developed through qualitative synthesis of WAPS operational characteristics, training needs identified in the reviewed literature and existing STCW responsibility structures for navigational, engineering and electro-technical personnel.

3 OPERATIONAL CHARACTERISTICS AND SAFETY IMPLICATIONS OF WAPS

Four principal types of Wind-Assisted Propulsion Systems (WAPS) are currently employed in commercial shipping: wing sails, rotor (Flettner) sails, suction sails and kite sails [2]. Although all four technologies utilise wind energy to generate supplementary thrust and reduce fuel consumption, they differ in their aerodynamic principles, operational characteristics and supporting technical systems. These differences are important because they influence ship handling, onboard operations and the competencies required from navigational, engineering and electro-technical personnel.

Wing sails use rigid aerofoil structures to generate aerodynamic lift and may affect bridge visibility due to their deck-mounted configuration. Rotor sails generate thrust through the Magnus effect and can produce significant aerodynamic side forces, influencing vessel manoeuvrability and course-keeping. Suction sails combine an aerofoil structure with active boundary-layer control and rely heavily on automated control functions. Kite sails operate at higher altitudes, where stronger winds are available, and place greater emphasis on deployment, recovery and weather assessment than on deck-mounted operations [2, 3, 5]. Although their configurations differ, all WAPS technologies depend on environmental conditions, sensor inputs and automated control systems to achieve effective performance. Safe operation therefore requires a shared understanding of system capabilities, limitations and emergency procedures among all shipboard departments. Navigational officers

require the most detailed understanding of how WAPS affect ship behaviour and decision-making. Engineering officers focus on mechanical and structural systems supporting WAPS operation, while electro-technical officers are primarily concerned with electrical, monitoring and automation systems. The technology-specific competence areas associated with the principal WAPS types are summarised in **Table 1**.

Table 1. Technology-specific competence areas associated with principal WAPS technologies

WAPS type	NAV	ENG	ETO
Wing sails	Aerodynamic lift, angle of attack, operational limitations, visibility effects	Hydraulic systems, structural foundations and supports	Sensors, automation systems, monitoring and safety interlocks
Rotor sails	Magnus effect, activation and deactivation criteria, manoeuvring implications	Drives, bearings and mechanical maintenance	Motor control systems, speed regulation and sensors
Suction sails	Sail positioning and performance optimisation	Fans, compressors and associated mechanical systems	Pressure-control systems and automation functions
Kite sails	Deployment, recovery and weather assessment	Routine maintenance and manufacturer-specific familiarisation	Control pods, communication links and monitoring systems

NAV = Navigational officers; **ENG** = Engineering officers; **ETO** = Electro-technical officers. Source: Made by the authors based on [2, 4, 5, 13].

From a navigational perspective, the most significant consequence of WAPS deployment is the introduction of aerodynamic forces in addition to conventional propulsion forces. Depending on wind conditions, vessel characteristics and system configuration, these forces may influence leeway, turning response, track-keeping ability, stopping performance and bridge visibility [5, 6]. For example, aerodynamic side forces generated by deployed systems may increase leeway and alter turning behaviour, while aerodynamic forces may continue to influence vessel motion following engine power reduction or propulsion failure. Such effects become particularly relevant in confined waters, close-quarters situations and emergency manoeuvres, where accurate assessment of vessel behaviour is essential for safe navigation.

4 PROPOSED TRAINING FRAMEWORK

The operational implications of WAPS suggest that future competence development should adopt a role-based approach. Similar to the ECDIS implementation model, a combination of generic and type-specific training offers a balance between standardised competence development and familiarisation with the specific equipment installed onboard [12, 14]. While generic training can address common operational, safety and regulatory aspects applicable across WAPS technologies, type-specific familiarisation should focus on the characteristics, limitations and operating procedures of the installed system.

For navigational officers, generic training should combine theoretical instruction and simulator-based exercises. Theoretical content should cover the aerodynamic principles relevant to WAPS operation, including the relationship between generated forces, vessel manoeuvrability, leeway, stopping

performance and compliance with COLREG requirements. Basic concepts such as force and moment interactions, side-force generation and their influence on course-keeping and turning behaviour should also be addressed. Simulator exercises should focus on bridge interfaces, alarm management and the practical effects of varying wind conditions and sail configurations on ship handling.

Type-specific training should focus on the installed system and follow principles similar to ECDIS familiarisation [12, 14]. Theoretical instruction should address operating limitations, automation modes and deployment or depowering procedures, while simulator exercises should emphasise practical operation, route-keeping, manoeuvring performance and emergency response. Training scenarios should progress from basic familiarisation under different wind conditions to traffic situations requiring collision-avoidance actions and emergency procedures. A representative simulator exercise may involve a vessel fitted with multiple rotor sails. Differences in rotor position and rotational speed may generate varying side forces and turning moments, influencing leeway, course-keeping and rudder demand. Such scenarios effectively demonstrate the relationship between WAPS operation and vessel manoeuvrability.

Table 2. Skills covered depending on responsibility level for navigational personnel

Skill	Responsibility level		
	Management	Operational	Support
Safety procedures and emergency situations handling	X	X	X
Aerodynamic principles and ship-handling effects of the installed WAPS technology	X	X	
System limitations and deploying, depowering and trimming	X	X	
Collision avoidance	X	X	
Voyage planning and weather routing	X		
Visual inspection	X		

Source: Made by authors

The competency areas presented in **Tables 2** and **3** are linked to the existing STCW responsibility structure, where management, operational and support levels represent different shipboard functions and corresponding decision-making responsibilities for navigational and engineering personnel [8]. Consequently, the depth of training and assessment should increase with responsibility level, with management-level personnel requiring the broadest understanding of operational, safety and voyage-planning considerations.

Training for engineering officers should build upon existing competencies in machinery operation, maintenance and energy management. Because many WAPS technologies share similar mechanical and hydraulic arrangements, a general training module supplemented by manufacturer guidance and onboard familiarisation may be more appropriate than separate type-specific certification [4]. Training should cover structural, mechanical and hydraulic components, their interaction with propulsion and power-generation systems, maintenance requirements and the influence of WAPS operation on fuel consumption and energy efficiency. Emphasis should be placed on fault recognition, emergency shutdown procedures and coordination with bridge and electro-technical personnel during abnormal operating conditions. The competence areas proposed for engineering personnel at different responsibility levels are presented in **Table 3**.

Table 3. Skills covered depending on responsibility level for engineering personnel

Skill	Responsibility level		
	Management	Operational	Support
Safety procedures and emergency situations handling	X	X	X
Maintenance, visual inspection	X	X	X
Understanding effects on main and auxiliary engines	X	X	
Fault identification	X	X	
Maintenance planning	X		
Spare parts supplying	X		

Source: Made by authors

The proposed distribution of competencies reflects the increasing management and decision-making responsibilities associated with higher STCW responsibility levels and the differing operational responsibilities of engineering personnel onboard WAPS-equipped vessels.

WAPS training for electro-technical officers should focus on extending existing competencies in electrical power systems, automation and control. The principal competence areas and their corresponding emphasis are summarised in **Table 4**.

Table 4. Skills covered by ETOs with each skill emphasis

Electro-technical officers	
Skills	**Emphasis of each skill**
Power distribution	Power supply across ship and abnormal load conditions associated with WAPS
Automation and control	Sensors, Programmable Logic Controllers (PLCs), human–machine interfaces (HMIs)
Diagnostics and fault identification	Identifying and isolation of faults, recovering procedures
Software maintenance	Integration with bridge and machinery systems and applying manufacturer updates

Source: Made by authors

As increasing levels of automation and remote monitoring are introduced, cybersecurity and configuration management are also likely to become important competence areas. Because STCW defines Electro-Technical Officer competence through Regulation III/6 and Table A-III/6 at the operational level, without a separate management-level certification structure, a unified WAPS training framework for ETOs appears to be a practical starting point. Additional system-specific familiarisation may be provided through manufacturer guidance and onboard training.

5 DISCUSSION

The findings indicate that the implications of WAPS extend beyond energy efficiency and environmental compliance. While their primary purpose is to reduce fuel consumption and greenhouse-gas emissions, WAPS may also influence ship manoeuvrability, route-keeping, stopping performance and bridge operations through the introduction of additional aerodynamic forces. Consequently, their safe integration depends not only on technical reliability but also on the competence of the personnel responsible for navigation, maintenance and system monitoring.

The analysis suggests that existing STCW provisions provide a foundation for many WAPS-related competencies, particularly in the areas of ship handling, machinery operation, automation and emergency response. However, the interaction between aerodynamic propulsion, automated control systems and conventional navigational decision-making is not explicitly addressed within the current framework [4, 8]. In this respect, the introduction of ECDIS provides a useful precedent. The combination of generic and type-specific training allowed common competencies to be standardised while accommodating differences between equipment manufacturers and onboard installations [12, 14]. Similar principles appear applicable to future WAPS competence development.

The review also highlights implications for navigational safety and the practical application of COLREGs. Although WAPS-equipped vessels remain classified as power-driven vessels, deployed systems may affect leeway, manoeuvrability, stopping characteristics and bridge visibility [5, 6, 10]. As a result, certain operational situations, particularly close-quarters encounters, restricted waters and propulsion failures, may require additional consideration when applying existing collision-avoidance principles. For example, Rule 8 requires collision-avoidance actions to be effective and readily apparent to other vessels, while WAPS-induced leeway or altered turning characteristics may influence the execution of such manoeuvres. Similarly, situations involving propulsion failure while deployed sails continue to generate aerodynamic forces may require bridge teams to account for residual aerodynamic effects when assessing vessel manoeuvrability and emergency response.

The proposed framework should be regarded as preliminary and requires validation through simulator studies, operational trials and feedback from seafarers, training institutions and equipment manufacturers. Nevertheless, the findings support the view that future WAPS implementation should be accompanied by structured competence development to ensure that environmental benefits are achieved without compromising navigational safety.

6 CONCLUSION

Wind-assisted propulsion systems (WAPS) can support maritime decarbonisation and ship energy-efficiency requirements, but safe implementation of WAPS requires appropriate crew competence. This paper has examined implications of WAPS for maritime training and navigational safety while providing a preliminary role-based competence framework for navigation, engineering, and electro-technical personnel.

Proposed approach builds on existing STCW competence structures and combines skills for WAPS operation with familiarisation for specific technology installed onboard. It is intended as initial contribution to the safe integration of WAPS into maritime operations, rather than as a validated certification model. Further research should validate proposed framework and proposed requirements through simulator studies, operational trials and feedback from seafarers and manufacturers.

Use of AI tools: AI-assisted tools were used for manuscript organisation and language refinement. All scientific content and conclusions were developed and verified by the authors.

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III. Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems

Comprehensive Identification and Analysis of Key Challenges in the Blue Economy Sectors

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ABSTRACT

The Blue Economy and innovations are interrelated concepts aimed at the sustainable use of marine and coastal resources. Innovation processes increase efficiency, reduce ecological footprint, and strengthen competitiveness among marine-related sectors. As such, innovations are not only an instrument for enhancing economic efficiency; they are a crucial factor in achieving sustainability goals, resilience, and long-term competitiveness of the Blue Economy. This paper presents the research results referring to the collaboration improvement and innovations within the Blue Economy sectors. The research objective was to raise awareness of various pressures within the Blue Economy sectors. The aim was to identify key challenges in Blue Economy sectors that innovative marine technologies could resolve. Special emphasis has been placed on the diverse backgrounds of the stakeholders participating in the research. Stakeholders from traditional sectors of the Blue Economy, as well as stakeholders from growing sectors, participated in the research. According to the results, stakeholders' contributions are essential for shaping future initiatives and technological solutions that promote sustainability and innovations within the Blue Economy sectors. However, they also indicate the need for establishing stronger collaboration among various sectors and the development of integrated approaches that could improve efficiency and resilience of the Blue Economy in general.

Keywords: blue economy; innovations; sustainability; challenges; stakeholders

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1 INTRODUCTION

The Blue Economy concept was first mentioned in 2009 at the United States Senate Committee on Commerce, Science, and Transportation congress regarding economic, social and ecological impacts on the coast, oceans and coastal economies caused by climate change, ocean acidification, pollution, overfishing, sea-level rise, and marine litter [5]. The World Bank defines the Blue Economy as the sustainable exploitation of marine resources aimed at achieving economic growth, increasing the standard of living, and creating new job possibilities while contemporaneously protecting marine ecosystems. In other words, the Blue Economy is understood as a need for the development of individual ocean sectors to manage impacts on ocean health [6]. The Blue Economy definition used by the European Commission includes all economic activities regarding oceans, seas, and coasts, as well as a wide range of interrelated, established, and new, growing sectors [2]. Gunter Pauli, a Belgian economist, entrepreneur, innovator, and author, is recognised as the creator of the Blue Economy concept. He promotes an approach in which ecological problems are linked to scientific solutions based on the physical processes of nature, aiming to develop solutions that are ecologically sustainable and economically and socially useful. Furthermore, Pauli advocates Blue Economy principles as sustainable business models, which create additional jobs, thus reconciling the frequently opposing objectives of sustainability and economic profitability [7]. The concept itself presumes cross-sector and cross-border coordination among various stakeholders [1].

The Blue Economy's activities provide jobs for 5.4 million people in the EU and account for a gross value added (GVA) of approximately 500 billion euros per year [3]. Therefore, the Blue Economy is one of the essential development models of the 21st century. However, its success is not measured by economic indicators only, but by the ability to preserve natural resources, strengthen the resilience of local communities, and ensure intergenerational equity. Nowadays, the Blue Economy holds an important place in scientific and expert discussions on sustainability as it encompasses a comprehensive approach to the economic exploitation of water resources, while simultaneously ensuring environmental protection and social responsibility. The basic idea of the concept is that seas and oceans are not only areas of economic exploitation, but also fragile ecosystems whose preservation is crucial for long-term human welfare. Consequently, it is important to understand how to optimally align growth, development, and sustainability in Blue Economy [4].

From a global perspective, the Blue Economy develops in accordance with international sustainability policies, especially with the United Nations' objectives. The open seas represent the last remaining global common good. The efficient management of ocean re-sources becomes a necessary precondition for reaching sustainability goals [8]. The European Commission's strategy regarding the Blue Economy highlights research and innovations as the driving force of sustainable development, where investments are directed towards three essential areas of activity:

- Achieving climate neutrality;
- Preserving and restoring marine and coastal ecosystems;
- Encouraging innovations aimed at ocean sustainability [9].

In the last few decades, the Blue Economy has been recognised as a strategic framework for the sustainable development of marine and coastal areas. As a multidisciplinary concept, the Blue Economy encompasses a wide range of activities, including traditional ones such as fisheries, mariculture, and maritime transport, as well as new and dynamically growing ones, such as renewable energy sources, biotechnology, and digital solutions. This diversity of activities makes the Blue Economy a sector of significant potential, with a wide range of challenges that are not clearly defined, which leaves space for further research and discussions. In this regard, innovations become causes of transformation, as they enable not only the modernisation of traditional sectors, but also the development of new ones. However, without a clear understanding and identification of the most

significant challenges stakeholders face in the Blue Economy, the most important process, i.e., the innovation process, remains open and multi-layered, requiring an interdisciplinary perspective and continuous adaptation.

The paper draws on research conducted within the DIH InnovaMare project, funded under the Interreg Italy-Croatia 2021-2027 cross-border programme. The goal of the project was to strengthen research capacities and to promote the transfer of technology for developing innovative marine technologies.

The paper presents the results of activities carried out within the DIH InnovaMare project, based on a jointly developed methodology and cross-border cooperation between Italian and Croatian partners. Within this framework, an open call was designed and implemented to identify key challenges in blue economy sectors. The identified challenges, presented in this paper, form the basis for developing new innovative solutions.

2 METHODOLOGY

The results presented in this paper are based on methodology developed as a part of the DIH InnovaMare project activities, and is the result of cross-border collaboration between Italian and Croatian partners: Methodology for the Open Call for the identification of challenges in the Blue Economy sectors that could be resolved by innovative marine technologies. It consists of four key parts:

- Preparing the Open Call to identify key challenges in the Blue Economy sectors;
- Announcement and dissemination of the Open Call;
- Evaluation of the identified key challenges;
- Descriptive analysis of the selected challenges.

Sectors were classified into established sectors of the Blue Economy and emerging Blue Economy sectors as defined by the EU Blue Economy report 2022-2023. Sector names and their descriptions are shown in **Table 1** and **Table 2**. The tables present only Blue Economy sectors in which key challenges were identified through the Open Call, while other Blue Economy sectors are not included.

Table 1. Established sectors and their descriptions

ESTABLISHED SECTORS OF BLUE ECONOMY	
Sector name	**Sector description**
Fisheries and Aquaculture	This sector covers the harvesting of renewable biological resources, their processing into food/feed and other bio-based products, and the their distribution.
Maritime Transportation	This sector includes sea and coastal passenger and inland passenger water transport, freight transport by sea and coastal and inland waterways, as well as associated transport services.
Coastal tourism	This sector comprises recreational activities carried out near the sea in the maritime area, including nautical sports.

Source: Authors based on [10]

Table 2. Emerging sectors and their descriptions

EMERGING BLUE ECONOMY SECTORS	
Sector name	**Sector description**
Blue Biotechnology	The Blue biotechnology sector focuses on the commercial use of marine organisms such as algae bacteria fungi and invertebrates and their renewable biomass for applications ranging from food additives and pharmaceuticals to cosmetics animal feeds and energy.
Maritime Defence, Security, and Surveillance	This sector includes activities that ensure the safety and security of maritime zones.
Research and Infrastructure	This includes the development of submarine cables and marine robotics, which are essential for improving the resilience and technological capabilities of maritime activities.

Source: Authors based on [10], [11]

Following the identification of challenges collected through an open call, the methodology involved an evaluation of challenge applications in which all applicants, in addition to identifying a challenge, were required to propose maritime technologies needed to address that challenge, including a description of how the proposed technologies would solve the identified problem. Each application was assessed through a scoring system, and the twenty best challenges achieved a total score of 100 points or more. The evaluation was carried out by an expert team composed of members of the project consortium, comprising 34 members affiliated with eight institutions – four from Italy and four from Croatia.

When evaluating submitted key challenges, the team of experts used the following criteria developed as part of the project, applying a scale from 1 to 5:

- Relevance to the Blue Economy;
- Innovation Potential;
- Feasibility of Proposed Solutions;
- Impact on Stakeholders.

3 RESULTS

The analysis of the identified challenges shows that the majority belong to the maritime transport sector. Among the five highest-ranked challenges, three are related to maritime transport, one to blue biotechnology, and one to fisheries and aquaculture.

The best-graded challenge by the team of experts, Sensor Suite Design for Monitoring Regenerative IMTA Systems in the Adriatic Sea, belongs to the Blue Biotechnology sector. It got 141 points. Although the mentioned challenge was not rated as the most significant for the Blue economy, it was ranked first in the overall evaluation due to its Innovation Potential and Feasibility of proposed solution. Reviewers assessed that all five top ranked challenges have an almost equally significant impact on stakeholders.

The challenge that ranked second in terms of scored points belongs to the Maritime Transportation sector and is called Marine Litter in Coastal Areas - Finding an Innovative and Eco-Friendly Solution. This challenge got 138 points. The third-ranking challenge with 137 points was Insufficient Port Infrastructure that Can Support Ships in Reducing Pollution while Docked. Considering the subject matter it addresses, the team of experts classified this challenge into two sectors, namely Maritime Transportation

& Coastal Infrastructure. The fourth and the fifth places, with an equal number of points, i.e., 134, share two challenges: the Efficient Autonomous Underwater Monitoring for Marine Ecosystem Protection and Port Infra-structure Safety, and Poor Waste Management Practices for Tracking and Recycling System for Fishing Gear and Fish Processing Byproducts. The challenge called the Efficient Autonomous Underwater Monitoring for Marine Ecosystem Protection and Port Infrastructure Safety belongs to the Maritime Transportation sector, while the challenge Poor Waste Management Practices for Tracking and Recycling System for Fishing Gear and Fish Processing Byproducts belongs to the sector of Fisheries and Aquaculture. All 20 selected challenges are shown in **Table 3**.

Table 3. Selected Open Call challenges

No.	Blue Economy sector	Challenge title	Total score
1	Blue Biotechnology	Sensor Suite Design for Monitoring Regenerative IMTA Systems in the Adriatic Sea	141
2	Maritime Transportation	Marine Litter in Coastal Areas - Finding Innovative and Eco-Friendly Solutions	138
3	Maritime Transportation & Coastal Infrastructure	Insufficient Port Infrastructure that Can Support Ships in Reducing Pollution while Docked	137
4	Maritime Transportation	Efficient Autonomous Underwater Monitoring for Marine Ecosystem Protection and Port Infrastructure Safety	134
5	Fisheries and Aquaculture	Poor Waste Management Practices for Tracking and Recycling Systems for Fishing Gear and Fish Processing Byproducts	134
6	Maritime transportation	Marine Pollution - Liquid and Solid Waste in Nautics	133
7	Fisheries and Aquaculture	Inefficient Waste Management in the Fish Processing Industry	132
8	Maritime transportation	Lack of Ability of Dynamical Validation of Efficiency Measures, Fuel Savings, Emissions Reductions in the Adriatic Sea	131
9	Maritime Defence, Security, and Surveillance	Operational and Maintenance Inefficiencies Across the Maritime Lifecycle: From Shipbuilding to Fleet Management	130
10	Maritime Transportation	Real-Time Hydrographic and Meteorological Data Integration	128
11	Research and Infrastructure	Integration Between Rail Transport and Port Logistics	127
12	Research and Infrastructure	Lack of Underwater Data Transmission Technologies - Expanding the Range of Sources for Multi-Source Environmental Data Acquisition and Processing Platforms	123
13	Fisheries and Aquaculture	Seabream Predation and Climate Change Weather Extremes in Mussel and Oyster Production Systems	120
14	Research and Infrastructure	Poor Integration between Railway Infrastructure and Ports, especially in the Last-Mile	120
15	Coastal tourism	Lack of Integrated Visitor Data for Tourism Planning	118
16	Other	Insufficient Legacy Onboard Sensors	117
17	Maritime Transportation	High Maritime Traffic Congestion during Peak Tourism Seasons	115
18	Maritime Transportation	Legal Aspects of Autonomous Surface Vessels	110
19	Maritime Transportation	Digitalization & Sustainability in Maritime Transport	109
20	Other	Energy Supply from Renewable Sources in Croatia	104

4 CONCLUSION

The identified challenges highlight the need for innovative approaches that could enable long-term sustainability and competitiveness of the Blue Economy through better integration of various sectors and advanced infrastructure digitalisation. Implementation of smart management systems that integrate data from various sources and enable timely decisions can significantly improve the resilience and flexibility of marine and coastal-related industries.

Furthermore, regarding other key topics, special attention has been given to developing new energy sources, advancing sensor technologies, and optimising logistics processes. These elements can have a decisive role in reducing expenses, increasing safety, and improving the total efficiency of the Blue Economy while simultaneously contributing to decarbonisation and environmental protection goals.

Most of the identified challenges clearly show a strong alignment with sustainability and innovation objectives. This indicates the existence of a broad knowledge base and creative solutions that could be further developed and applied in practice.

In order to approach the problems of identified challenges, future efforts should focus on strengthening sector collaboration, promoting data-based decision-making, as well as developing scalable, technology-based solutions that meet the needs of local communities and the international market. This creates an opportunity for making new business models, encouraging investments, and strengthening the region's competitiveness in the Blue Economy sector.

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III. Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems

Climate Risk in the Rhine–Danube–Sava Inland Waterway Corridor

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ABSTRACT

Inland waterway transport is an important low-emission freight mode in Europe, but it is highly exposed to climate-related hydrological change. This paper examines the economic and financial implications of drought and flood risk for inland waterway logistics corridors, focusing on the Rhine-Danube-Sava system. Drawing on transport economics literature, institutional assessments and verified market reporting, the analysis explains how reduced navigability affects vessel loading capacity, freight rates, supply-chain reliability, insurance availability and public adaptation investment. The findings show that low-water disruption can produce substantial welfare and macroeconomic losses, while recent Rhine evidence confirms that freight rates can rise sharply within short periods during drought episodes. The analysis also indicates that climate-related financial risk remains insufficiently reflected in logistics contracts, insurance products and adaptation-financing frameworks. Danube and Sava evidence on drought duration, record-low water levels and flood losses reinforces the need for proactive corridor planning. The paper concludes that inland waterway climate risk should be treated not only as an operational or engineering issue, but also as a financial-planning challenge requiring coordinated action by shippers, carriers, port authorities, insurers and public institutions.

Keywords: inland waterway transport; climate risk; Rhine-Danube-Sava corridor; drought disruption; climate finance; insurance

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1 INTRODUCTION

Inland waterway transport (IWT) plays an important role in European freight logistics because it can move large volumes of bulk and containerised cargo with comparatively low emissions per tonne-kilometre and is frequently presented as part of the European Union's broader transition towards sustainable transport. However, the same physical characteristics that make inland navigation efficient also make it vulnerable: unlike road or rail transport, the economic performance of IWT depends directly on river discharge and available draught, so when water levels fall, vessels must sail with reduced loads and the cost per tonne can rise sharply.

The purpose of this paper is therefore to examine inland waterway climate risk as both an economic and a financial issue. Reduced navigability is the immediate physical trigger, but its consequences are transmitted through freight prices, delivery reliability, industrial production, insurance costs, contract design and public infrastructure budgets. The contribution of the study is to connect these channels in a corridor-based interpretation of climate risk, showing why adaptation planning for inland waterways must combine hydrological monitoring with financial instruments and public-investment decisions.

The analysis focuses on the Rhine and Danube as the main European inland waterway corridors and considers the Sava as a secondary corridor of direct relevance to Croatia. Three questions guide the paper. First, what economic costs have been associated with low-water and flood-related disruption on major European river corridors? Second, how are these physical disruptions transformed into financial exposure for shippers, carriers, insurers and infrastructure operators? Third, which policy and financial instruments could strengthen adaptation planning, particularly for the Danube-Sava corridor? The Danube and Sava are treated together because the Sava is a major southern tributary whose hydrological and logistics conditions can influence the wider Danube system (Popa et al., 2025).

2 BACKGROUND

2.1 Historical context of European inland navigation

Inland navigation on the Rhine, Danube and Sava has long been shaped by institutional, infrastructural and hydrological constraints. The Rhine developed as a major European trade corridor, but tolls, staple rights and fragmented political control kept transport costly until nineteenth-century reforms established freer navigation. The Sava-Kupa corridor followed a different path within the Habsburg-Ottoman borderlands, where river improvement gradually supported trade despite difficult navigation conditions. This history matters because it shows that present climate risk is layered on older corridor-specific constraints, especially the weaker evidence base and lower freight intensity on the Sava compared with the Rhine.

2.2 Climate-related hydrological risk

Climate projections and transport economics research indicate that inland navigation in Central and Western Europe is likely to face more frequent periods of hydrological stress. On the Rhine, low summer discharge reduces available draught and constrains cargo capacity, particularly at critical bottlenecks such as Kaub. Earlier modelling by Jonkeren et al. (2011) showed that extreme low-water conditions can substantially increase transport prices and generate significant welfare losses. Although model results vary by scenario, vessel type and market segment, the literature consistently shows that the economic impact of low water is non-linear: relatively small changes in water depth can produce disproportionately large changes in loading capacity and transport cost.

Observed disruption in recent years has confirmed the practical importance of these findings. The 2018 Rhine drought is widely cited as an example of how river constraints can affect national industrial

performance, exposing the dependence of chemical, energy, agricultural and manufacturing supply chains on reliable inland navigation. Research by the Kiel Institute for the World Economy links prolonged low-water periods on the Rhine to measurable reductions in German industrial production (Mayer, 2025), and market reporting from the 2026 episode confirms that freight-rate increases can occur over very short time horizons (Reuters, 2026a; Reuters, 2026b).

The Danube system is exposed to similar mechanisms, although its geography, traffic structure and institutional setting differ from those of the Rhine. Low-water periods can reduce barge loading capacity, delay grain and bulk cargo movements, and place additional pressure on road and rail alternatives. The Sava, as a tributary connection between Croatia and the wider Danube network, currently carries more limited freight volumes, but its navigability is affected by low flow, sediment conditions and infrastructure constraints, so it should be considered within the same broader climate-risk framework. Recent Danube drought episodes lasted between four and eight months in 2012, 2017, 2018 and 2022 (Popa et al., 2025); **Table 1** below extends this frequency-and-duration picture across all three rivers over a longer horizon.

Table 1. Chronology of low-water episodes and reported navigation impacts on the Rhine, Danube and Sava, 2003-2026.

River	Key low-water episodes	Reported impact
Rhine	2003, 2011, 2018, 2022, 2026	Reduced draught, capacity limits, closures and rapid freight-rate increase at critical gauges such as Kaub.
Danube	2003, 2011, 2015, 2018, 2022, 2026	Navigation restrictions, blocked freighters, reduced traffic volumes and record-low levels at several gauges.
Sava	1993, 2003, 2012, 2015, 2026	Station-level historical minima and constrained navigability, with fewer formally documented freight impacts than on the Rhine or Danube.

Source: Made by authors, based on ICPDR (2015), Reuters (2026a, 2026b), DHMZ (2012), Hrvatske vode (2022), BGNES (2026), HRT (2026), Xinhua (2026) and other sources listed in the references.

The chronology shows that severe low-water episodes recur across the Rhine and Danube and that the Sava is increasingly relevant to the same risk framework, although its impacts are more often documented through historical gauge minima than through detailed navigation statistics. The 2026 episode is especially important because several Croatian gauges set new all-time lows.

Flooding represents a second, complementary dimension of climate risk for inland waterways. While drought primarily reduces navigability and cargo capacity, floods can interrupt cargo handling, damage infrastructure and increase safety risks. Recent Rhine flood events show that inland waterway corridors are exposed to both extremes within short periods (Deidda et al., 2025), which complicates adaptation planning since infrastructure and financial instruments must be designed for variability rather than a single hazard type (PIANC, 2020). The financial scale of this second hazard is substantial: reported Danube-basin flood damage reached about EUR3.6 billion in 2002 and EUR2.4 billion in 2013 (Popa et al., 2025).

3 METHODOLOGY

The study applies a qualitative review and comparative analytical method. It combines three groups of evidence: peer-reviewed transport economics studies on the relationship between water levels, vessel loading and freight prices (Jonkeren, 2009; Jonkeren et al., 2011); institutional and technical assessments of inland waterway adaptation (PIANC, 2020; European Parliamentary Research Service,

2022; Climate-ADAPT, n.d.); and verified market reporting on recent Rhine and Danube disruption episodes (Kollewe, 2025; Reuters, 2026a; Reuters, 2026b; Mooney et al., 2026). This combination allows older model-based estimates to be interpreted alongside recent market evidence, connecting operational disruption with questions of finance, insurance and public investment. The evidence base also incorporates the 2025 Danube hydrological review by Popa et al., which provides comparable indicators on river dimensions, freight volumes, drought duration, flood losses and monitoring coverage.

The analysis is structured in three stages that correspond to the research questions. First, the study identifies the main physical risk channels affecting the Rhine, Danube and Sava, distinguishing drought-related navigability loss from flood-related infrastructure disruption. Second, it compares available economic evidence, including freight-rate movements, estimates of welfare loss and reported impacts on industrial activity. Third, it assesses the adequacy of existing financial responses, including contractual risk allocation, insurance products, parametric coverage and public adaptation finance.

The paper does not generate new hydrological measurements or econometric estimates. Its contribution lies in integrating evidence from transport economics, logistics practice and climate finance in order to clarify how physical river conditions are translated into economic costs and financial risks. This synthesis is particularly relevant for corridors such as the Sava, where detailed empirical datasets are still limited but where early adaptation planning may reduce future exposure.

4 RESULTS

The evidence reviewed points to three main findings. First, the cost response to low water is strongly non-linear: relatively small reductions in available draught can produce disproportionately large increases in transport cost. Earlier modelling on the Rhine indicated that low-water conditions can substantially increase freight prices, especially for larger vessels and longer routes. More recent market evidence confirms that these effects can be rapid and substantial. In the 2026 Rhine episode, tanker barge rates on the Rotterdam-Karlsruhe route rose from approximately EUR45 per tonne at the end of June to around EUR130-140 per tonne by 28 July, illustrating how a physical constraint on draught can quickly become a financial shock for logistics users.

Second, the consequences of low-water disruption extend beyond carriers and freight markets. When inland navigation becomes unreliable, industrial firms may face higher input costs, delivery delays, production interruptions and the need to shift cargo to less efficient modes. Evidence from the Rhine suggests that prolonged low-water periods can be associated with measurable reductions in industrial output; although comparable quantified evidence is less developed for the Danube and Sava, the same transmission mechanism is relevant: reduced navigability affects logistics reliability, which affects regional economic performance. The scale of activity exposed is illustrated by Danube Commission data reviewed by Popa et al. (2025): across 2019-2023, reported freight volumes at major monitoring points reached tens of millions of tonnes annually, with the very low 2022 water levels cited as one factor affecting river traffic.

Third, existing financial responses do not yet appear proportionate to the scale of the risk. Climate-related disruption in inland waterway transport remains only partially reflected in logistics contracts, insurance coverage and public investment frameworks. Traditional insurance products are often poorly suited to gradual, threshold-based disruptions such as low water, while parametric products linked to river-gauge levels remain at an early stage of development, creating a gap between the physical predictability of these risks and the financial mechanisms available to absorb them. At the same time, the physical risk is relatively observable: national monitoring networks along the Danube total roughly 133 stations across riparian countries, publishing water-level and forecast data at horizons from 24 to 120 hours (Popa et al., 2025), which strengthens the case for threshold-based contractual and insurance instruments.

5 DISCUSSION

These findings indicate that inland waterway climate risk should be interpreted as a pricing and financing problem as much as an operational one. For shippers, the main issue is not only whether cargo can move during a low-water period, but also at what cost, under which contractual conditions and with what degree of reliability. Firms that rely on fixed-price transport contracts may be exposed to substantial margin risk if low-water surcharges, alternative-mode options and delivery-time tolerances are not specified in advance. More transparent contractual allocation of hydrological risk would therefore improve commercial planning, reduce disputes and support more efficient pricing of climate exposure.

For carriers and infrastructure operators, the underdevelopment of business-interruption and parametric insurance represents both a vulnerability and a potential area of innovation (PwC Germany, 2025). Parametric products based on river-gauge thresholds could provide faster and more transparent payouts than traditional claims-adjusted insurance, provided that basis risk is carefully managed. Such instruments would not eliminate physical disruption, but they could reduce liquidity stress and provide clearer price signals for climate exposure along specific river reaches.

For public authorities, the comparison between documented economic losses and the still-limited scale of dedicated inland-waterway adaptation finance points to a planning gap. Adaptation should not be understood solely as large-scale engineering expansion. Financially robust resilience may instead depend on a portfolio of measures: improved forecasting, targeted maintenance and dredging where environmentally acceptable, shallow-draught fleet design, digital traffic management and clearer coordination between river commissions, port authorities and transport ministries. A practical adaptation-finance framework could track a small set of corridor KPIs, such as days below critical navigation levels, forecast lead time, freight-rate uplift per tonne and duration of navigation restrictions. The 24–120-hour monitoring windows reported for the Danube show that at least part of this KPI set can be operationalised using routinely observed hydrological data (Popa et al., 2025).

For Croatia and the Sava-Danube corridor, the implications are practical. Lower current freight volumes should not be interpreted as low future exposure: low-water clauses, contingency planning for modal shifts and targeted corridor investment would help reduce future logistics and financial risk.

The main limitation is uneven data availability. Rhine evidence is relatively strong, while Sava-specific evidence remains limited. Future research should link river discharge, vessel loading, freight prices, delays and modal substitution at daily or weekly frequency.

6 CONCLUSION

Climate change is already affecting inland waterway logistics corridors in Europe through more frequent and more consequential hydrological extremes. Low-water periods reduce vessel loading capacity, increase freight rates and expose industrial supply chains to higher costs and reliability risks, while flood events create additional disruption for port operations and infrastructure. The evidence reviewed in this paper shows that these effects are economically significant and that their financial management remains incomplete, still insufficiently embedded in transport contracts, insurance products, corporate risk management and public adaptation strategies. A more resilient approach requires integrating hydrological forecasting, contractual risk allocation, targeted infrastructure investment, shallow-draught fleet adaptation and innovative insurance mechanisms. For the Sava-Danube corridor, early action is especially important because lower current freight volumes should not be mistaken for low future exposure. By addressing climate risk before disruption becomes structurally more costly, Croatia and the wider Danube region can strengthen the reliability, sustainability and financial resilience of inland waterway transport. Future research should build corridor-specific datasets linking river discharge, vessel loading, freight rates and modal substitution

at daily or weekly frequency and should test parametric insurance and contractual risk-sharing instruments for the Sava-Danube corridor, in order to translate the financial-planning perspective developed here into operational tools for shippers, carriers, insurers and public authorities.

Use of AI tools: AI-assisted tools were used to support structural organisation and language refinement. The authors developed, reviewed and verified all scientific content, analysis, interpretation and conclusions and remain fully responsible for the accuracy, originality and integrity of the manuscript.

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III. Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems

Sustainable Coastal Management in Zadar County: Public Perceptions

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ABSTRACT

Coastal areas represent one of the most important, but also the most sensitive, natural and economic resources of the Republic of Croatia, as well as the rest of the world. Numerous social, economic and recreational activities take place in them, which often conflict with the need to preserve natural resources and the environment. A substantial share of the global population inhabits coastal zones, which exposes these areas to significant demographic pressure. At the same time, the development of tourism, industry, urbanisation and intensive exploitation of marine resources are placing additional pressure on coastal ecosystems, while climate change is further increasing their vulnerability and the need for sustainable management. The aim of the study was to examine the attitudes of the local population of Zadar County toward sustainable coastal management, with special emphasis on the perception of key problems, levels of awareness and involvement in management processes, and their support for sustainable development measures. The authors examined the above aspects using a survey questionnaire. The findings indicate that the local residents use the coastal area intensively in everyday life, primarily for recreation, walking and swimming, confirming its important social and recreational function. The respondents rated the condition of the coastal area as unsatisfactory, with the main challenges being excessive urbanisation, coastal concretisation, tourism pressures, and pollution of the sea and beaches. The results indicate insufficient information and involvement of the local population in the coastal area management processes, which indicates the need for greater transparency of institutions and strengthening participatory management. At the same time, the respondents expressed a high level of support for environmental protection measures, responsible spatial planning, and sustainable coastal management. A particular contribution of this work lies in the empirical insight it provides into the attitudes of local residents as a key stakeholder group in coastal area governance. The findings may serve as a basis for designing more effective policies for sustainable coastal area management, based on a balance between economic development, environmental protection and the interests of the local community.

Keywords: coastal area; local residents; Zadar County; sustainable coastal management

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Coastal areas are the most significant resources of every coastal country. They have a crucial role in the economy since a significant portion of national revenue comes from sectors such as the maritime sector or tourism. These areas are, as a rule, densely populated and extremely suitable for urbanisation.

Coastal areas are very frequently subject to conflicts among different users, with the intensity of these conflicts increasing as population density rises. Such conflicts result in the loss of valuable land resources and assets, and disruption of marine and terrestrial ecosystems. Moreover, they endanger historical and archaeological heritage and limit public access to space and resources.

The local population is one of the key stakeholders in the coastal area governance, showing a great interest in its development and management. At the same time, they are aware of the intensive exploitation of coastal resources that can lead to a disruption in the quality of life, which indicates the need to achieve balance between various development activities and the principle of sustainable coastal area management.

The aim of the paper was to analyse the attitudes of the local population of Zadar County towards the condition and management of coastal areas, with special attention given to the perception of key challenges, level of awareness and involvement in management processes, and the support for sustainable development measures. In order to achieve that goal, quantitative research aimed at attitude assessment of the local population towards the existing situation and management models of Zadar County coastal area was carried out. A survey questionnaire enabled a systematic collection and analysis of data on the population's perceptions, attitudes, and level of awareness regarding the use and management of the coastal area.

2 LITERATURE OVERVIEW

A coastal area is the area where the land and the sea meet, where the interrelationship between these two natural systems creates specific and complex conditions for life and development (Šimunović, 2014). Its important components are natural resources, specifically the sea, space, and a favourable geographic position. The coastal area offers a wide range of ecosystem services, which have a key role in economic development, protection of the environment and social well-being. The most important functions of a coastal area are resource provision (food, materials, energy and transportation), tourism through active vacations, regulatory services such as climate regulation and atmospheric gas regulation, protection against floods and storms, provision of potable water, waste and sewage biodegradation, cultural services that include protection of cultural heritage and identity, cognitive benefits, recreation and non-use values, as well as supporting ecosystem services that provide the foundation for ecosystem functioning and the production of other ecosystem services (Štanfel et al., 2016). Peronja (2022) also points to negative effects, such as the increase in noise levels, overcrowding, and air pollution. Through the decades, the development and exploitation of coastal areas have intensified significantly, resulting in significant socioeconomic and environmental changes along the coastal area that are expected to continue in the future (Neumann et al., 2015).

Since the beginning of industrialisation, economic activities, infrastructure, and housing have been concentrated in coastal areas, and this pattern is still present today (Montanari et al., 2014). Various economic activities such as tourism, fishing, urban development, and energy projects often come into conflict due to limited space and incompatible resource utilisation objectives (Botero et al., 2025; Bramati et al., 2014). Early coastal management efforts have been initiated in response to coastal area degradation caused by bad planning and inappropriate utilisation (Runko Luttenberger, 2026).

A coastal area enables a wide range of human and economic activities; therefore, it is a desirable residential area. Vulnerable coastal areas all around the world have been facing population growth

(Kovačić & Komadina, 2011), development of industry and tourism, as well as intensive exploitation of marine resources (Koboević et al., 2012). Inhabitants, as the group of people living in a certain area, are still, in spite of technological advancement, the most important development factor of a certain area (Radman et al., 2014). They are the basis for spatial, regional, economic, social, and other planning. Furthermore, they are the basic spatial resource and potential, in other words, every country's national strategic interest (Šterc & Komušanac, 2012). A sense of connection motivates people to protect, maintain, or change spaces that are meaningful to them, which also influences their interest in participating in local development planning (Miletić et al., 2017). The participatory approach to local policymaking focused on coastal management is the precondition for sustainable local development. Since coastal areas involve various stakeholder groups frequently with different visions, attitudes and interests, achieving their alignment is a key prerequisite for efficient spatial and development planning.

In order to manage a coastal area, it is important to actively involve the local population, which has knowledge of their community and its environment. The local population's priorities focus on long-term economic development, as well as on the protection of the area they live in.

3 METHODOLOGY

The applied quantitative research approach focused on the attitude analysis of the Zadar County population towards the condition and ways of managing the coastal area. The research included perception aspects of key challenges of a coastal area, the level of awareness and the participation of the population in management processes, as well as their attitudes towards the implementation of measures intended for the sustainable coastal area development.

The data collected by the survey questionnaire were digital and distributed through the Google Forms platform. The survey questionnaire covered five topics, namely the respondents' sociodemographic characteristics, uses of the coastal area, perception of the condition of the coastal area and its preservation, attitudes towards coastal area management, and the level of awareness and participation of the local population in management processes.

The research was conducted from December 2025 to February 2026. The survey questionnaire was distributed via social networks, primarily Facebook platform.

Based on the total population number of Zadar County reported in the 2021 Census (159,766 inhabitants), and the estimated number of the adult population (approximately 130,000 inhabitants), a minimum sample size of 383 inhabitants was determined. A total of 545 respondents participated in the research.

Participation in the research was voluntary and anonymous. The respondents were informed about the research purpose and goals before completing the questionnaire. Fully completed questionnaires were analysed, whereas incomplete questionnaires were excluded from the data analysis. The data collected were analysed using the descriptive statistics method in the Jamovi statistical software. The results were presented through frequencies, percentages and figures, which enabled the interpretation of the attitudes and perceptions of the local population regarding the condition and management of the coastal area in Zadar County.

4 RESULTS AND DISCUSSION

The sample was evenly distributed among genders; women represented 49.9% of the respondents, men represented 48.1% of the respondents, while 2% did not want to answer. As far as age is concerned, the largest group included respondents from 30 to 44 years of age (36.3%), followed by

respondents from 18 to 29 (32.8%) and 45 to 59 years of age (26.2%). The smallest group represented respondents older than 60 (4.6%).

In terms of educational level, respondents with higher and tertiary education predominate. The largest proportion of respondents have completed undergraduate or graduate programmes (33.9%), followed by those with higher education qualifications (32.8%) and high school education (27.2%). The smallest proportion of respondents were those who had completed elementary education (3.1%), and those holding doctoral degrees (2.9%). The sample structure shows a balanced gender distribution, a predominance of young and middle-aged respondents, and a high level of education among the respondents.

The most common activities the local population is engaged in are presented in **Figure 1**.

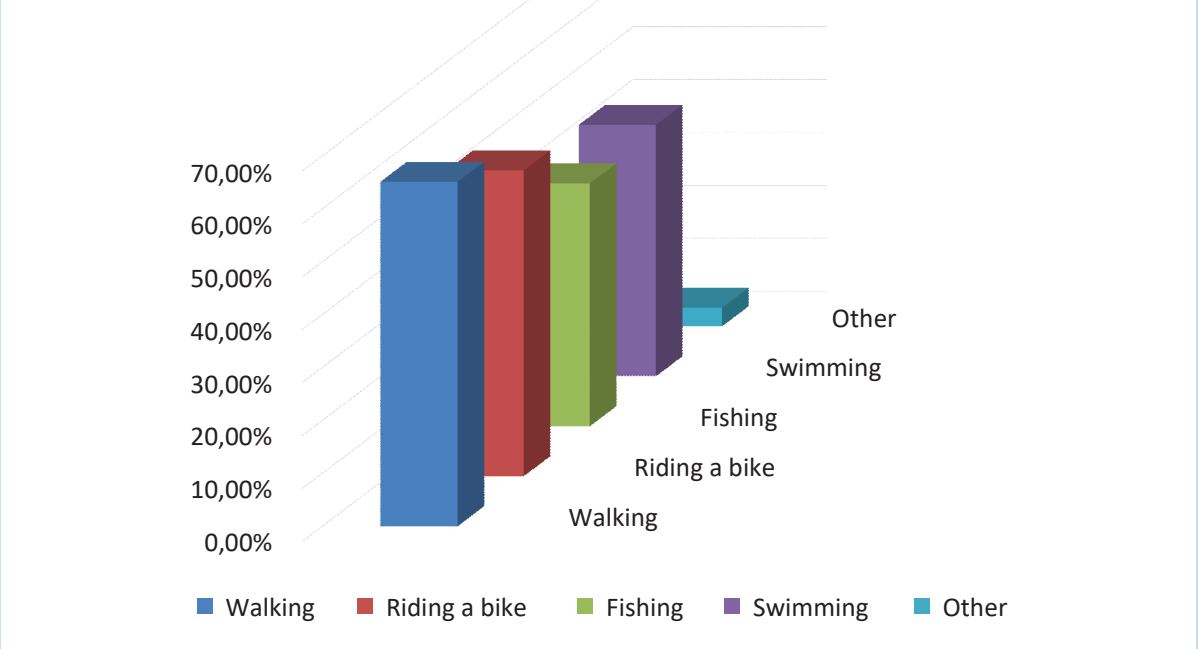


Figure 1. Activities in the coastal area

The results show that the inhabitants mostly use the coastal area for recreational purposes and for spending their free time there. The most prevalent activity is walking (65.1%), followed by riding a bike (57.8%). The activities connected to the sea, such as swimming (47.5%) and fishing (45.9%), are also highly represented. Therefore, it can be concluded that the coastal area in Zadar County has multiple purposes. Apart from its recreational purposes, it also serves as a setting for social and traditional activities related to the sea.

The next question referred to the general condition of the coastal area in the respondent's place of residence. The results show that most of the respondents have a negative perception of the condition of the coastal area. Out of a total of 545 respondents, 59.8% assess the condition of the coastal area as bad, while 40.2% assess it as good. According to the results and the local population's prevailing perception, the coastal area is not in a satisfactory condition.

As the greatest problems of the coastal area, the respondents specify tourism pressure (63.3%), pollution of the sea and beaches (52.3%), and degradation of natural habitats (51%). According to them, significant challenges/problems are excessive urbanisation (45.1%) and the lack of well-maintained public areas (41.8%). According to Zadar County inhabitants, the greatest problems of the coastal area are tourism pressure, excessive urbanisation, and environmental degradation.

The perception of the local population regarding the condition, pressure, and coastal area management in their place of residence was also assessed (**Table 1**).

The following indicators are shown in the table: N (number of responses), N/A (number of unanswered questions), M (arithmetic mean), SD (standard deviation), and minimum and maximum values of the Likert scale (from 1 to 5).

The respondents expressed the highest level of agreement with the statement that the coastal area is overcrowded during the summer months (M = 4.19), followed by statements on the excessive urbanisation (M = 4.01; SD = 1.13) and the worsened sea quality (M = 4.05; SD = 1.07). Promenade maintenance (M = 3.82) and maintenance of beaches (M = 3.89) were also recognised as problems, however, with a slightly lower level of agreement. The least pronounced attitude was observed in relation to the effects of climate change on the coast, which may indicate a weaker connection between climate change and the respondents' local experience.

Table 1. Statements regarding attitudes towards the condition of the coastal environment - descriptive data

	N	N/A	M	Md	SD	Min	Max
Seaside promenades in my place of residence are not well maintained.	545	0	3.82	4	1.16	1	5
Beaches in my place of residence are not well maintained.	545	0	3.89	4	1.12	1	5
In my place of residence, there is an excessive or uncontrolled urbanisation of the coastal area.	545	0	4.01	4	1.13	1	5
The coastal area in my place of residence is overcrowded during the summer months.	545	0	4.19	5	1.03	1	5
Sea quality in my place of residence has worsened recently.	545	0	4.05	4	1.07	1	5
Climate change has a noticeable impact on the coast in my place of residence.	545	0	3.79	4	1.18	1	5

N – Number of respondents; N/A – Missing data or not answered; M – Arithmetic mean; Md – Median; SD – Standard deviation

Local population recognises significant pressures on coastal areas, particularly tourism pressures, urbanisation, and changes in environmental quality. The respondents consider the coast a valuable, yet more and more vulnerable and stressed area that needs sustainable management and efficient protection.

The next question referred to the respondents' level of awareness of plans and measures for the coastal area management (**Table 2**).

Table 2. Frequency table of the level of awareness and measures for coastal area management

	N	% of the total
Extremely well informed	16	2.9 %
Very well informed	27	5.0 %
Well informed	66	12.1 %
Moderately informed	104	19.1 %
Poorly informed	145	26.6 %
Not informed at all	180	33.0 %
Not interested	7	1.3 %

The results suggest a very low level of awareness of the plans and measures for coastal area management. The majority of the respondents stated that they were not informed at all (33.0%) or were poorly informed (26.6%), which means that almost 60% of the respondents have a very limited knowledge of this matter. Less than a fifth of the respondents are well, very well, or extremely well informed, whereas only a small proportion of them (1.3%) stated that they were not interested in the matter. The results suggest a need for better information availability and better involvement of the public in the process of managing coastal areas.

The answers to the question *Have you ever participated in a public consultation or a debate?* suggest a very limited participation of the local population in public consultations or debates about coastal area management. The results emphasise the need for more transparent communication, better access to information, and greater participation of the local population in coastal planning and management processes.

The assessment of the respondents' attitudes towards measures for the protection of coastal areas is presented in **Table 3**.

Table 3. Respondents' attitudes towards measures for the protection of coastal areas

	N	N/A	M	Md	SD	Min	Max
Stricter urbanisation restrictions of a coastal area are needed.	545	0	4.01	4	1.16	1	5
Regulation of anchoring and navigation is needed for the protection of marine vegetation.	545	0	4.13	5	1.11	1	5
An increase in the number of protected coastal and marine areas is necessary.	545	0	4.18	5	1.06	1	5
An increase in the number of apartments and tourist accommodation along the coast should be limited.	545	0	4.19	5	1.08	1	5
Sustainable coast management is more important than short-term economic benefits.	545	0	4.23	5	1.05	1	5
The local community should have more influence on the decision-making regarding the coast.	545	0	4.17	5	1.06	1	5
Vehicle access to the coast (e.g., to the beaches or promenades) should be limited.	545	0	4.18	5	1.09	1	5

The descriptive analysis shows that the respondents expressed a high level of support for the proposed measures to protect the coastal area. The highest level of agreement was recorded for coastal area sustainable management with regard to its short-term economic benefits (M = 4.23; SD = 1.05), an increase in the number of protected areas (M = 4.18; SD = 1.06), and the restriction of tourism development along the coast (M = 4.19; SD = 1.08). The respondents also supported the regulation of anchorages and navigation, restriction of vehicle access, and greater involvement of the local community in the decision-making. The lowest level of agreement was recorded for the question of urbanisation along the coast (M = 4.01; SD = 1.16). The results suggest a high level of awareness among respondents for sustainable management and protection of the coastal area.

5 CONCLUSION

The research results confirm that coastal areas are areas of great economic, social, and ecological value that are exposed to growing urbanisation, tourism pressures, and climate change. Furthermore, they also indicate the need for sustainable coastal area management to protect natural resources and long-term balance between development and environmental protection.

The research conducted among the local population of Zadar County revealed that the coastal area is used intensively for recreational and other everyday purposes, which confirms its importance for the quality of life of the local community. According to the majority of the respondents, the condition of the coastal area is not satisfactory, with the greatest challenges being excessive urbanisation, tourism pressures, and pollution of the sea and coast. The results also indicate a low level of awareness and involvement of the local people in the processes of coastal area management, despite their valuable knowledge of the area they live in and its development needs.

The majority of respondents support coast protection measures, including stricter urbanisation control, protection of natural resources, and pollution reduction, which confirms their awareness of the need to align economic growth with environmental protection. Therefore, coastal area management should be guided by the principle of good stewardship, while protecting the public interests and promoting the active participation of the local community in decision-making processes. Long-term preservation of the coastal area requires finding a balance between economic growth, protection of the environment, and the welfare of the local community to ensure the sustainability of coastal areas for future generations.

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III. Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems

Port-City Relationships in the Context of Sustainable Development

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ABSTRACT

Port-city relationships have changed significantly over recent decades as a result of historical, institutional, economic, social, and environmental factors. This paper analyses contemporary scientific literature to identify common patterns, key challenges, and dominant development trends in port-city relationships. The findings indicate a shift from traditional models of spatial and functional separation towards renewed port-city integration, driven by green technologies, digitalisation, institutional reforms, growing social awareness, and enhanced stakeholder engagement. Studies of major port cities highlight the evolving role of ports as platforms for regional coordination and innovation, while examples from emerging regions demonstrate the potential negative consequences of port development in the absence of effective governance, environmental protection, and local community involvement. The analysis shows that modern ports are increasingly transforming from primarily logistics-oriented systems into complex and multifunctional urban and regional hubs, where balancing economic efficiency, environmental sustainability, and social interests is essential for sustainable port-city development.

Keywords: port-city relationships; port-city integration; sustainable port development; green transformation

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Historically, ports and cities developed as closely interconnected systems, with maritime trade, storage, administration, and residential activities concentrated within the same urban spaces (Hein, 2021). Industrialisation and containerisation gradually shifted port activities towards peripheral areas, driven by the need for deeper waters, larger logistics areas, and specialised infrastructure (Russo & Musolino, 2023; Vroomans et al., 2022). Today, the traditional image of a port as a confined industrial area has evolved towards the "port cityscape", representing a network of port-related spaces and activities extending beyond physical port boundaries (Hein, 2021). At the same time, cooperative, sustainable, and digital port models indicate a new phase of port-city reintegration, where economic and logistics performance must increasingly be combined with urban liveability, community interests, and environmental protection (Roberts et al., 2021a; Wang et al., 2025).

The objective of this literature review is to analyse current academic research on port-city interactions and identify the main trends shaping their future development. Ports remain critical nodes in global supply chains and important drivers of regional economies, while also generating socio-economic, spatial, and environmental pressures in urban areas. With maritime transport accounting for nearly 80% of global trade by volume, ports face increasing pressure to efficiently handle cargo flows while responding to local community expectations (Ogara et al., 2023; Santos & Pereira, 2021). Sustainable port-city development therefore requires the integration of operational efficiency, urban liveability, and environmental protection.

To address the study objective, three research questions were defined. The first research question (RQ1) examines the main methodological and thematic trends in contemporary port-city relationship research, identifying dominant analytical approaches, research topics, and emerging directions in the literature. The second research question (RQ2) investigates how physical-spatial, infrastructural, economic, management-social, and environmental dimensions interact in shaping modern port-city relationships, with particular attention to the interdependencies and conflicts that arise between these thematic areas. The third research question (RQ3) explores the key challenges and future development pathways for sustainable port-city relationships, focusing on issues such as governance, social acceptance, environmental sustainability, and technological innovation.

2 METHODOLOGY AND LITERATURE REVIEW

This paper analyses recent scientific literature on port-city relationships (PCR), providing an overview of the historical development of PCR, examining current trends and challenges, and identifying potential directions for future research and development.

2.1 Methodology

The scientific literature was assessed using selected principles of the PRISMA 2020 guidelines (Page et al., 2021) to ensure the consistency of literature identification, however the guidelines were not followed fully. Articles published between 2020 and 2025 were collected from ScienceDirect, and additional sources identified through Microsoft Copilot using the keywords "Port-city relationship(s)", "Port city relationship(s)", "Port-city development", and "Port city development". **Figure 1** shows the paper search and screening process, resulting in 29 papers being selected for the analysis.

A total of 29 articles were selected for the thematic analysis presented in **Figure 2**.

Additional methodological references were used to support the review procedure and thematic classification. Based on the classification proposed by Zarei et al. (2024), the papers were organised into five thematic groups: Physical-Spatial, Infrastructure-Support, Economic, Management-Social, and Environmental.

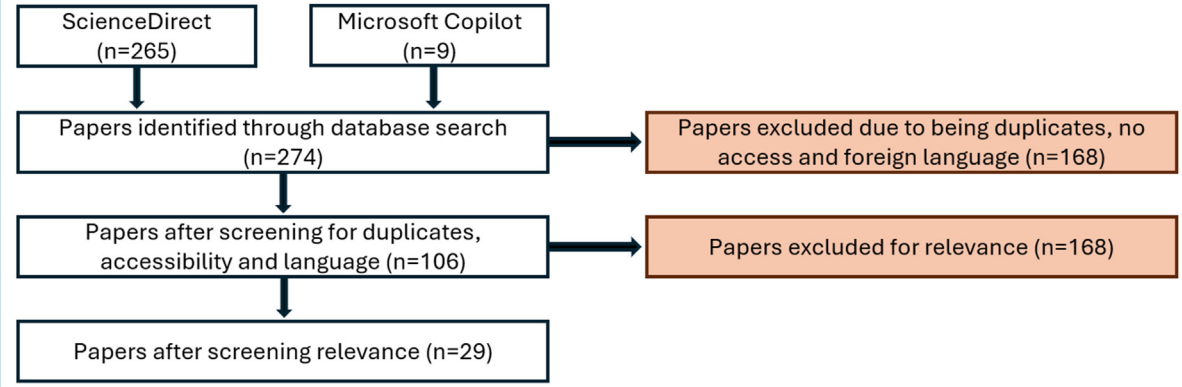


Figure 1. Diagram of systematic literature selection process

Source: Made by authors

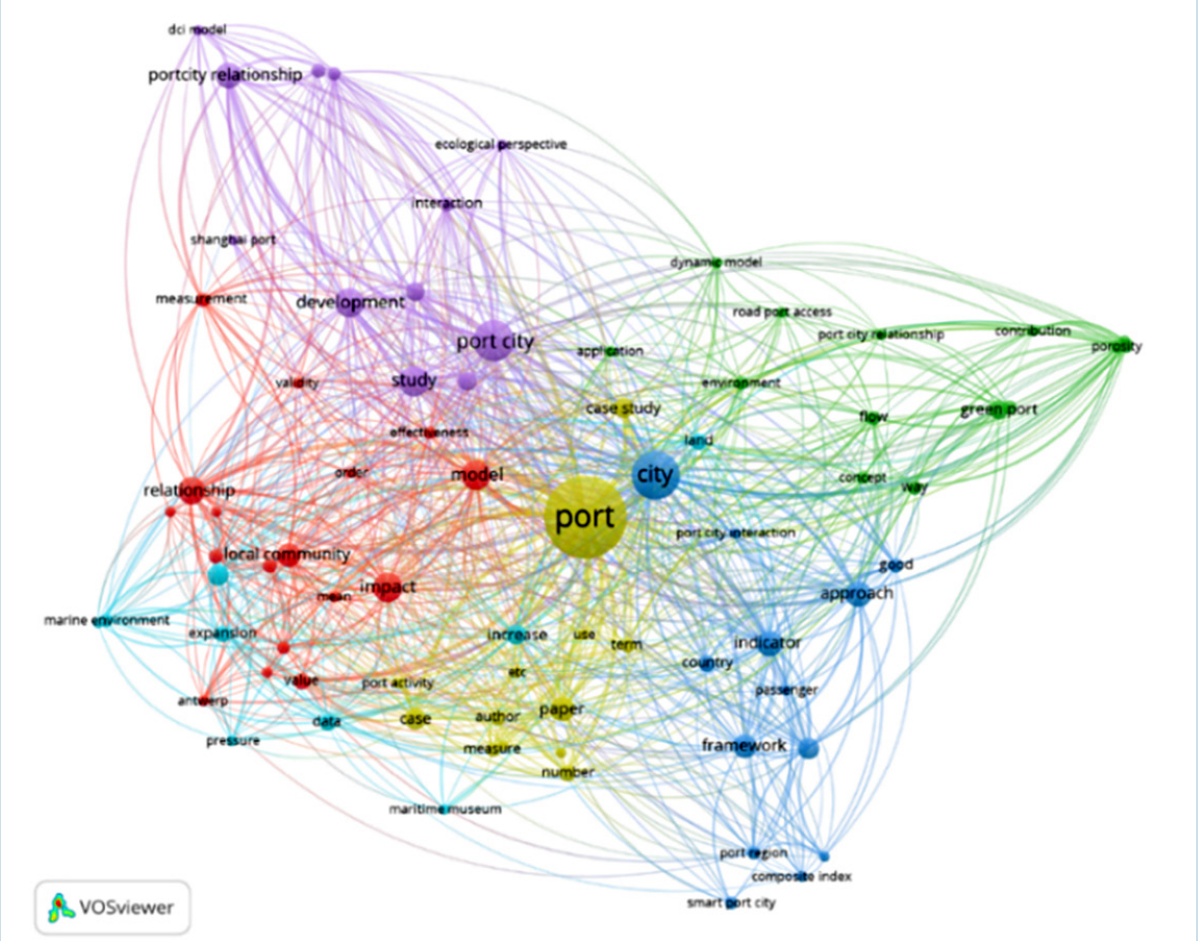


Figure 2. Visualisation of most frequently occurring words in selected literature, and their connections

Source: Authors elaboration using VOSviewer software, 2026

The selected studies apply both quantitative and qualitative approaches and demonstrate a shift from the traditional focus on port operations and economic performance towards sustainability, governance, coexistence, and social integration. While quantitative models and simulations remain important (Moeremans & Dooms, 2025; Santos & Pereira, 2021; Torrisi et al., 2025; Wang et al., 2025), mixed-methods

and qualitative approaches are increasingly used to explore aspects such as community trust and shared values (Hein, 2021; Ogara et al., 2025; Tsvetkova et al., 2025; Vroomans et al., 2022).

Geographically, research is mainly concentrated in Europe and China, including major port-city hubs (Ding et al., 2025; Guo et al., 2020; Wang et al., 2025; Zanne & Twrdy, 2023). Chinese research particularly addresses Port-City (PC) and Port-Industry-City (PIC) integration and regional development (L. Yu et al., 2020; T. Yu et al., 2025; Zhang et al., 2024; Zhao et al., 2024). However, existing sustainability frameworks show a bias towards the Global North, while emerging studies increasingly address specific challenges in developing countries (Fattah et al., 2022; Ogara et al., 2023, 2025).

Management-Social issues represent the most prominent thematic group, highlighting social acceptance, governance, and stakeholder engagement (Altınpınar, 2025; Felício et al., 2023; Moeremans & Dooms, 2021). Infrastructure-Support and Economic themes mainly address congestion, operational efficiency, infrastructure, and regional economic effects, while Environmental and Physical-Spatial dimensions are increasingly integrated through sustainable spatial development and green technologies.

3 THEMATIC ANALYSIS OF PORT-CITY RELATIONSHIPS

The selected literature is analysed through five dimensions based on Zarei et al. (2024) and the bibliometric clustering presented in **Figure 1**: Physical-Spatial, Infrastructure-Support, Economic, Management-Social, and Environmental.

3.1 Physical-Spatial

Historically, port-city relationships evolved from close spatial integration towards increasing separation. Industrialisation and containerisation transformed ports into specialised logistics and industrial areas, while former port areas were increasingly redeveloped as urban waterfronts. More recently, mutual dependencies have encouraged renewed interaction, reflected in concepts such as the butterfly model and the broader "port cityscape", where the port-city interface is increasingly understood as a dynamic threshold where maritime and urban functions overlap (Hein, 2021; Jansen & Hein, 2023; Vroomans et al., 2022).

Spatial separation has largely been driven by increasing ship sizes and requirements for deeper waters, larger terminals, and improved hinterland connections. It has also been reinforced by environmental and social concerns related to traffic, noise, and pollution (Moeremans & Dooms, 2021; L. Yu et al., 2020). However, excessive separation can increase transport distances and logistics costs, while poorly planned connecting infrastructure can generate congestion, pollution, and negative community perceptions (L. Yu et al., 2020; Moeremans & Dooms, 2025; Zanne et al., 2021). Port gates and access infrastructure are connecting nodes between ports and cities. Their location and design strongly influence traffic efficiency, urban impacts, and overall port-city development, with poorly optimised access points generating significant external costs and reducing the vitality of the wider port-city system (Zanne et al., 2021; Zanne & Twrdy, 2023). Contemporary development therefore requires a balance between the spatial requirements of port operations and functional integration with the urban environment.

3.2 Infrastructure-Support

Infrastructure is central to port-city interactions. Effective port gate planning and digital technologies can reduce urban congestion and improve traffic flows, while "soft measures", such as truck appointment systems (TAS) and vehicle booking systems (VBS), can reduce waiting times and emissions, while port gate location and support infrastructure such as dedicated motorway connections can significantly improve traffic distribution and reduce conflicts between port and urban functions (Santos & Pereira, 2021; Zanne et al., 2021; Zanne & Twrdy, 2023).

Recent studies apply traffic simulation and graph theory to assess port impacts on urban transport networks and identify critical nodes and vulnerabilities. Increasing heavy vehicle traffic can significantly increase travel times and reduce network efficiency where infrastructure is inadequate. (Torrisi et al., 2025; Ziemska-Osuch & Guze, 2023). Port-related traffic also generates external costs through congestion, emissions, fuel consumption, infrastructure deterioration, and impacts on quality of life and public health, which disproportionately affect lower income population (Fattah et al., 2022; Zanne & Twrdy, 2023). Hinterland connectivity is therefore important for port-city resilience. Shifting freight from road to rail and connecting ports with dry ports and inland terminals can reduce pressure on the urban interface while improving supply chain performance (Guo et al., 2020; Momirski, 2021; Zanne & Twrdy, 2023). Overall, research indicates a shift from infrastructure expansion towards integrated solutions combining physical infrastructure, digitalisation, operational optimisation, and modal shift.

3.3 Economic

Modern port-city relationships increasingly involve interaction between the port, industry, and city. Despite their interdependence, coordination may be limited by mismatches between industrial development and logistics capacity. Economic synergy increases when ports develop from transport nodes into catalysts of industrial diversification and regional development (Guo et al., 2020; Wang et al., 2025; T. Yu et al., 2025; Huang et al., 2025).

The relationship between port traffic and urban economy is bidirectional. Port activities generate direct, indirect, and induced effects on regional added value and employment, although these effects may occur with a time lag (Russo & Musolino, 2023; Huang et al., 2025). Economic resilience also depends on industrial diversity, as port cities highly specialised in maritime activities are more vulnerable to market fluctuations (Vroomans et al., 2022). Complementary industries, knowledge exchange, skilled labour, and innovation networks can therefore strengthen competitiveness (Jansen & Hein, 2023).

Regional development strategies and investments in transport and logistics can generate spillover effects in neighbouring regions, although excessive concentration may reinforce territorial inequalities (Wang et al., 2025; Zhang et al., 2024; Zhao et al., 2024). Dry ports and intermodal terminals can support wider regional integration (Ding et al., 2025; L. Yu et al., 2020). Industrial diversification and stronger integration with local supply chains are therefore important for more resilient port-city economies (Vroomans et al., 2022; Wang et al., 2025).

3.4 Management-Social

Port-city resilience depends strongly on governance, institutional capacity, and leadership (Momirski, 2021). Recent policies favour coordinated governance models promoting PIC integration, although effective coordination remains challenging (Kong & Liu, 2021; T. Yu et al., 2025; Wang et al., 2025). Port-city relationships are also shaped by human, cultural, social, and creative capital, shared values, local culture, and historical context (Jansen & Hein, 2023; Vroomans et al., 2022).

The “social license to operate” has become an important factor in sustainable port development, with procedural fairness, transparency, and trust influencing community acceptance (Felício et al., 2023; Moeremans & Dooms, 2021, 2025). Ports increasingly invest in public engagement, educational initiatives, and waterfront accessibility to strengthen community relationships (Felício et al., 2023; Roberts et al., 2021b). However, community perceptions remain insufficiently monitored, particularly in developing countries, highlighting the need for more context-sensitive approaches (Fattah et al., 2022; Ogara et al., 2025).

Digitalisation and smart port-city concepts provide further opportunities for improving coexistence through real-time data sharing and more effective management of transport and environmental impacts with systems of varying complexity (from TAS, VBS and vehicle emission monitoring to digital

twins, smart traffic networks, terminal automation and port management systems). Their success, however, depends on stakeholder collaboration and the reduction of institutional barriers (Santos & Pereira, 2021; Tsvetkova et al., 2025).

3.5 Environmental

Port expansion can affect coastal ecosystems through habitat loss and environmental degradation, with consequences for both ecological resilience and local communities (Jansen & Hein, 2023; Ogara et al., 2025). At the same time, international climate policies increasingly position ports as actors in the blue and green economy, requiring them to evolve from traditional logistics hubs towards green energy integrators (Kong & Liu, 2021; Wang et al., 2025).

Green transition measures include onshore power supply, electrification, alternative fuels, renewable energy, and digital environmental monitoring, which can reduce emissions and improve environmental performance (Santos & Pereira, 2021; Tsvetkova et al., 2025; Twrdy et al., 2025; Wang et al., 2025; Zanne et al., 2021). Literature increasingly evaluates green transition performance through models that treat emissions as undesirable outputs that should be minimised while maintaining economic productivity (Kong & Liu, 2021; Wang et al., 2025). Digital technologies are enabling detailed monitoring of environmental impacts and optimising operational procedures to improve energy efficiency and reduce pollution (Santos & Pereira, 2021; Tsvetkova et al., 2025).

Environmental performance is also closely linked to local acceptance. Transparency regarding pollution and investment in green initiatives can strengthen community trust (Felício et al., 2023). Since environmental costs are often concentrated locally while economic benefits extend across wider regions, proactive environmental management is essential for sustainable port-city relationships (Moeremans & Dooms, 2025).

4 DISCUSSION AND CONCLUSION

The literature reveals a clear shift from viewing ports as separate logistics facilities towards a broader “port cityscape”, where port activities are increasingly integrated with the spatial, economic, social, and environmental dimensions of urban development. Port performance is therefore no longer evaluated only through traditional indicators such as throughput and economic contribution, but increasingly through sustainability, resilience, social acceptance, and the ability to manage negative externalities.

Regarding methodological and thematic trends (RQ1), quantitative methods, including economic models, simulations, and system-based approaches, remain important in contemporary port-city research. However, mixed-methods and qualitative approaches are gaining importance, particularly for analysing governance, stakeholder relations, community trust, and other values that cannot easily be captured through quantitative indicators. Most research is geographically concentrated in Europe and China, while studies from developing regions remain limited, highlighting the limitations of applying frameworks developed for mature port systems to different socio-economic, infrastructural, and environmental contexts.

The analysis demonstrates that the five identified dimensions: Physical-Spatial, Infrastructure-Support, Economic, Management-Social, and Environmental, are strongly interconnected (RQ2). Spatial separation can improve port operational capacity but may increase transport distances and infrastructure requirements. Economic growth generated by ports can support regional development while simultaneously creating local congestion and environmental pressures. Infrastructure and digitalisation can reduce some of these externalities, but their effectiveness depends on governance and stakeholder coordination. Social acceptance increasingly connects these dimensions, highlighting the central challenge of balancing global demands for efficient cargo flows with local expectations for environmental quality and quality of life.

Regarding key challenges and future development directions (RQ3), sustainable port-city development will increasingly depend on integrated governance, green technologies, digital solutions, sustainable hinterland connections, and stronger stakeholder participation. Ports and cities cannot plan their development independently; infrastructure, land use, environmental measures, and economic strategies need to be coordinated across the wider port-city region. Particular attention should also be given to context-sensitive assessment frameworks and the integration of social and environmental indicators into port performance evaluation.

Several limitations are identified in the review, which can be interpreted as research gaps and used in future research. Existing studies predominantly focus on large hub ports, leaving small and medium-sized ports comparatively understudied. Many quantitative models rely on historical data and may have limited ability to capture rapid technological, geopolitical, and socio-economic changes. Social indicators, including the "social license to operate", also remain difficult to standardise and compare across different port-city contexts.

Future research should therefore expand geographical, port-type and port-size coverage, with a focus on smaller ports, beyond solely container terminals in developed countries, develop more dynamic and comparable assessment frameworks, and further investigate interactions between the five dimensions identified in this review.

The findings provide relevant implications for port managers, urban planners, and policymakers. Sustainable port-city development requires coordinated planning that combines logistics efficiency with environmental and social objectives, supported by transparent governance, stakeholder cooperation, green technologies, digitalisation, and integrated regional logistics networks.

In conclusion, port cities represent systems in transition, where the traditional relationship between port and city is being redefined through a search for greater integration and symbiosis. Throughput and economic growth alone are increasingly insufficient measures of success when achieved at the expense of natural and social capital. Sustainable port-city relationships therefore depend on integrating economic needs with environmental constraints and social expectations. Achieving this balance will be essential for creating resilient, competitive, and liveable port cities.

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III. Decarbonisation, Climate Resilience and Sustainable Maritime and Coastal Systems

Pursuing Standardization: Identifying Operational Criteria for Effective Beach Safety Flag Management

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ABSTRACT

Drowning has been highlighted as one of the leading causes of unintentional injury death worldwide despite favourable trends in drowning mortality and continuous efforts to increase public awareness. Beach safety flags are an essential proactive means of communicating bathing conditions and protecting beach users from potential hazards. Although the International Organization for Standardisation (ISO) and the International Life Saving Federation (ILS) have established standardised beach safety flag systems, many inconsistencies remain in their interpretation, operational implementation, and utilisation due to differences in national regulations. Also, the current body of literature provides limited insights into designing a relevant framework with identified and selected criteria for the proper deployment of beach safety flags according to on-site conditions. To address this research gap, this study proposes an operational framework for effective beach safety flag management, based on the identification and analysis of the operational criteria to be considered in deploying general and coastal flags along beaches. The purpose of this study is to enhance the current observational criteria of lifeguard services with a predefined set of parameters, reducing subjectivity in the decision-making process through a standardised approach. To achieve the research objectives, the study considers a systematic review of relevant scientific literature, the regulatory framework, and industry best practices. The findings are integrated into an operational framework of individual criteria, based on current knowledge, operational safety principles, meteorological conditions, and expert judgement. The proposed framework establishes a set of objectively measurable, operationally relevant, and internationally recognised criteria for the deployment of general and coastal beach safety flags. The operational framework enables the deployment of safety flags according to predefined criteria while remaining adaptable to local environmental conditions. Additionally, the outputs of this research contribute to reducing the current subjectivity in beach safety flag deployment and support the standardisation of operational decision-making. Development of a systematic and credible safety management framework based on objectively measurable criteria has the potential to improve beach safety flag management, enhance consistency in operational practice, and strengthen bathing safety through evidence-based decision-making.

Keywords: beach safety flags; drowning prevention; beach management; decision-making framework

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1 INTRODUCTION

Drowning has been highlighted as one of the leading causes of unintentional injury death worldwide, and has been responsible for about 236,000 lives each year (UN, 2026). Despite recording a 4% decrease in 2022 by drowning and submersion in the European Union (Eurostat, 2025), applying effective preventive measures to evade accidents and increase care of bathers remains a priority. The favourable trends, considering the decrease in drowning mortality over the years, and the preventable nature of individual accidental drowning, call for a rise in public awareness and further development of global and understandable tools to increase safety. Beaches, predominately perceived with leisure and recreation, also pose numerous potential hazards associated with tidal movements, undercurrents, riptides, dangerous marine life, and boating accidents, so the health and safety status, especially the perception of the risk and adoption of precautionary behaviour to risk mitigation, is crucial for safeguarding visitors (Ritchie et al., 2025). Among prescribed safety management measures, proper signage as a proactive mechanism for the protection and awareness of beachgoers from the potential risks on beaches is essential for the efficient communication concerning safety conditions for bathing (Basterretxea-Iribar et al., 2022). Therefore, to standardise the concept of safety flag recognition and interpretation, particularly in terms of clarity and continuity among countries, the International Standardization Organization (ISO) has developed a standardised concept of six beach safety flags in 2008 (ISO, 2007). Following the ISO standard, the International Life Saving Federation has further expanded the beach safety flag system to nine, including six ISO flags in 2010 (International Life Saving Federation, 2010). Generally, national lifeguarding organizations affiliated with ILS use ISO/ILS flags in the vast majority of countries globally, especially in Europe (ILS, 2022). Despite the visible progression in the tendency to reach the uniformity of the system, many inconsistencies occur, primarily within the interpretation and meaning between the two official safety systems, followed by diverse utilisation of the flags due to the differentiation of the national regulations (Roefs et al., 2023). The basic purpose of the standardisation process was to define a simplistic mode of transferring the information to bathers in the form of two colours with a simple, understandable design (Roefs et al., 2025). The differentiation between general and coastal flags is crucial for effective safety management on beaches, as the general flags are most commonly placed at the entrance and indicate the safe conditions of the entire beach area, while on opposite coastal flags are used for spatial distribution of specific activities, but also for defining the danger zone (Basterretxea-Iribar et al., 2022). The issue arises due to the application of alternative flags unique to the individual scale system, which can be national, regional, or even based only on a specific beach outside the scope of ISO/ISL standard. Besides introducing a separate beach safety flag system, the danger arises as a consequence of deviation of prescribed meaning of the standardised flagging system, which can significantly influence the effectiveness of the safety management concept, having its foundation in the familiarity of beach warning flags among bathers (Roefs et al., 2023). Several studies on beach safety flags show that most fatalities occur outside the designated area, primarily defined with coastal flags and indicating safe bathing (Sherker et al., 2010), thus outside the red and yellow safety flags (Williamson et al., 2012). In general terms, the main objectives of beach safety flags can be summarised in three main categories, protection of bathers due to the presence of several safety risks, proper information on safety conditions for bathing, and spatial distribution of beach bathing zones for different activities. It is also worth indicating the presence of safety flags on patrolled beaches only, thus where a presence of lifeguarding service is secured (Basterretxea-Iribar et al., 2022). This often relates to those beaches managed by a specific company, usually under the concession, or by various other management models specific to the individual region (city, municipality, county or similar). For instance, the Red Cross has been nominated as a principal body for the prevention of drowning and water-related accidents in Croatia, based on public authority, thus the Croatian Red Cross Act (Croatian Red Cross, 2026). Despite the tendency to increase the level of awareness and knowledge on the potential beach hazards in terms of public campaigns, signage and brochures, education and

training, social media and public service announcements, along with all other available tools to increase familiarisation, several studies indicate weak effectiveness of beach signage (Matthews et al., 2014; Brannstrom et al., 2015). This is the reason behind the growing interest in beachgoer's familiarity and perception of beach safety flags and behavioural patterns among specific focus groups, which can be highlighted as the main research interest among scholars within the existing body of literature. Despite the adoption of standardisation of beach safety flag management and the growing interest of scholars in producing high-level research on numerous beach signage issues and challenges, the current state of literature offers limited insights in designing a relevant framework with defined criteria for the proper deployment of the safety flags on beaches according to the on-site conditions.

To address the emphasised research gap, this study proposes an operational framework for effective beach safety flag management, based on the identification and analysis of the operational criteria to be considered in deploying general and coastal flags along beaches. The purpose of this study is to enhance the current observational criteria of lifeguard service in charge of beach safety with a predefined set of parameters. This is done to reduce and convert the current subjectivity in the decision process with standardised decision-making, and prevent individuals' assessment of local risk and judgement of environmental conditions.

2 REGULATORY OVERVIEW, INDUSTRY STANDARDS AND INTERNATIONAL PRACTICE ON BEACH SAFETY FLAG MANAGEMENT SYSTEM

The WHO recognizes drowning as a significant public health concern and calls for awareness-raising in drowning prevention by prescribing a set of evidence-based solutions for efficient drowning prevention (WHO, 2024). In contrast, the international practice standardises the meaning of beach safety flags through the ISO and ILS voluntary standardisation system, which represents the sole and partially adopted guiding system recognised globally. This indicates the lack of international legally binding regulation governing beach safety flags, and selective implementation of the standards and guidance within the national regulation. Thus, national legislation prevails in setting the regulations on beach safety flag management, usually through professional lifesaving organizations. There is high differentiation in the regulatory approach of countries in governing the safety management on beaches regarding the flag system and the allocation of responsibilities. In Croatia, the Red Cross, along with other similar activities, manages the water lifesaving and coastal environmental protection service based on internationally accepted standards, and conducts risk assessment on bathing areas (Croatian Parliament, 2020). However, this applies only to arranged bathing areas, where the Regulation on safety at arranged bathing areas (Ministry of Science, Education and Youth, 2005) addresses the obligation to display the appropriate beach safety flag during the swimming season. Also, the Regulation, in addition to providing the technical setting of the flag design, position, and the inclusion of the beach safety flag meaning within the beach safety rules, also highlights the cases of beach safety violations, including the events of increased waves, increased water pollution, stronger winds, increased water turbidity, stronger water flow of more than 0.3 m/s, and other similar circumstances. Also, the Croatian Red Cross is certified for the provision of the risk assessment process on beaches based on the prescribed rules on conducting risk assessments at bathing sites (Croatian Red Cross, 2023). On the other hand, in Australia, which possesses one of the world's most developed beach safety management systems, similar conditions occur. This is manifested in the absence of universal legislation related to beach safety, which is instead managed by several organizations. The primary authority that manages coastal water safety, drowning prevention and rescue is Surf Life Saving Australia, with the safety system consisting of volunteer surf lifesavers, together with the Australian Lifeguard Service (SLS, 2024). Local government lifeguards deliver the majority of Australian beach safety services, while many Australian councils directly employ lifeguards (Ausleisure, 2025).

Public safety is supported by the Australian Public Coastal Safety Guidelines, which establish best-practice recommendations, but also explicitly indicate that they do not replace state legislation or local government regulations (ILS, 2011a). Basterretxea-Iribar et al. (2022) highlight the decentralized governance framework of Spain's beach safety management, where the national government establishes the legal framework for coastal management, while Autonomous Communities and municipalities are responsible for implementing operational beach safety measures and lifeguard services. This includes appointing lifeguard services, conducting rescue operations, beach surveillance, implementing public warning systems, and beach safety flag management. The differentiation of responsibility among communities and municipalities contributes to high variation among operational procedures and beach flag systems, even between neighbouring beaches where beach safety management is undertaken by different local governments. For example, in Catalonia, Civil Protection provides operational guidance regarding beach flags (Gencat, 2026). The responsibility of beach safety management in the United Kingdom (UK) is dispersed among local authorities, HM Coastguard and the Royal National Lifeboat Institution (RNLI). Local authorities are generally responsible for beach management and public safety within their jurisdictions, while the RNLI provides professional lifeguard services on behalf of local authorities through service agreements and operates the largest beach lifeguard service in the UK (RNLI, 2025a). Operational beach safety is therefore implemented through agreements between local authorities and the RNLI rather than through a dedicated Beach Safety Act. Also, RNLI provides lifeguard services following a comprehensive beach risk assessment, according to the scientific classification of UK beaches being developed by the University of Plymouth (ILS, 2011b). Furthermore, HM Coastguard, the UK's national maritime emergency service, provides public guidance and advice services to swimmers in order to rise the beach safety (HM Coastguard, 2025). Beach warning systems in the United States are implemented by local governments, beach patrols, county authorities and lifeguard agencies, while national organizations such as the United States Lifesaving Association (USLA) provide professional guidance on flag meanings and beach safety communication (USLA, 2026). Federal agencies such as the National Weather Service (NWS) provide beach hazard forecasts, rip current risk information, and public safety warnings. However, operational flag deployment is generally handled locally by beach authorities or lifeguard services (National Weather Service, 2026). This decentralized system contributes to the high differentiation of beach warning practices between states, counties, and municipalities, based on surf conditions, currents, rip current risk, marine hazards, and local professional judgement. This analysis of international practice and industry standards highlights the absence of a single uniform legal model considering the governance of beach safety flag management. The responsibilities are generally distributed among national authorities, regional or local governments, beach concessionaires, lifeguard services, and professional lifesaving organizations. This fragmentation of the governance structure implies that the legislation lays down the general responsibilities and duties, while the practical deployment of flags is allocated to local operational procedures, professional guidance, and lifeguard judgement rather than uniform statutory criteria.

3 IDENTIFICATION AND CLASSIFICATION OF OPERATIONAL CRITERIA FOR BEACH SAFETY FLAG DEPLOYMENT AND FRAMEWORK DESIGN

Based on the defined objectives of this study, a comprehensive overview of the fundamental operational criteria considered in the process of deployment of beach safety flags on beaches has been conducted. This included the analysis of the available data indicated in the scientific literature, relevant legislation of the analysed country representatives, industry guidance, and practical operative measures. As previously emphasised, the research problem of this paper relates to the lack of clear, defined, standardised, and classified criteria for effective beach safety management, especially concerning the drowning hazard and high level of subjectivity in lifeguard decision-making. **Figure 1** illustrates the flowchart for the selection and analysis of operational criteria.

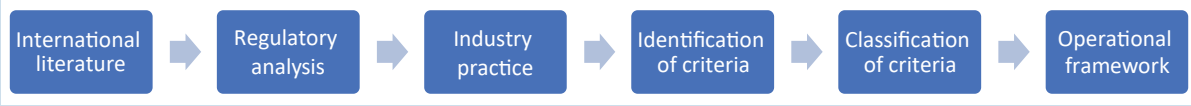


Figure 1. Flowchart of the research

The paper by Basterretxea-Iribar et al. (2022) provides a comprehensive and systematic overview of the most significant hazards to date and can be considered the most relevant and complete study that addresses beach hazards, logically organized and connected. **Figure 2** provides an illustrative overview of the identified major beach hazards.

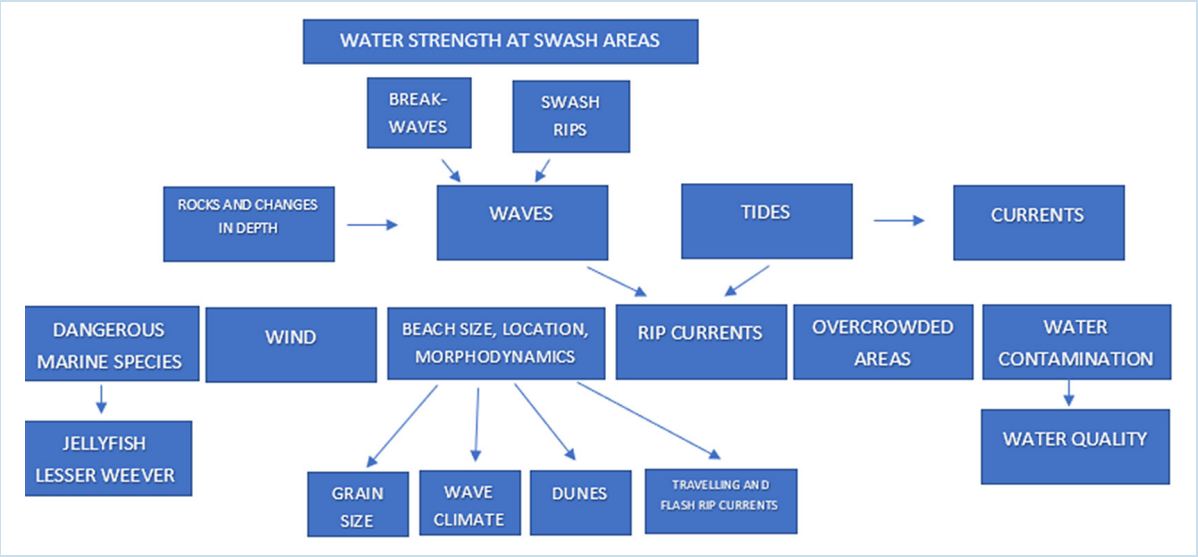


Figure 2. Main beach hazard categories and associated components according to the study of Basterretxea-Iribar et al. (2022)

Rip currents are especially highlighted in the literature as one of the most influential hazards to beachgoers on a global scale (Brander and MacMahan, 2011), and are considered crucial for beach safety management (Leatherman, 2011), since the majority of drownings are related to the lack of understanding of rip currents (Woods et al., 2022). The beach morphology, as a beach-specific element, is also identified as a hazard driver and one of the causes of the emergence and development of rip currents (Brander and Short, 2000). As previously mentioned, the Croatian Regulation emphasises waves, water contamination and quality, wind and currents as the main hazards which influence the deployment of safety flags along the beaches (Ministry of Science, Education and Youth, 2005). In the UK, HM Coastguard identifies the rise of awareness in relation to sea conditions, including currents and winds, when adopting the safety management on beaches (HM Coastguard, 2025), while RNLI further identifies rip currents, waves, tides, weather conditions, including strong winds and changes in weather conditions, as well as the hazards specific to the beach (RNLI, 2025b). An interesting fact within the Government of Catalonia (Civil Protection) guidance on the meaning of different colours among the beach flags is the clear definition of the thresholds for wave height when the yellow (waves above 1.5 m) and red (waves above 2.0 m) flags are raised (Gencat, 2017). Similarly, the NWS in the USA identifies several environmental hazards that may affect beach safety, including dangerous currents, rip currents, high surf, tsunamis, heat and lightning. Also, beach users are advised to consult local beach forecasts before entering the water and to pay particular attention to warnings regarding waves, dangerous currents and other beach hazards (NWS, 2026). Finally, the principal

operational hazards available in the literature and the analysed databases considered in Australian beach safety management include rip currents, wave conditions, surf conditions, currents, tides, weather conditions and beach morphology. Among these, rip currents are recognised as the primary coastal hazard (SLS, 2026). Although beach safety flag systems are generally standardised in terms of their meaning, the final operational decision regarding flag deployment remains dependent on continuous professional lifeguard assessment of prevailing environmental conditions and local beach hazards (Basterretxea-Iribar et al., 2022; RNLI, 2025a). Basterretxea-Iribar et al. (2022) also emphasise the objectivity in the process of changing beach flags, which contributes to a high level of subjective assessment in its deployment.

The comparative analysis of various individual literature sources showed a high level of similarity within the operational criteria considered when deploying beach safety flags across the analysed countries, despite the significant differences in regulatory frameworks, governance structures, and institutional responsibilities. Sea state, wind conditions, water currents, and professional lifeguard assessment were consistently identified, while beach morphology, water quality, dangerous marine life, and other site-specific hazards were included depending on local environmental conditions and beach characteristics. Based on the individual beach hazard and operational factors identified, this study enables grouping these criteria into five hazard categories: oceanographic (sea state, wave conditions, rip currents), meteorological (wind, weather conditions), environmental (water quality, dangerous marine species, pollution), beach-specific (morphodynamics, beach features, local hazards), and operational, which is primarily related to the lifeguard services, beach management, and surveillance. **Table 1** provides a categorisation of the main operational criteria for beach safety flag deployment based on the literature analysis.

Table 1. Categorisation of the main operational criteria for beach safety flag deployment

Operational criteria	Hazard category	Operational relevance	Source
Sea state/wave conditions	Oceanographic	Primary determinant of bathing safety	Croatia Regulation, Basterretxea-Iribar et al. (2022), RNLI, SLSA
Water currents	Oceanographic	Direct hazard to bathers	Croatia Regulation, RNLI, USLA (2026)
Rip currents	Oceanographic	Leading cause of rescues and drownings	Brander & MacMahan (2011), Leatherman (2021), Woods et al. (2022)
Wind	Meteorological	Controls wave development and sea conditions	Croatia Regulation, Basterretxea-Iribar et al. (2022), RNLI
Weather conditions	Meteorological	Dynamic environmental hazard	RNLI, SLSA, NWS
Water quality	Environmental	Public health protection	Croatia Regulation, Catalonia
Dangerous marine life	Environmental	Biological hazard	USLA (2026), Catalonia
Beach morphology	Beach-specific	Controls local hazard distribution	Brander & Short (2000), Basterretxea-Iribar et al. (2022)
Local beach hazards	Beach-specific	Site-specific operational hazards	RNLI, Basterretxea-Iribar et al. (2022)
Professional lifeguard assessment	Operational	Integrates dynamic environmental conditions into final operational decision	RNLI, SLSA, USLA (2026)

Although the comparative analysis identified a broad range of operational hazards and environmental factors, several individual operational criteria consistently emerged across the reviewed legislation, scientific literature and industry guidance. These criteria represent a framework of objectively measurable environmental variables that directly influence bathing safety and therefore should form the basis of future standardised operational decision-making regarding beach safety flag deployment (**Figure 3**). Also, along with each individual criterion selected, a proposed measurable indicator is defined. Each criterion should be associated with clearly defined operational limits derived from scientific evidence, historical observations, and expert consensus, as a threshold value (e.g., wave height) or operational trigger criteria (e.g., dangerous marine life). Such threshold values provide a transparent and reproducible basis for operational decision-making while remaining adaptable to local environmental conditions and beach characteristics. However, these measures require future validation and definition of standardised threshold values before being incorporated into operational decision-support systems.

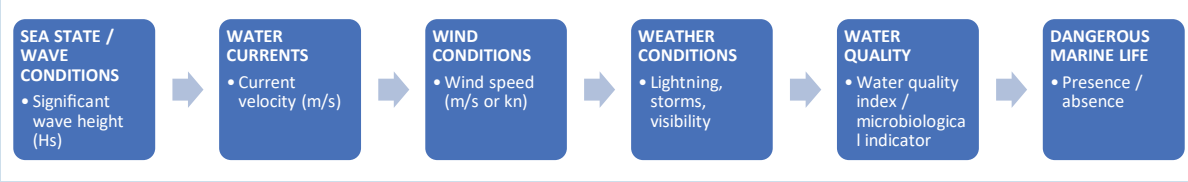


Figure 3. Operational framework of six individual criteria for effective beach safety management

4 DISCUSSION

Beach safety flag deployment has been, as a practice, managed by lifeguards as the primary decision-makers based mainly on subjective assessment of conditions occurring ex post, rather than using the framework of measurable, reliable, available, and globally acceptable operative criteria. The analysis of industry practices and national regulations revealed significant variation in the application of the ISO/ILS signage standard, with differences occurring not only between beaches within the same region but also between cities and, especially, countries. This raises concerns about the proper practical education of the beach users on the accurate meaning of the safety flags and the preventive purpose of their application as a signage tool. The same analogy can be transposed to the safety management system of beach flag deployment, which arises solely from the judgement of the relevant on-duty lifeguard, rather than based on a set of predefined standardised parameters. The literature and relevant documentation review indicated the aspect of beach safety flag interpretation, public perception, and individual coastal hazards as the primary focus of the relevant bodies in defining the signage system, rather than prescribing the operational measures for its setting. It also showed the high differentiation of individual entities among countries in defining the causes of beach hazards, as several differ concerning the specifics of the location and severity, intensity, and frequency of their origin. The results of this study are twofold and directly tackle the gaps identified within the analysis of the relevant regulation. The paper firstly addresses, identifies, and categorises the hazards according to the nature of their origin, and finally provides the operational framework of the six most influential parameters and measurable indicators. The contribution of developing the standardised protocol is evident in reducing subjective judgment and assessment in beach flag deployment and strengthening decision-making by prescribing a relevant, measurable, accessible, and standardised safety management system based on the selected fundamental operative criteria. Utilising the proposed framework should enhance transparency and credibility in beach management, as well as the safety of beachgoers, by providing objective, accurate representations of on-site conditions. Waves, currents, and wind effects were

found to be the most common causes of beach hazards among analysed countries and industry standards, while the presence of dangerous marine life, water quality, and severe weather conditions were those criteria that were associated with standardised safety flag meanings and their significant importance for beach safety, also reliable from the objective measurement and observation standpoint. Despite being selected as the main operative criteria within the proposed framework, which can be considered universally applicable, the individual beach features, typology and location, along with the overall number of visitors, should always be considered as a part of a risk assessment on the hazards and risk of bathing areas. However, identification of the main hazards and framework development should be followed by the proper definition of the threshold values, which was highlighted as the main deficiency of the current regulatory and practical environment. Review of the relevant best practices in selected countries identified only two properly defined operative thresholds among all the analysed criteria, namely the water flow of more than 0.3 m/s within Croatian regulation and wave height in Catalonia segmented for raising the yellow (waves above 1.5 m) and red (waves above 2.0 m) flags. Consequently, future research phases should include defining the thresholds of the selected criteria according to the individual specifics of each bathing area of interest, within the risk assessment report. This measurable data with defined thresholds or operational triggers should resolve the objectivity in the deployment of the appropriate beach flag according to the actual on-site conditions, and thus, analogously, the overall safety of the visitors. Despite drawing on important conclusions and providing significant contributions to the general scope of beach safety management globally, this research has several limitations. This includes a limited sample of best practices and regulatory scope analysed among countries, accompanied by the uncertain selection of operative criteria within the developed framework, as well as the absence of extensive analysis of the relevant literature, along with already emphasised undefined threshold values. Future studies should focus on eliminating these constraints.

5 CONCLUSION

This study contributes to the ongoing efforts towards the standardisation of beach safety flag management by identifying and classifying the operational criteria relevant for beach safety assessment. The findings demonstrate that, despite differences in national regulations and governance arrangements, a common framework of operational criteria can be recognised across the analysed legislation, scientific literature, and industry practice. Their systematic identification provides an evidence-based foundation for a more objective and transparent approach to beach safety flag deployment. Future research should focus on defining and validating threshold values for the identified criteria according to local environmental conditions and integrating them into operational decision-support systems while maintaining professional lifeguard judgement as the final decision-making element.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Global Supply Chain Disruptions and Import Resilience: Evidence from Croatia, 2015–2024

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ABSTRACT

This paper examines the relationship between global supply chain disruptions and logistical challenges and the import dynamics of the Republic of Croatia over the period 2015–2024, with particular emphasis on system resilience in the context of global instability. Special attention is given to the COVID-19 pandemic and geopolitical disruptions related to the war in Ukraine, which significantly affected international transport and logistics flows. The empirical analysis is based on secondary data from Eurostat and the World Trade Organization (WTO) and employs descriptive statistics and multiple linear regression. The baseline results indicate a statistically significant positive association between global trade activity and Croatia's import dynamics, while the crisis-related variables are also statistically significant in the baseline specification. However, these relationships are not confirmed in the first-difference sensitivity specification and should therefore be interpreted cautiously given the small sample and common time trends. The findings provide exploratory evidence on aggregate import dynamics and highlight the importance of considering both global trade conditions and crisis-related developments when assessing supply chain resilience. The study contributes by integrating economic and logistics perspectives and provides practical implications for supply chain management, including supplier diversification, enhanced flexibility of logistics systems, and policy design aimed at strengthening resilience in small open economies.

Keywords: supply chains; logistics; imports; global disruptions; resilience; transport systems

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1 INTRODUCTION

Globalisation and the intensification of international trade have led to the rapid development of global supply chains, which today represent a key component of modern economic systems. Companies increasingly rely on international suppliers, cost optimisation, and just-in-time procurement models, thereby improving efficiency while simultaneously increasing vulnerability to external shocks. In such an environment, the stability and resilience of supply chains have become crucial for ensuring business continuity and economic growth. Recent research has therefore increasingly emphasised supply chain resilience, risk assessment, collaboration, and supply chain reconfiguration as key responses to large-scale disruptions (Gebhardt et al., 2022).

In the context of global exchange of goods and services, logistics and transport represent essential components of supply chain functioning. The efficiency of transport systems, the availability of transport capacity, and the stability of logistics flows directly influence delivery reliability and overall operational costs. Consequently, disruptions in logistics and transport systems can have significant implications for international trade, particularly in small open economies.

In recent years, global supply chains have faced a series of major disruptions. The COVID-19 pandemic caused interruptions in production, restrictions in transport, and a decline in international trade activity. Empirical evidence indicates that pandemic-related supply chain disruptions affected production and international trade, particularly in sectors exposed to imported intermediate inputs (Xu et al., 2020; Meier & Pinto, 2024). In addition, geopolitical tensions, particularly the war in Ukraine, have led to disruptions in the supply of energy and raw materials, increased transport costs, and changes in logistics and trade flows. These developments have highlighted the need for greater flexibility, supplier diversification, and enhanced resilience of logistics systems.

The Republic of Croatia, as a small open economy, is highly dependent on imports of goods, making it particularly sensitive to changes in global supply chains and logistics flows. The structure of the Croatian economy, characterised by a high import component in industry, energy, and trade, further emphasises the importance of stable and reliable transport and supply channels. Under conditions of global disruptions, changes in the availability, cost, and dynamics of transport can have a significant impact on overall economic activity.

Despite the growing interest in supply chain resilience, empirical studies that integrate economic and logistics perspectives, particularly at the level of small open economies such as Croatia, remain relatively limited. Most existing research focuses on global or European contexts, while national-level analyses that consider the specific characteristics of transport and logistics systems are less common.

Accordingly, the aim of this paper is to analyse the relationship between global supply chain disruptions, logistical challenges, and the import dynamics of the Republic of Croatia over the period 2015–2024. Special attention is given to the associations between the pandemic and geopolitical shocks and import dynamics, using empirical methods based on secondary data.

2 BACKGROUND

Global supply chains represent the foundation of modern international trade and production, enabling firms to optimise costs and increase efficiency through the international division of labour. However, such systems simultaneously increase exposure to risks and vulnerability to external shocks, particularly in highly interconnected global economies. The growing complexity and interdependence of supply chains mean that disruptions in one part of the system can generate cascading effects across production, transport, and trade networks (Christopher, 2016).

Research on supply chain disruptions has intensified significantly following the global financial crisis, and particularly after the COVID-19 pandemic, which exposed structural weaknesses in global production and logistics networks. Studies show that sectors heavily dependent on imported intermediate goods, especially from Asia, experienced substantially larger declines in production, employment, and trade during the initial phase of the pandemic (Meier & Pinto, 2024). The pandemic caused simultaneous disruptions on both the supply and demand sides, including factory shutdowns, restrictions on labour mobility, and interruptions in transport and logistics flows. Logistics systems, including maritime, road, and air transport, faced severe challenges such as port congestion, container shortages, capacity constraints, and increased freight costs. UNCTAD (2022) reports that disruptions in maritime transport contributed to congestion, delays, higher shipping costs, and interruptions in global supply chains, highlighting the importance of resilient transport infrastructure and logistics capacity.

Systematic literature reviews confirm that the pandemic had a strong and multidimensional impact on supply chains, identifying key issues such as logistical bottlenecks, market disruptions, and the need to redefine supply chain management strategies (Younis et al., 2023). In this context, increasing attention is given to the integration of economic and logistics perspectives in analysing system resilience.

Recent research has increasingly emphasised the concept of supply chain resilience, defined as the ability of a system to absorb shocks, adapt to changing conditions, and recover quickly. Empirical findings suggest that traditional models, such as just-in-time systems, may be insufficiently robust under global crisis conditions, leading to a growing emphasis on supplier diversification, increased safety stocks, improved risk management, and the development of more flexible logistics networks (Gebhardt et al., 2022). These developments are consistent with broader policy discussions on strengthening the resilience of global supply chains and reducing vulnerabilities arising from concentrated dependencies (Crowe & Rawdanowicz, 2023).

In addition to the pandemic, geopolitical factors such as trade conflicts and the war in Ukraine have significantly affected global supply chains. The war has contributed to continued disruptions in global economic activity and trade, particularly through energy and commodity markets and increased uncertainty (World Bank, 2023). At the same time, geopolitical tensions have increased concerns about fragmentation and the restructuring of international trade relationships. The World Trade Organization (2023) highlights evidence that geopolitical tensions are already affecting trade flows and stresses the importance of international trade and cooperation for strengthening economic resilience. These developments further highlight the importance of logistics infrastructure, transport capacity, and diversified supply networks in maintaining supply chain stability.

Despite the growing literature on global supply chain disruptions and resilience, empirical evidence focusing specifically on small open economies remains comparatively limited. The Croatian case provides an opportunity to examine how global trade dynamics, domestic economic activity, and major crisis events are associated with aggregate import flows. This research gap provides the foundation for the present study, which links theoretical concepts of supply chain resilience with an empirical analysis of import flows in the context of global and logistical disruptions.

2.1 Research hypotheses

Based on the presented literature review and the identified research gap, the following hypotheses are formulated:

H1: Global supply chain disruptions and logistical challenges are significantly associated with the imports of the Republic of Croatia.

H2: Global trade dynamics are significantly associated with the value of imports of the Republic of Croatia.

H3: Individual crisis events, represented by the COVID-19 pandemic and geopolitical disruptions, are significantly associated with the value of imports of the Republic of Croatia.

3 METHODOLOGY

The empirical analysis in this study is based on the application of multiple linear regression in order to assess the relationship between global disruptions, logistical challenges, and the import dynamics of the Republic of Croatia. The selected methodological approach enables the quantification of the associations between key economic and logistics variables and allows for testing the proposed research hypotheses.

3.1 Data sources

The empirical research is based on secondary data obtained from official international statistical databases. Data on the annual value of merchandise imports of the Republic of Croatia were obtained from Eurostat (dataset tet00002), expressed in million euros. Data on Croatian gross domestic product (GDP) at market prices were obtained from Eurostat national accounts (dataset nama_10_gdp) and are expressed in current prices in million euros. Global trade activity was derived from World Trade Organization (WTO) merchandise trade statistics using annual world merchandise export and import volume fixed-base indices (2015 = 100).

The analysis covers the period from 2015 to 2024, resulting in 10 annual observations. The use of official and internationally comparable statistical sources enables a consistent analysis of the pre-crisis period and the periods marked by the COVID-19 pandemic and geopolitical disruptions.

3.2 Definition of variables

Dependent variable: Imports (IMPORT) – annual value of merchandise imports of the Republic of Croatia from all countries of the world, expressed in million euros.

Independent variables: Gross Domestic Product (GDP) – Croatia's GDP at market prices, expressed in current prices in million euros and used as a control variable for domestic economic activity; Global trade (TRADE) – a proxy for global merchandise trade activity, calculated as the arithmetic mean of the WTO world merchandise export and import volume fixed-base indices (2015 = 100).

Dummy variables: COVID – 1 for 2020–2021 and 0 otherwise; WAR – 1 for 2022–2024 and 0 otherwise. These dummy variables identify the periods associated with the COVID-19 pandemic and geopolitical disruptions related to the war in Ukraine.

3.3 Model specification

To estimate the relationship between global disruptions, logistical challenges, and imports, a multiple linear regression model is employed:

$$\mathrm{IMPORT}_t = \beta_0 + \beta_1 \mathrm{GDP}_t + \beta_2 \mathrm{TRADE}_t + \beta_3 \mathrm{COVID}_t + \beta_4 \mathrm{WAR}_t + \varepsilon_t \quad (1)$$

where IMPORT_t is the value of imports at time t, GDP_t is gross domestic product, TRADE_t is global trade activity, COVID_t and WAR_t are dummy variables representing crisis periods, and ε_t is the stochastic error term.

The model is estimated using the Ordinary Least Squares (OLS) method. Given the limited number of annual observations, the estimates are interpreted primarily as evidence of statistical associations rather than causal effects.

3.4 Methods of analysis

The analysis combines descriptive statistics (mean, trends, and variability), graphical analysis of the dynamics of imports and other variables over time, and OLS regression to estimate the relationship of the independent variables with imports. Descriptive and graphical analysis identify key trends, while regression analysis quantifies relationships between variables.

Given the small sample and the presence of pronounced trends in several variables, additional diagnostic and sensitivity checks were performed. Multicollinearity was assessed using pairwise correlations and variance inflation factors (VIF). Residual diagnostics included the Durbin–Watson and Breusch–Godfrey tests for autocorrelation, the Breusch–Pagan test for heteroskedasticity, and the Jarque–Bera test for residual normality. Augmented Dickey–Fuller (ADF) tests were used as an exploratory assessment of stationarity.

3.5 Data processing

The data were initially processed and structured using Microsoft Excel with the Data Analysis ToolPak add-in. Prior to conducting the regression analysis, the data were verified against the official statistical sources, structured into time series, and checked for consistency and completeness. The baseline OLS regression was estimated using the complete 2015–2024 dataset. Additional regression diagnostics and robustness checks were subsequently performed on the same underlying dataset using appropriate statistical procedures.

3.6 Research limitations

The analysis is based on aggregated secondary data, which may limit the possibility of more detailed sectoral analysis and the precise identification of specific logistical bottlenecks. Aggregation may also conceal heterogeneous sector-level responses, as declines in some import categories may be offset by increases in others.

A further limitation is the very small sample of 10 annual observations. With four explanatory variables and an intercept, the baseline model has only five residual degrees of freedom, limiting statistical power and requiring cautious interpretation of coefficient significance. In addition, the strong correlation between GDP and global trade and the presence of common time trends may affect the precision and interpretation of individual coefficient estimates. Stationarity tests are also of limited power with such a short annual time series.

In addition, the relatively short time period may affect the robustness of the statistical results. Furthermore, the model does not include all potential variables that may influence imports, such as specific transport costs or logistics performance indicators. Consequently, the empirical results should be interpreted as exploratory evidence of associations within the observed period rather than as definitive causal estimates**.** This represents a potential direction for future research.

4 RESULTS

This section presents a descriptive analysis of the main variables used in the study, with particular emphasis on the import dynamics of the Republic of Croatia. The analysis includes graphical representation and a basic interpretation of changes observed during the analysed period.

4.1 Descriptive analysis

During the observed period from 2015 to 2024, the value of merchandise imports of the Republic of Croatia generally increased, although temporary declines occurred in 2020 and 2023. The decline in

2020 coincided with the global disruptions caused by the COVID-19 pandemic, while imports recovered strongly in 2021 and 2022. Following a temporary decline in 2023, imports increased again in 2024. The dynamics of imports are presented in more detail in **Figure 1**.

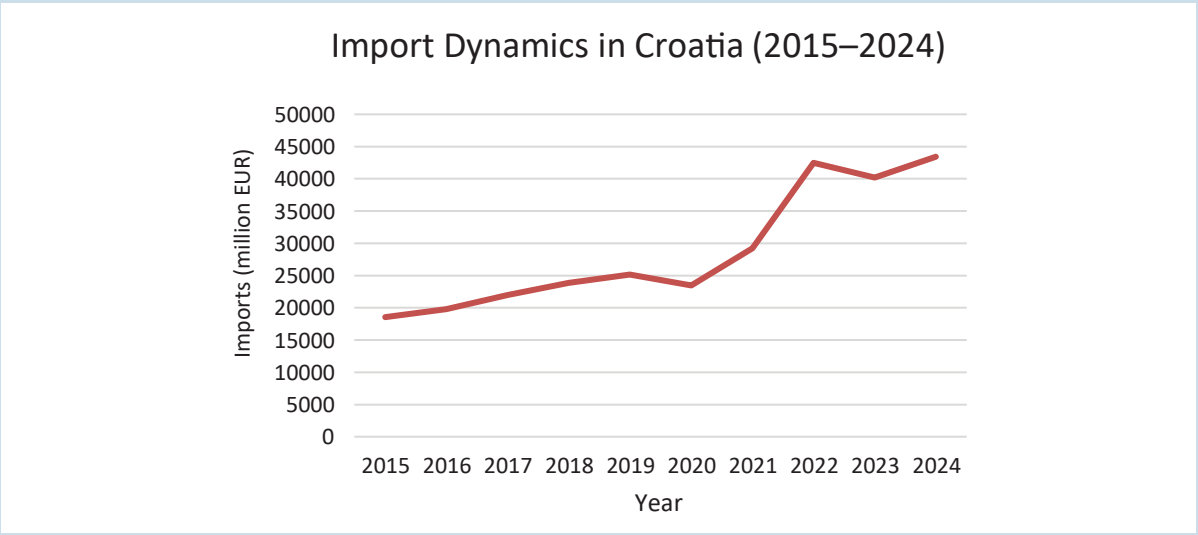


Figure 1. Trends in imports of the Republic of Croatia, 2015–2024
Source: Authors' calculation based on Eurostat data.

As shown in **Figure 1**, merchandise imports of the Republic of Croatia exhibit a strong overall upward trend over the observed period, interrupted by temporary declines in 2020 and 2023. Following the pandemic-related decline in 2020, imports recovered in 2021 and increased substantially in 2022. After a temporary decline in 2023, imports increased again in 2024, reaching the highest value in the analysed period. Overall, the descriptive evidence indicates substantial growth in aggregate merchandise imports between 2015 and 2024.

The dynamics of gross domestic product in the Republic of Croatia are presented in **Figure 2**.

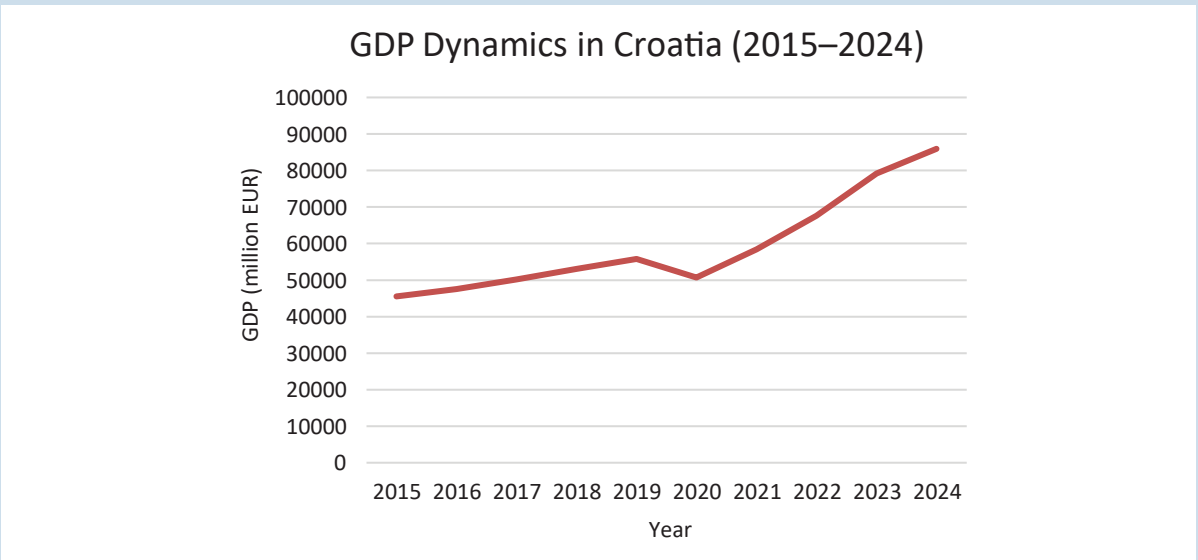


Figure 2. GDP dynamics in the Republic of Croatia, 2015–2024
Source: Authors' calculation based on Eurostat data.

As shown in **Figure 2**, gross domestic product generally increased over the analysed period, with a temporary decline in 2020 followed by a strong recovery from 2021 onwards. Overall, the data indicate substantial growth in domestic economic activity between 2015 and 2024.

A comparison of import dynamics and global trade activity is presented in **Figure 3**.



Figure 3. Imports and global trade activity, 2015–2024
Source: Authors' calculation based on Eurostat and WTO data.

As shown in **Figure 3**, imports and global trade activity exhibit broadly similar dynamics over the analysed period, including a decline in 2020 followed by a subsequent recovery. The baseline regression results indicate a statistically significant positive association between global trade activity and Croatia's merchandise imports. However, this relationship should be interpreted cautiously in view of the small sample, common time trends, and the results of the first-difference sensitivity analysis.

4.2 Regression results

The results of the multiple linear regression analysis based on the complete 2015–2024 period (n = 10) are summarised in **Table 1**.

Table 1. Results of the regression analysis

Variable	Coefficient	p-value
GDP	-0.034	0.570
TRADE	670.123	<0.001
COVID	2654.563	0.007
WAR	13994.000	<0.001

*Model statistics: $R^2 = 0.997$; Adjusted $R^2 = 0.995$; $F = 446.40$; $p < 0.001$

Source: Authors' calculation.

The model exhibits a very high coefficient of determination (R^2 = 0.997) and is statistically significant overall (F = 446.40; p < 0.001). However, given the very small sample and the pronounced trends in several variables, the high R^2 should not be interpreted as evidence of strong causal explanatory power.

Among the individual variables, global trade activity (TRADE) is statistically significant and positively associated with Croatia's merchandise imports (β = 670.123; p < 0.001). GDP is not statistically significant (β = −0.034; p = 0.570). The COVID dummy is positive and statistically significant in the baseline specification (β = 2654.563; p = 0.007), while the WAR dummy also shows a positive and statistically significant coefficient (β = 13994.000; p < 0.001). Given the small sample, common time trends, and the results of the sensitivity analysis presented below, these coefficients should be interpreted as statistical associations within the observed period rather than as causal effects of the crisis events.

Diagnostic checks provide additional information on the robustness and limitations of the model. The correlation between GDP and TRADE is high (r = 0.883), while the corresponding variance inflation factors are 11.20 for GDP and 4.78 for TRADE, indicating that multicollinearity remains a relevant concern, particularly for GDP. The Durbin–Watson statistic is 2.84. The Breusch–Godfrey test provides mixed evidence regarding first-order serial correlation (LM p = 0.018; F p = 0.087), which should be interpreted cautiously given the very small sample. The Jarque–Bera test does not indicate departure from residual normality (p = 0.721), while the Breusch–Pagan test does not indicate statistically significant heteroskedasticity (LM p = 0.299).

Exploratory Augmented Dickey–Fuller tests do not provide evidence of stationarity for IMPORT, GDP, or TRADE in levels (p = 0.937, p = 0.997, and p = 0.718, respectively). Given the very short annual time series, these tests have limited statistical power and should be interpreted cautiously. As a sensitivity check addressing the possibility of common trends, a first-difference specification was estimated. The first-difference model is not statistically significant overall (R^2 = 0.459; adjusted R^2 = −0.082; p = 0.561), and none of the individual predictors reaches conventional levels of statistical significance. In particular, the coefficient for the change in global trade remains positive (β = 912.464) but is not statistically significant (p = 0.223).

Overall, the baseline specification indicates statistically significant positive associations between merchandise imports and global trade activity, as well as the COVID and WAR period indicators. However, these relationships are not confirmed in the first-difference sensitivity specification. Given the very small sample, multicollinearity, common time trends, and limited degrees of freedom, the baseline coefficients should therefore be interpreted as exploratory statistical associations rather than as evidence of causal effects.

5 DISCUSSION

The empirical results indicate that global trade dynamics are positively associated with the import dynamics of the Republic of Croatia during the observed period. Global trade activity (TRADE) is statistically significant in the baseline model, indicating that developments in international trade are closely associated with changes in Croatian merchandise imports. However, this relationship is not statistically significant in the first-difference sensitivity specification. Given the small sample, common time trends, and multicollinearity between GDP and TRADE, the baseline coefficient should therefore be interpreted cautiously and as evidence of statistical association rather than a causal effect.

The COVID-19 variable is positive and statistically significant in the baseline model (p = 0.007). Similarly, the WAR variable has a positive and statistically significant coefficient (p < 0.001). These results indicate that, conditional on the other variables included in the baseline specification, aggregate imports were higher during the periods represented by these crisis indicators. However, these coefficients should not be interpreted as evidence that the pandemic or the war caused an increase in

imports. Both dummy variables represent broad crisis periods that coincide with substantial changes in economic activity, prices, trade patterns, and supply chain conditions, while the very short annual sample limits the possibility of isolating individual effects. Moreover, the lack of statistical significance in the first-difference sensitivity specification indicates that the estimated crisis-period associations are sensitive to model specification.

An important implication concerns the aggregated nature of the dependent variable. Aggregate merchandise import data may conceal heterogeneous developments across sectors and product categories. Declines in imports in sectors particularly exposed to specific disruptions may be offset by increases in other sectors, thereby masking sector-specific vulnerabilities in aggregate data. Consequently, the observed aggregate import dynamics should not be interpreted as evidence that individual sectors were unaffected by supply chain disruptions. The apparent resilience of total import flows may therefore partly reflect aggregation across sectors rather than uniform resilience at the sector level. Future research using sector-specific or product-level import data could examine these heterogeneous responses directly.

From a business perspective, the findings underline the importance of monitoring global trade developments and strengthening supply chain flexibility. Supplier diversification, risk management, and adaptable logistics networks may contribute to reducing exposure to external disruptions. These implications are consistent with previous studies emphasising resilience, diversification, and adaptation in global supply chains (Gebhardt et al., 2022; Xu et al., 2020; Younis et al., 2023).

Overall, the findings provide exploratory evidence that Croatian merchandise imports are associated with global trade conditions and with the crisis periods captured by the COVID and WAR indicators in the baseline specification. However, these relationships are not confirmed in the first-difference sensitivity analysis. The results should therefore be interpreted within the methodological limitations of the study, particularly the very small sample, common time trends, multicollinearity, and aggregation of import data.

6 CONCLUSION

The aim of this paper was to analyse the relationship between global supply chain disruptions, logistical challenges, and the import dynamics of the Republic of Croatia over the period 2015–2024. The empirical analysis, based on multiple linear regression and additional diagnostic and sensitivity checks, examined the associations between global trade dynamics, domestic economic activity, crisis-related factors, and aggregate merchandise imports.

The baseline results indicate statistically significant positive associations between Croatia's merchandise imports and global trade activity, as well as the COVID and WAR period indicators, while GDP is not statistically significant. However, these relationships are not confirmed in the first-difference sensitivity specification. Given the very small number of annual observations, common time trends, multicollinearity, and the broad nature of the crisis-period dummy variables, the results should be interpreted as exploratory statistical associations rather than as evidence of causal effects.

With regard to the research hypotheses, H1 is supported by the baseline results, which indicate statistically significant associations between import dynamics and the variables capturing global trade and crisis periods. H2 is also supported in the baseline specification, as global trade activity is positively and statistically significantly associated with merchandise imports. However, neither of these relationships is confirmed in the first-difference sensitivity analysis. The evidence regarding H3 is specification-sensitive: the COVID and WAR indicators are statistically significant in the baseline model but not in the first-difference specification. Accordingly, the hypothesis-related findings should be interpreted cautiously and within the methodological limitations of the study.

The study contributes to the literature by providing empirical evidence on import dynamics in the context of a small open economy and by linking supply chain and logistics perspectives with macroeconomic trade data. From a managerial perspective, the findings underline the importance of monitoring global trade developments, diversifying suppliers, and strengthening supply chain flexibility. At the same time, aggregate import resilience should not be equated with uniform resilience across individual sectors, since heterogeneous sectoral responses may be concealed in total import flows.

The study is subject to several limitations, particularly the small annual sample, aggregation of import data, multicollinearity among explanatory variables, and potential influence of common time trends. Future research should therefore employ longer time series, sector- or product-level import data, direct transport and logistics indicators, and more advanced time-series or panel-data methods to provide a more detailed assessment of supply chain resilience and crisis-related effects.

Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, analysis, interpretation, and conclusions were developed and verified by the authors, who remain fully responsible for the content.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Cargo Consolidation Strategies and Documentation Flow in LCL Logistics

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ABSTRACT

This paper examines the formation and operational characteristics of Less-than-Container Load (LCL) cargo flows, in which smaller consignments from multiple shippers are consolidated into a single container. LCL transport is an important component of maritime logistics chains, enabling the transport of small consignments and their subsequent deconsolidation at the destination. Its operational efficiency depends on effective cargo consolidation, utilisation of available container capacity, and coordination of physical cargo flows with documentation processes. The paper develops a theoretical framework defining the main concepts, participants and operational specificities of LCL transport. It then applies a case study methodology to examine consolidator's operations and information flows. The analysis covers workflow organisation, cargo-handling procedures and documentation processes, with particular attention to the interaction between physical cargo flows and documentation flows from booking and cargo receipt at the container freight station (CFS), through consolidation and ocean transport, to deconsolidation and final delivery. The study also identifies key operational challenges associated with cargo consolidation, handling, customs documentation and information exchange. The aim is to analyse the organisation of LCL cargo flows and the integration of physical and documentation processes in maritime transport. The paper contributes by examining the transport, logistics and documentation framework as a factor influencing the operational efficiency of LCL services in international maritime supply chains.

Keywords: container cargo flows; cargo consolidation; LCL logistics; documentation flows

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1 INTRODUCTION

Less-than-Container Load (LCL) is an increasingly prevalent logistics model in international trade, as the consolidation of smaller consignments from multiple shippers into a single container rationalises costs and enhances supply chain flexibility. By integrating maritime, rail, and road transport within a unified supply and logistics system, containerised transport enables the efficient organisation of cargo flows, particularly on routes spanning multiple countries and modes of transport.

Despite the growing importance of LCL transport, research on its organisational and logistics dimensions remains limited. Existing studies focus mainly on containerised transport, intermodality, and the role of container ports, while LCL flows and the role of consolidators remain underexplored.

Accordingly, the core research problem of this paper is the limited research into the organisation of LCL cargo flows, particularly with regard to shipment formation, consolidation, and the optimisation of operational and documentation procedures within appropriate LCL consolidation strategies.

The objective of the study is to analyse the organisation of LCL cargo flows, focusing on shipment formation, consolidation, and related procedures that may influence efficiency and reliability of transport operations. LCL transport plays an important role in the transportation of general cargo, as it enables smaller shippers to access containerised and intermodal transport without booking an entire container. However, consolidating shipments from different shippers requires effective organisation of cargo consolidation, cargo handling and coordination among all participants in the logistics chain. Such organisation also depends on well-managed documentation flows that accompany the cargo from transport booking to final delivery. Therefore, LCL logistics strategies should integrate cargo consolidation with the optimisation of documentation procedures in order to streamline logistics processes and optimise LCL transport.

The paper is structured as follows: Section 2 reviews prior research, Section 3 examines the formation and consolidation of LCL cargo flows, Section 4 presents the case study, and the final section concludes the paper.

2 OVERVIEW OF PRIOR RESEARCH

The literature relevant to this study combines cargo-consolidation research with broader work on documentation and information flows in transport and forwarding. Beškovnik and Stojaković [1] define LCL as the consolidation of shipments from different shippers into one container, followed by deconsolidation at the destination. They identify container space and payload utilisation, consolidation close to cargo origins, reduced handling, and hub selection as central LCL decisions. Modal choices must also balance cost and transit time. Jugović [2] identifies container volume and load-bearing capacity, the possibility of cargo rotation, stability requirements, exposure to cargo damage, and loading time as factors influencing cargo stowage planning. These factors are relevant to the physical constraints on consolidating LCL consignments within a container. Shipment consolidation may generate economies of scale by combining individual orders into larger loads, reducing transport costs per item, order, or unit of weight [3]. However, shipment consolidation involves trade-offs in the application of consolidation policies. It can reduce transport costs and enable more efficient transport operations, but it may also lengthen the order cycle and adversely affect customer service [3].

Broader research on transport and trade facilitation examines documentary and information coordination. Tijan et al. [4] review electronic data exchange, data exchange standards, and the Single Window concept in international trade, transport, and seaports, highlighting documentary compliance procedures and stakeholder connectivity. Marčetić et al. [5] identify electronic forwarding documents, interoperable data-sharing initiatives, coherent digital customs systems, and software solutions as enablers of an integrated logistics chain.

Studies focused specifically on LCL transport examine complementary operational decisions. Liu et al. [6] integrate cargo-collection route optimisation with vehicle and unloading-dock scheduling, taking account of vehicle capacity and operational time windows. Jamrus and Chien [7] propose a container-loading algorithm that seeks to use container space efficiently while limiting the mixing of different customers' cargo. At the network level, Jost et al. [8] examine how hinterland routing, hub consolidation and port selection interact, comparing integrated planning with a simplified approach.

However, the sources reviewed here do not examine how cargo consolidation decisions and documentation flows interact within the end-to-end workflow of a single LCL consolidator.

3 SPECIFICITIES IN THE FORMATION AND CONSOLIDATION OF LCL CARGO FLOWS

The importance of international seaborne flows is evidenced by the fact that two-thirds of total world merchandise trade moves by sea. Consequently, dense and high-value trade lanes emerge between major production and consumption regions [9]. A significant share of these cargo flows is containerised, and the formation and consolidation of such flows are conditioned by numerous factors, depending on whether they are full container load (FCL) or LCL flows. The remainder of this study analyses the concept, components, and determinants of container traffic formation, as well as the position and role of consolidators in the organisation, execution, and optimisation of groupage (LCL) container transport.

3.1 Concepts and components of LCL containerised cargo flows

Cargo flows represent the movement of specific goods along defined transport corridors or routes and are a key indicator of the scale, structure, and dynamics of global freight transport [10]. Container flows denote the flows of containerised cargo moving along container shipping routes within a specific containerisation technology tailored to the container transport market. The development of container flows is therefore closely associated with the continued expansion of containerisation as a key component of contemporary maritime transport.

The importance of containerised transport within global maritime trade has continued to increase, reflecting the growing role of container shipping in international supply chains. In its 2024 Review of Maritime Transport, UNCTAD projected average annual growth of 2.4% in seaborne trade and 2.7% in containerised trade over 2025–2029 [11].

From the perspective of cargo utilisation and shipment organisation, containerised transport can generally be divided into two principal forms: full container load (FCL) and less-than-container load (LCL). LCL transport enables smaller consignments from multiple shippers to be consolidated within a single container, providing shippers and consignees with access to containerised transport without requiring sufficient cargo to fill an entire container. However, precise global statistics on LCL transport volumes are not readily available.

The fundamental elements of cargo flows should be viewed within the framework of transport demand and supply as the key determinants of the transport services market. By analogy, the elements of LCL flows are: transport demand for LCL consignments and transport supply tailored to LCL consignments. Transport demand refers to the need for trade in goods within LCL movements on specific routes. That demand must be met by an appropriate transport supply, which includes:

- the transport network (routes across different modes),
- transport nodes (seaport terminals, inland terminals, freight and distribution centres, warehouses, etc.) [10].

Beyond container ports, the critical nodes for forming LCL flows are container freight stations (CFS), where cargo is consolidated into or stripped from containers, and destination logistics warehouses where cargo is handed over to consignees. A CFS is a warehouse located within or outside the port where storage, consolidation and deconsolidation, packing, and customs-related services are performed [12].

Accordingly, the basic elements that form maritime LCL flows are:

- cargo,
- the container as a consolidation unit,
- containerised maritime routes,
- container vessels, and
- container hubs (ports and CFS facilities).

These elements highlight the key participants in the logistics chain, including importers and exporters, ocean carriers, logistics intermediaries, and other stakeholders such as customs authorities, ports, warehouses, and inland carriers, who together shape both the physical and documentary flows.

3.2 Operational specificities in organising LCL services

All ocean freight forwarders offer FCL, but not all offer LCL. For an LCL service to be economical, the forwarder must have at least two consignments that can be consolidated into the same container with optimal use of cube capacity. Higher shipment volumes and better utilisation of container space and weight capacity reduce ocean freight costs per unit of cargo. Where freight forwarders do not provide LCL consolidation services themselves, they typically entrust the transport and consolidation of LCL consignments to specialised LCL consolidators. An LCL consolidator is a specialised logistics service provider that collects or arranges the receipt of LCL consignments from multiple shippers, consolidates compatible cargo into a single container, and coordinates the associated transport and documentation processes, including deconsolidation at the destination and handover to the onward carrier or consignee.

Consolidators almost always deal with freight forwarders rather than directly with importers or exporters, allowing forwarders to remain the client-facing party while consolidators avoid marketing costs and maintain reliable partnerships. This arrangement is more efficient because freight forwarders explain Incoterms and ancillary charges to customers, collect customs documentation, and help ensure the secure payment of freight charges.

Unlike FCL transport, which is usually arranged on a port-to-port basis, LCL shipments generally include pre-carriage from the origin CFS to the port of loading and on-carriage from the port of discharge to the destination CFS. At the origin CFS, cargo from multiple shippers is consolidated until sufficient cargo has accumulated for a destination, after which a container is stuffed to maximise volume and payload, usually without palletisation.

Operational planning of an LCL consolidation involves more than accumulating sufficient cargo for a particular destination. Before stuffing, the consolidator must reconcile cargo availability with the vessel cut-off time, verify cargo compatibility, and balance volumetric utilisation against the permitted payload. The loading sequence, packaging, segregation, labelling, and handling requirements are particularly important for fragile, high-value, or dangerous goods, as they may limit which consignments can be loaded together. The CFS therefore has a central role in checking cargo condition, dimensions, markings, and documentary compliance before containerisation.

LCL containers typically carry general cargo, consumer goods, raw materials, food and beverages, pharmaceuticals, machinery, vehicles, and other finished products. Maximising container utilisation remains a continuous challenge in international transport planning. The problem of loading a large

number of small handling units into a single load unit, i.e., a container, is inherently complex and has no single universal solution [2].

LCL flows follow two delivery patterns: single-destination and multi-destination. Consolidator costs are lower for single-destination deliveries, where stripping occurs only at the destination CFS. Multi-destination flows require additional handling at central and destination warehouses, which raises costs.

The reliability of an LCL service also depends on the timely coordination of physical and documentary flows. The booking confirmation, shipping instructions, cargo receipt, customs documents, and house and master bills of lading must contain consistent data on the parties, cargo, packages, weight, volume, and routing. Because several consignments are consolidated into one container, an error or late document concerning a single shipment can delay customs clearance, stuffing, or release of the whole consolidation. Standardised digital data exchange between the forwarder, consolidator, CFS, carrier, and customs broker can reduce manual re-entry and enable earlier identification of discrepancies.

In practice, and according to logistics service providers, LCL transport is most advantageous in the following situations:

- for small consignments (13 m^3 or less), since freight is charged based on actual volume and weight;
- for last-minute bookings, as LCL space is often released before FCL capacity is fully booked, allowing for lower negotiated rates;
- for larger shipments split between FCL and an LCL balance;
- when delivery is not time-critical [13].

Drawbacks include longer transit times due to stuffing and stripping at origin and destination CFSs, a higher risk of mechanical damage from increased handling and heterogeneous loads, and dependence of individual delivery timing on other shipments and their customs documentation.

4 CASE STUDY: WORKFLOW, OPERATIONAL PROCEDURES AND DOCUMENTATION IN ORGANISING LCL CONTAINERISED TRANSPORT

The case study examines the factors and challenges affecting the consolidation of LCL consignments and the associated documentation procedures and then presents the integrated workflow of consolidator's activities in organising transport, from receipt of the consignment to its final delivery. In the context of LCL transport, a consolidator is a freight forwarder or logistics operator that combines individual LCL consignments into a consolidated container load and coordinates the associated transport, documentation, consolidation and deconsolidation activities between origin and destination [14].

4.1 Challenges and solutions in cargo consolidation and documentation for LCL shipments

Cargo flows are dynamic phenomena influenced by numerous factors that shape their formation and spatial distribution. These factors make it difficult to predict the intensity, structure, dynamics, and geographic patterns of goods movements. They can generally be grouped into geo-transport, socio-economic, and logistics determinants, which also influence the formation of groupage (LCL) container flows. For LCL flows, geo-transport position is particularly relevant because proximity and connectivity to production and consumption centres, ports and hinterland transport networks influence routing and consolidation opportunities [10]. LCL flows are also influenced by socio-economic conditions and market demand, which affect the volume and spatial distribution of consignments.

Within the examined consolidator's operations, LCL import flows serving Central and Eastern European (CEE) markets were primarily organised through the North Adriatic gateways of Koper and

Rijeka, while Northern Range ports, including Hamburg, Antwerp and Rotterdam, were used to a lesser extent. For shipments routed through the Northern Range, containers were deconsolidated at partner consolidators' CFS facilities, after which the cargo was transported by groupage road services to a warehouse in Slovenia and subsequently delivered to the respective consignees at the final destinations specified in the respective bills of lading. These routing patterns reflect the operational practices observed in the examined company and should therefore be interpreted as case-specific observations rather than as representative of the entire CEE LCL market.

A key objective for an LCL consolidator is to manage total transport and handling costs while meeting service requirements. The LCL freight rate, in addition to the ocean leg, also embeds inland pre-/on-carriage costs, which makes the optimal selection of load and discharge ports as well as origin/destination CFS locations critical to reducing total transport and handling costs. Consequently, consolidators prefer high-frequency gateways with strong maritime connectivity and robust hinterland access to the proximal and extended markets served by LCL cargo.

At the operational level, LCL flows are shaped by transport supply and demand, competing routings, port and CFS availability, transport costs and delivery lead times. Consolidators therefore play an important role in coordinating consolidation, deconsolidation and distribution across alternative LCL routings.

LCL consolidation decisions depend not only on cargo compatibility and container capacity but also on the chosen port, CFS and onward route. A direct service to the destination CFS may involve fewer handovers than a route through an intermediate hub, but each option must be coordinated with sailing cut-offs, cargo documents, customs and release requirements. Inconsistent or late documents may require changes to the planned movement; whether other consignments are affected depends on whether the disruption occurs before or after deconsolidation. The case study illustrates these operational dependencies but does not measure the benefits of alternative routes.

4.2 Workflow, operational procedures and documentation in organising LCL transport

The workflow presented in **Table 1** was developed as a case study of LCL import operations at a cargo-consolidation company. In the case examined, the freight forwarder engages the consolidator to provide the LCL service. The table presents the end-to-end LCL import workflow, including the principal activities, responsible stakeholders, key documents, potential operational bottlenecks and their impacts. One of the co-authors, a doctoral researcher employed by the case company as an import specialist, has five years of professional experience in LCL import operations and was directly involved in coordinating and monitoring the processes examined in this study, from booking through to the final handover of cargo to the consignee. The case material was derived from direct observation conducted as part of her regular professional activities and from examination of the associated operational and shipment documentation, including booking confirmations, shipping instructions, commercial documents, bills of lading, customs and transit documentation, arrival notices and delivery-related documents. The observations were not conducted within a separately defined formal observation period but reflect recurring operational practices encountered during the researcher's professional experience. The workflow was compiled by mapping recurring operational activities, responsible stakeholders and associated documents according to their sequence in the observed LCL import process.

The resulting process structure was checked against the operational sequence and documentation used in practice. However, no independent external validation was performed. **Table 1** therefore provides a practitioner-informed account of the case company's LCL import workflow rather than an independently validated process map. The bottlenecks and operational impacts identified in the table represent potential operational risks derived from the observed workflow and professional experience. Their frequency and effects were not systematically measured.

Table 1 shows that the LCL import process comprises interdependent operational and documentation activities involving multiple stakeholders. Critical handovers occur particularly between booking and CFS receipt, during pre-arrival documentation and transit planning, and between deconsolidation and final cargo release. At the first handover, the consolidator depends on timely and accurate cargo information provided by the client or forwarder; incomplete or subsequently changed cargo particulars may require quotation revision, capacity re-planning or booking amendment, while discrepancies between the physical cargo and its documentation may prevent inclusion in the planned consolidation.

Table 1. Workflow, key documents and potential operational bottlenecks in import LCL transport

Responsible Stakeholders	Key Documents	Potential Operational Bottleneck	Operational Impact
1. PHASE / ACTIVITY: LCL transport enquiry, rate quotation, acceptance of quotation Receive and validate the LCL enquiry, including cargo description, number of packages, dimensions, gross weight, volume, packaging, stackability and any special handling requirements. Confirm origin, destination, Incoterms and cargo ready date. Obtain the consolidator's rate and indicative schedule, issue the quotation and receive the customer's acceptance			
Freight forwarder; consolidator.	Request for quotation (RFQ) including cargo specification or preliminary packing list, (if available); written quotation by consolidator stating service scope, included / excluded charges and validity; customer's written acceptance / transport order.	Incomplete or inaccurate cargo particulars, especially dimensions, volume, weight, stackability or special cargo status; unclear service scope or allocation of origin / destination charges; delayed rate confirmation or customer acceptance; cargo ready date falling outside quotation validity or the intended consolidation cut-off.	Additional clarification and quotation revision; delayed booking; potential additional charges; possible loss of the intended consolidation / sailing and postponement of shipment.
2. PHASE / ACTIVITY: Carrier booking Reserve vessel space for the planned LCL consolidation; confirm container type and equipment availability with the carrier, routing and applicable cut-off times.			
Consolidator / booking agent; ocean carrier.	FCL booking confirmation; shipping instructions;	Limited vessel space or unavailable empty containers; delayed booking confirmation; changes to sailing schedules or cut-off times;	Booking amendment or rebooking; delayed departure of all included LCL shipments
3. PHASE / ACTIVITY: CFS receipt and planning Receive, inspect and label the cargo; verify package count, dimensions, weight and condition against shipment documents; plan consolidation and stuffing; prepare export customs documentation and bill of lading instructions.			
Consolidator; CFS operator, freight forwarder; shipper; customs representative.	CFS cargo receipt; packing list; commercial invoice; discrepancy / damage report (if any); draft HBL / MBL; export customs declaration.	Discrepancies between the cargo and shipment documents, cargo damage or unsuitable packaging, missing or inconsistent customs / B/L data.	Cargo held pending clarification, repacking or customs clearance; revised stuffing plan; exclusion of affected shipments from the planned consolidation or postponement of consolidation; additional handling and storage costs.

Responsible Stakeholders	Key Documents	Potential Operational Bottleneck	Operational Impact
4. PHASE / ACTIVITY: Stuffing and port handover Load and secure cargo in the container; seal the container, obtain VGM and deliver it to the port terminal			
Consolidator; CFS operator; haulier; terminal operator; customs authority.	Container freight manifest; packing list; commercial invoice; export customs declaration; CMR.	Late-arriving cargo; cargo volume exceeding planned capacity; loading or securing issues; delayed terminal delivery or missed gate-in cut-off.	Additional handling or restuffing; exclusion of affected cargo from the consolidation; missed sailing (rebooking for the next sailing); revision of MBL / HBL, storage costs and detention costs
5. PHASE / ACTIVITY: Maritime transport Load the container onto the vessel and monitor its voyage to the discharge port.			
Ocean carrier; consolidator.	Final MBL and HBLs.	Discrepancies in bills of lading; sailing delays or disruptions to the vessel schedule.	Amendments to bills of lading; delayed arrival at port of discharge.
6. PHASE / ACTIVITY: Arrival notice and transit planning Send arrival notices and collect documents for transit from the port to the CFS or beyond.			
Consolidator; freight forwarder; customs representative; haulier	Arrival notice; B/L; commercial invoice; packing list; required MSDS/certificates; transport invoice (if applicable).	Late, incomplete or inconsistent documents from one or more consignees; pending carrier release or transit approval.	Delayed transit documentation, container release or transfer to the CFS; additional storage and demurrage costs.
7. PHASE / ACTIVITY: Port arrival and deconsolidation Transfer the container to the bonded CFS; unload and sort consignments by HBL; verify package count and condition; return the empty container to the carrier.			
Terminal operator; haulier; consolidator; CFS operator, customs representative.	FCL delivery order (carrier's release of entire container to consolidator), Bill of lading; commercial documents; transit declaration; CMR; devanning report; customs warehousing declaration.	Delayed container release or transfer to the CFS; prolonged waiting time for devanning; cargo discrepancies or damage identified during devanning; delayed empty container return.	Delayed availability of consignments; cargo claims; additional handling, storage and detention costs.
8. PHASE / ACTIVITY: Onward groupage dispatch Group deconsolidated consignments by destination; arrange onward road transport and confirm dispatch schedules.			
Consolidator; CFS operator, inland haulier; customs representative (if required).	HBL / cargo release confirmation; commercial documents; CMR; transit declaration and MSDS / certificates, where required.	Incomplete documents; limited transport capacity; cargo not ready by the dispatch cut-off.	Rescheduled dispatch; prolonged CFS storage; delayed delivery; additional storage or transport costs.

Responsible Stakeholders	Key Documents	Potential Operational Bottleneck	Operational Impact
9. PHASE / ACTIVITY: Destination arrival and release			
Receive cargo into the bonded warehouse; verify payment, B/L release status and customs requirements; authorise cargo release against a delivery order.			
Consolidator; customs authority; bonded warehouse; freight forwarder.	Temporary storage or customs warehousing declaration; damage report (if any); delivery order (surrendered original HBL, issued sea waybill or telex release).	Missing HBL delivery order due to required original B/L, incomplete customs formalities or outstanding charges.	Delayed cargo release and delivery; prolonged storage and additional storage charges.
10. PHASE / ACTIVITY: Customs clearance and cargo collection			
The consignee or appointed customs representative completes import customs clearance or arranges onward customs transit; the warehouse hands over cargo to the consignee or authorised haulier once customs and commercial release conditions have been met.			
Consolidator; freight forwarder; consignee; customs representative; warehousing operator; collecting haulier.	Import or transit declaration; delivery order; cargo collection receipt; CMR.	Incomplete customs documentation; pending customs release; changes to collection arrangements or haulier availability.	Delayed cargo collection; additional storage costs; amendments to customs or transport documents.

Source: Made by authors (based on the observed operational workflow and documentation practices of the examined LCL consolidator).

During pre-arrival processing, the consolidator depends on timely and consistent documentation from consignees and customs representatives. Missing or inconsistent documents related to an individual consignment may delay transit preparation, container release and transfer to the CFS, potentially resulting in additional storage or demurrage costs. Because multiple LCL consignments share the same consolidated container, such delays will also affect other consignments within the same container, even when their documentation is complete, thereby postponing their deconsolidation and onward delivery. At destination, unsettled charges, missing bill-of-lading release evidence or incomplete customs formalities may delay cargo release and extend storage time. Potential preventive measures include verification of cargo particulars before booking, document-completeness checks before relevant cut-off times, early identification of missing or inconsistent documents, and advance verification of cargo-release requirements. These measures may support more reliable coordination and process transparency; however, the identified disruptions and their impacts represent potential operational risks and were not systematically measured in this case study.

5 CONCLUSION

This study examines the specific characteristics of forming and consolidating less-than-container load (LCL) containerised cargo flows, with particular emphasis on the role of the consolidator in organising and coordinating this segment of international logistics. The analysis considers the main elements and factors influencing the formation and consolidation of LCL container transport flows, including geo-transport position, socio-economic conditions, and market supply–demand relationships. These factors provide an important contextual basis for the organisation and selection of LCL transport routes.

The case study further illustrates the importance of coordinating operational processes with their corresponding documentation flows, from booking and cargo receipt at the CFS, through consolidation and ocean transport, to deconsolidation and final delivery to the consignee. The examined workflow indicates that documentation functions not only as an administrative requirement but also as an important mechanism for coordinating interactions among shippers, consolidators, carriers, CFS and port operators, customs authorities, and consignees. In the examined case, inconsistencies or delays in information and documentation may require additional coordination, corrections, or operational adjustments, potentially affecting the continuity and reliability of the transport process. The case therefore highlights the importance of integrating documentation management with the physical organisation of LCL cargo flows.

The analysis suggests that effective LCL transport organisation requires coordination between cargo consolidation, transport planning, operational procedures, and documentation flows. Accordingly, standardised documentation checks, timely exchange of shipment information, and coordinated operational procedures may contribute to greater process consistency and reduced risk of operational disruption. These measures should, however, be regarded as proposed operational improvements rather than empirically demonstrated outcomes, as their effects were not quantitatively measured in this study.

The findings should be interpreted within the scope of the examined case. The study is based on a single descriptive case and therefore does not provide a basis for generalising the identified workflow characteristics, operational effects, or proposed solutions to the wider LCL logistics sector.

Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, analysis, interpretation, and conclusions were developed and verified by the author(s), who remain fully responsible for the content.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Reconstruction of the Rijeka Railway Junction as a Prerequisite for the Development of the Port of Rijeka

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ABSTRACT

This paper analyses the role of the reconstruction and functional reconfiguration of the Rijeka railway junction in the development of the Port of Rijeka and in strengthening the Rijeka–Zagreb–Central Europe intermodal transport route. The emphasis is placed on the spatial and functional separation of passenger and freight rail traffic, whereby freight capacities are relocated to peripheral locations in the wider Rijeka area, while passenger traffic is integrated into the urban fabric of the City of Rijeka. With the commissioning of the Rijeka Gateway container terminal and the growth of container traffic, the existing railway infrastructure does not provide sufficient capacity or the required levels of reliability and speed. Therefore, the construction of a new double-track lowland railway line between Rijeka and Zagreb is emerging as a key infrastructure project of national and international importance. The paper presents the transport and logistics characteristics of the Port of Rijeka, analyses the current state of the Rijeka railway junction, and considers the planned railway infrastructure modernisation and reconstruction projects. Particular attention is given to the technical and operational characteristics of the new lowland railway line and their effects on the efficiency of container dispatch and receipt by rail. The conclusion confirms that the functional reconfiguration of the Rijeka railway junction and the construction of the new line are fundamental prerequisites for the sustainable development of the Port of Rijeka and for strengthening its competitiveness within the North Adriatic port system.

Keywords: Rijeka railway junction; Port of Rijeka; Rijeka–Zagreb lowland railway line; intermodal transport; railway transport system.

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1 INTRODUCTION

The Port of Rijeka is the most important Croatian seaport and a key maritime gateway linking the Adriatic with Central Europe. Its competitive position depends strongly on the efficiency of the Rijeka-Zagreb-Central Europe transport route and on the ability of the railway system to provide reliable inland transport for containerised and other freight flows [1]. The increasing role of container traffic and the activation of new terminal capacities have intensified pressure on the existing hinterland infrastructure.

The Rijeka railway junction is the central railway interface between the port system and the national railway network. Its historical development led to a close spatial interaction between passenger and freight traffic within the urban area of Rijeka. This organisation restricts capacity, reduces timetable stability and limits the possibilities for introducing more frequent urban and regional passenger services. At the same time, port-related freight trains require reliable and direct access to the main railway route towards the hinterland [2, 3].

The aim of this paper is to analyse the role of the reconstruction and functional reconfiguration of the Rijeka railway junction in the development of the Port of Rijeka and in the strengthening of intermodal transport. The paper focuses on the existing operational limitations, the utilisation of the Rijeka-Zagreb railway line, container traffic trends and the expected effects of a new lowland railway line and a reorganised junction. The professional contribution of the paper lies in integrating railway capacity indicators, port container traffic trends and junction reconfiguration requirements into a single infrastructure-development framework.

2 BACKGROUND

European transport policy is based on the establishment of an integrated and interoperable transport network. Within this framework, the trans-European transport network (TEN-T) defines strategic corridors that connect seaports, inland terminals, industrial centres and consumer markets [4, 5]. The Port of Rijeka is included in this wider European transport system and has an important role in connecting the Northern Adriatic with Central and Eastern Europe.

The geographical position of Rijeka gives the port a potential advantage in serving Central European markets, particularly in comparison with longer maritime routes to northern European ports. However, this advantage can only be fully exploited if port development is accompanied by efficient railway access, sufficient line capacity and reliable terminal-to-hinterland connections. Previous research emphasises that port competitiveness increasingly depends on the quality of inland connections and the integration of ports into broader logistics networks [6, 7].

The existing Rijeka-Zagreb railway line represents the backbone of the inland connection of the Port of Rijeka, but its technical characteristics reflect the conditions under which it was constructed. The main constraints include unfavourable gradients in the mountainous sections, small curve radii, limited useful track lengths at stations and predominantly single-track operation. These factors influence train length, train weight, operating costs, speed and reliability, and therefore directly affect the competitiveness of rail-based intermodal transport [8, 9].

In this context, the Rijeka railway junction has a dual role. On the one hand, it must serve port-related freight flows, including container trains, bulk cargo and liquid cargo. On the other hand, it forms part of the urban and regional passenger system of the City of Rijeka and its wider functional area. The coexistence of these functions within a restricted urban corridor creates operational conflicts that cannot be solved only through timetable adjustments or isolated station improvements.

3 METHODOLOGY

The research applies a combined qualitative and quantitative approach. The qualitative part includes the interpretation of strategic, planning and development documents related to the Port of Rijeka, the Rijeka railway junction and the planned Rijeka-Zagreb lowland railway line [8, 10, 11]. The quantitative part is based on the processing of railway traffic indicators, line capacity data and container traffic indicators.

Three groups of indicators are used. The first group refers to freight train traffic in the Rijeka railway junction in 2025, including arrivals, departures and the distribution of traffic by station. The second group refers to the capacity and utilisation of sections of the Rijeka-Zagreb railway line in 2024, based on the comparison between theoretical capacity and realised traffic. The third group concerns container traffic at the Port of Rijeka from 2018 to 2024 and the modal split between rail and road transport [12-15]. The capacity assessment follows a capacity-utilisation ratio method, in which the realised average daily number of trains is compared with the theoretical daily capacity of each line section reported by HŽ Infrastruktura. Capacity utilisation is calculated as $U = (N_{avg} / C_{th}) \times 100$, where N_{avg} is the realised average number of trains per day and C_{th} is the theoretical capacity in trains per day.

The results are interpreted as indicators of system performance and infrastructure pressure. Particular caution is applied to projections and planning assumptions, because future traffic development depends on market conditions, investment dynamics, terminal development and the implementation of railway infrastructure projects.

4 RESULTS

The analysis confirms that the Rijeka railway junction is exposed to substantial freight traffic associated with the port and the wider industrial and logistics system. In 2025, a total of 11,480 freight trains were recorded in the junction, of which 4,928 were inbound and 6,552 outbound trains. The largest loads were recorded at Rijeka Brajdica and Šoići, while Bakar and Rijeka also played important functional roles in the distribution of freight flows.

Table 1 shows a functionally differentiated structure of the junction. Rijeka Brajdica is the most important container-related station, while Šoići has a strong role in tank train traffic. The predominance of outbound trains confirms the role of the Port of Rijeka as a logistics node oriented towards the interior and towards Central European markets.

Table 1. Freight train traffic in the Rijeka railway junction in 2025

Station	In	Out	Total	Main traffic function
Bakar	392	635	1,027	bulk cargo
Rijeka	988	951	1,939	mixed freight and terminal access
Rijeka Brajdica	1,616	2,781	4,397	container traffic
Šoići	1,932	2,185	4,117	liquid cargo and tank trains
Total	**4,928**	**6,552**	**11,480**	**port and hinterland freight**

Source: HŽ Infrastruktura Ltd.; authors' calculations.

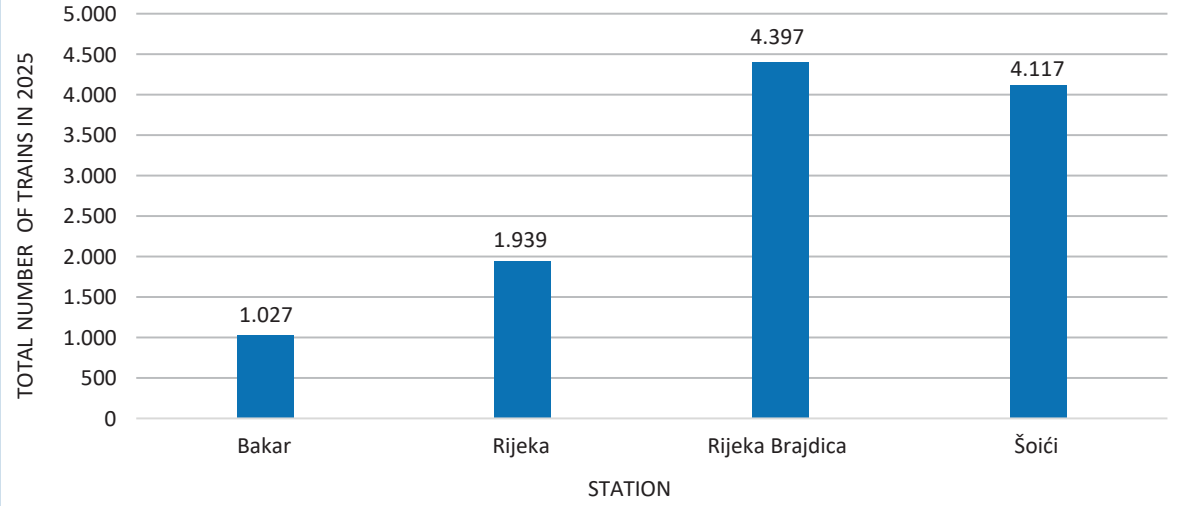


Figure 1. Freight train traffic by station in 2025

Source: HŽ Infrastruktura Ltd.; authors' calculations and graphical presentation.

The capacity analysis of the Rijeka-Zagreb railway line indicates that operational limitations are not evenly distributed along the route. **Table 2** presents theoretical capacity, realised traffic and the average daily number of trains by section in 2024.

Table 2. Capacity and utilisation of the Rijeka-Zagreb railway line in 2024

Section	Capacity (trains/day)	Trains in 2024	Utilisation (%)	Average (trains/day)
Zagreb GK-Karlovac	63	20,664	89.8	57
Karlovac-Oštarije	72	21,881	83.3	60
Oštarije-Moravice	100	14,557	39.9	40
Moravice-Lokve	89	12,328	37.9	34
Lokve-Škrljevo	85	17,234	55.6	47
Škrljevo-Rijeka	74	14,514	53.8	40

Source: HŽ Infrastruktura Ltd. [12]; authors' calculations.

Figure 2 compares theoretical capacity with the realised average daily number of trains on individual sections.

Figure 2 shows that traffic on the Zagreb GK-Karlovac and Karlovac-Oštarije sections is close to available capacity, while central sections indicate a larger numerical reserve. However, lower utilisation does not necessarily imply sufficient operational capacity. On the mountain and coastal sections, limited useful track lengths and train-crossing possibilities can restrict the operation of longer freight trains; consequently, practical capacity may be lower than the theoretical number of trains per day [16, 17].

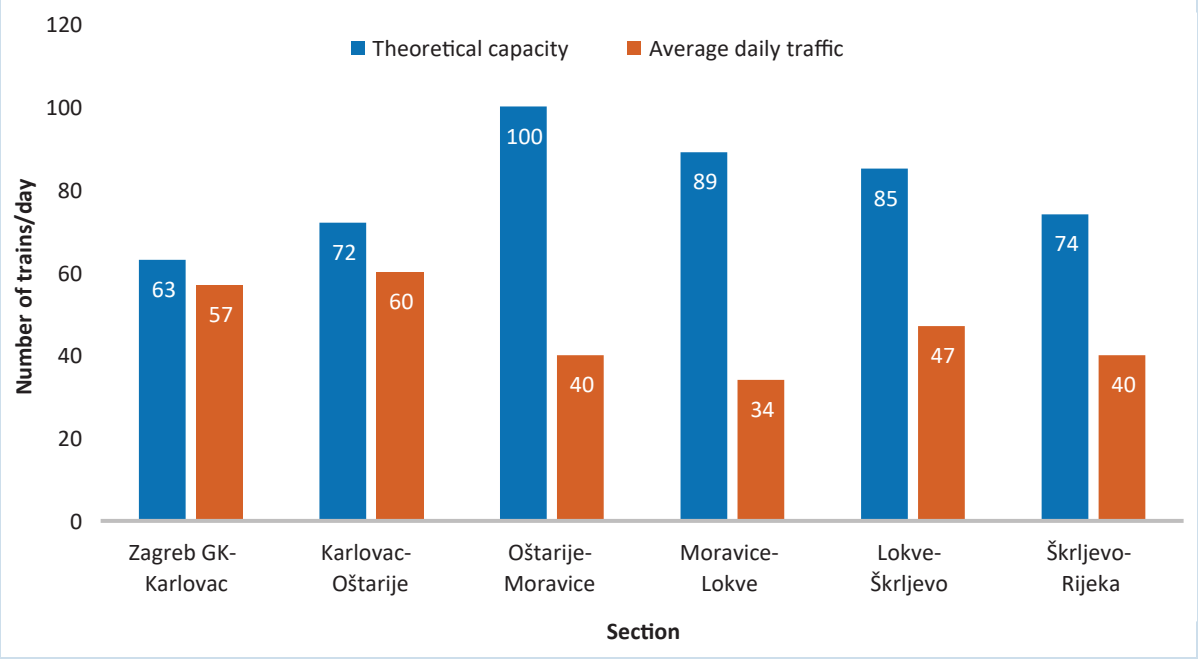


Figure 2. Comparison of capacity and average daily train traffic on the Rijeka-Zagreb railway line in 2024
Source: HŽ Infrastruktura Ltd. [12]; authors' calculations and graphical presentation.

Container traffic at the Port of Rijeka increased significantly during the observed period. In 2024, the port reached 409,415 TEU, while the rail share in container dispatch was 41.0%. **Table 3** presents the estimated distribution by transport mode, and **Figure 3** shows the development of rail and road shares. The rail share reached 47.5% from 2021 to 2023, but its decrease in 2024 indicates that further growth depends on the capacity and reliability of the railway system.

Table 3. Estimated container traffic of the Port of Rijeka by transport mode

Year	Total TEU	Rail share (%)	Road share (%)	TEU by rail	TEU by road
2018	227 375	35.0	65.0	79 581	147 794
2019	271 817	35.0	65.0	95 136	176 681
2020	303 626	35.0	65.0	106 269	197 357
2021	312 321	47.5	52.5	148 352	163 969
2022	373 343	47.5	52.5	177 338	196 005
2023	385 794	47.5	52.5	183 252	202 542
2024	409 415	41.0	59.0	167 860	241 555

Source: prepared by the authors based on terminal operator data and publicly available reports [14,15].

The planned functional reconfiguration of the Rijeka railway junction is based on a clearer separation of passenger and freight flows. Passenger traffic is intended to become more integrated with the urban structure, while freight and logistics capacities would be shifted towards peripheral locations that are more suitable for longer trains, terminal operations and industrial connections. This concept would reduce conflicts in the central urban area and create better conditions for the development of reliable rail services.

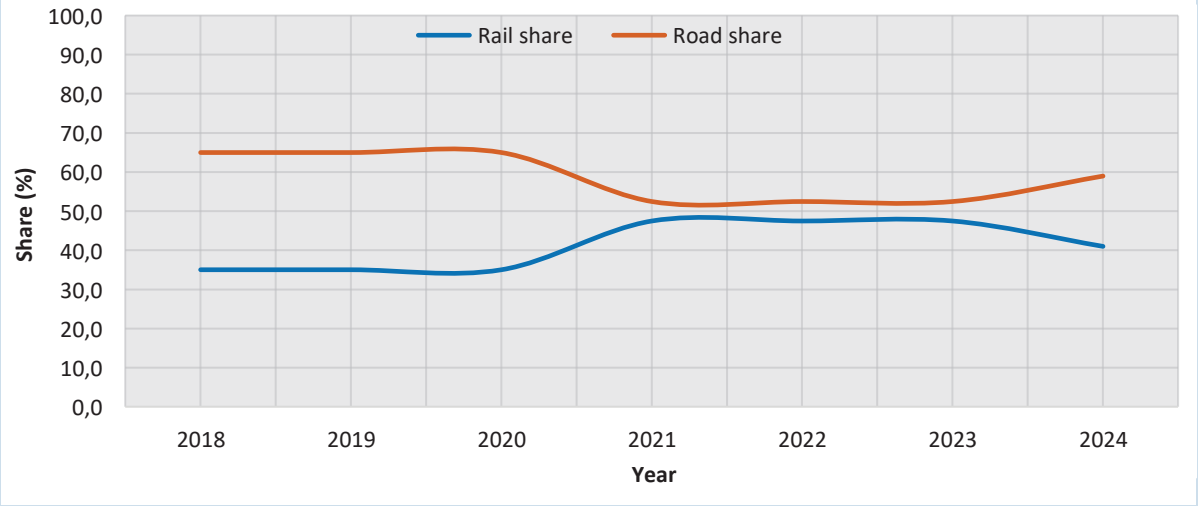


Figure 3. Rail and road shares in container dispatch from the Port of Rijeka
Source: prepared by the authors based on terminal operator data and publicly available reports [14,15].

Table 4 summarises the main difference between the existing and planned states of the junction. The expected benefits are not limited to freight traffic. A more coherent organisation of railway functions would also improve the relationship between the railway and the urban area by reducing freight-related pressure on central tracks and by enabling a more systematic development of passenger services.

Table 4. Existing and planned functional characteristics of the Rijeka railway junction

Junction element	Existing state	Planned state after reconstruction
Traffic organisation	Passenger and freight traffic interact within the central urban area.	Spatial and functional separation of passenger and freight flows.
Freight facilities	Freight trains use infrastructure close to the city centre and port basin.	Freight and logistics functions relocated towards peripheral locations.
Capacity	Limited by crossing movements, track layout and station constraints.	Increased through clearer flow organisation and reduced conflicts.
Passenger services	Urban integration is restricted by freight movements and operational conflicts.	More favourable conditions for frequent urban and regional passenger rail.
Port connection	Terminal growth increases pressure on existing railway access.	More direct and reliable connection between terminals, yards and hinterland route.

Source: prepared by the authors based on planning documentation [2, 3, 10].

The new lowland railway line has been considered through different route and capacity-development variants. Their relevance lies not only in total route length, but also in the share of demanding engineering structures and in the extent to which each option changes the operational characteristics of the existing Rijeka-Zagreb connection.

Table 5. Comparison of selected route variants of the new lowland railway line

Variant	Total route length (km)	Structures	Basic characteristic
Drežnica variant	approx. 170	approx. 45 km of tunnels and bridges	New alignment with technically demanding sections.
Second track Ogulin-Škrljevo	approx. 220	based mainly on upgrading the existing route	Capacity increase without a completely new alignment.
Kupa variant	approx. 149	approx. 61 km of tunnels and bridges	Shortest route, but with high construction complexity.

Source: prepared by the authors based on study documentation [2,8,9].

The comparison indicates that each variant involves a different balance between transport benefits, construction complexity and investment requirements. From the perspective of port competitiveness, the key criterion is the ability of the selected solution to provide sufficient capacity and reliability for longer and heavier intermodal trains, while also enabling better integration with the reconfigured Rijeka railway junction.

5 DISCUSSION

The results show a clear relationship between port development, container traffic growth and the limitations of railway infrastructure. Further growth of the Port of Rijeka depends not only on terminal capacity, but also on the stability, capacity and reliability of the hinterland railway system. If these conditions are not met, a larger share of cargo may shift to road transport, weakening the environmental and operational advantages of intermodal transport.

The reconstruction of the Rijeka railway junction is therefore not only a local urban or railway project, but also a strategic prerequisite for port competitiveness. The spatial and functional separation of passenger and freight flows would reduce operational conflicts in the urban area, improve timetable reliability and allow the development of more frequent passenger services. At the same time, the relocation of freight and logistics capacities to peripheral locations such as Krasica, Kukuljanovo and Bakar would create more suitable conditions for port-related freight traffic [3, 10].

The new double-track lowland railway line between Rijeka and Zagreb represents the second key element of the system. Its expected advantages include more favourable gradients, higher capacity and the possibility of operating longer and heavier freight trains with fewer operational restrictions [2, 8, 11]. However, the benefits of the new line can be fully achieved only if it is integrated with the reconfigured junction and with connecting routes towards port, logistics and regional development zones.

From a wider transport-policy perspective, the proposed infrastructure development supports the objectives of shifting freight from road to rail and strengthening sustainable intermodal transport. In relation to competing Northern Adriatic ports, Rijeka's main potential advantage lies in the combination of its maritime position and a railway corridor capable of serving Central European markets. Without coordinated investment in port and railway infrastructure, this advantage may remain only partly exploited [6, 7].

The results also indicate that capacity should not be interpreted only as a theoretical number of trains per day. For intermodal transport, reliability, useful track lengths, train crossing possibilities, terminal dwell time and the coordination of train paths are equally important.

The development of the Rijeka Gateway terminal gives additional relevance to these findings. Larger terminal capacity can increase the number of containers that need to be dispatched quickly from the port area. If railway capacity and junction organisation do not follow this growth, the port may face increased dependence on road transport, longer dwell times and reduced attractiveness for logistics operators that require predictable inland connections.

For these reasons, the new lowland line, the reconfigured Rijeka junction and the development of peripheral logistics zones should be treated as mutually connected parts of one transport system whose combined implementation would strengthen the role of the Port of Rijeka within the Northern Adriatic port system.

6 CONCLUSION

The analysis confirms that the reconstruction and functional reconfiguration of the Rijeka railway junction, together with the development of the new Rijeka-Zagreb lowland railway line, are fundamental prerequisites for the sustainable development of the Port of Rijeka. The existing system is constrained by the interaction of passenger and freight traffic in the urban area, limited station and line capacities, unfavourable technical characteristics and the operational complexity of the mountainous route.

The empirical indicators presented in the paper show a high level of freight traffic in the Rijeka railway junction and continued growth of container traffic in the Port of Rijeka. These trends increase the need for reliable rail dispatch, larger train capacities and better integration between terminals, freight yards and the main railway corridor. The planned separation of traffic flows, relocation of freight functions and construction of a modern lowland railway line would improve reliability, reduce operational conflicts and strengthen the competitiveness of the Rijeka transport route.

The contribution of the paper lies in connecting port development, railway capacity and intermodal transport within a single analytical framework. In practical terms, the paper demonstrates that the competitiveness of the Rijeka transport route depends on the coordinated development of port terminals, railway junction organisation and hinterland railway capacity. The main limitation is that part of the analysis relies on planning documents and projections. Future work should therefore include scenario-based demand and capacity modelling for different terminal-throughput levels, timetable-based assessment of critical line sections and junction nodes, cost-benefit and environmental evaluation of alternative lowland-line variants, and ex-post assessment after the implementation of individual development phases.

Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, analysis, interpretation and conclusions were reviewed and verified by the authors, who remain fully responsible for the content.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Suspended Steel-Wheel String-Rail Complexes as a Second-Level Freight Transport Mode: A Comparative Techno-Economic and Environmental Assessment

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ABSTRACT

Freight demand growth, congestion, land scarcity and decarbonisation targets are placing conventional road and rail networks under increasing pressure. Elevated transport that exploits the vertical dimension has re-emerged as a means of relieving these pressures, so far mainly through aerial ropeways for passengers. This paper assesses a less studied variant intended for cargo: mounted and suspended steel-wheel rolling stock running on a prestressed string-rail overpass, in which the load-bearing element is a rail reinforced by a core bundle of pre-tensioned steel wires. Using a structured desk-based comparative assessment, the reported technical parameters of three cargo configurations, namely containerised and piece cargo, bulk cargo, and general rolling stock, are compared with road, conventional rail and inland waterway freight across six criteria: throughput, speed, specific carbon dioxide intensity, land take, capital and operating cost, and technological maturity. Emission intensities are estimated using the activity-based approach of ISO 14083. The results indicate that the electric string-rail concept is competitive with electrified rail in operational carbon dioxide intensity, while offering a markedly smaller ground footprint and the ability to overcome water and terrain barriers, at the cost of higher reported capital intensity for containerised lines and limited independent validation. The mode appears best positioned as a second-level feeder linking ports, terminals and industrial sites. The principal limitations of the study are its reliance on manufacturer-reported data and the small number of demonstration installations.

Keywords: string-rail transport; elevated freight; second-level logistics; sustainable transport; techno-economic assessment; carbon dioxide emissions

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Global freight activity continues to grow faster than the transport sector is decarbonising. Road haulage carries the largest share of inland freight in most economies, yet it is also the least energy efficient of the land modes and a major source of greenhouse gas emissions, congestion and local air pollution [1]. Modal-shift policies in the European Union seek to move a substantial part of long-distance road freight to rail and waterborne transport by 2050, precisely because these modes offer lower carbon dioxide intensity per unit of transport activity [2, 3].

At the same time, the corridors along which conventional rail and road can expand are increasingly constrained by land scarcity, protected areas, difficult terrain and existing urban development.

One response to these constraints is to move transport into the vertical dimension by elevating the guideway above the ground. In passenger transport this idea has matured into urban aerial cable cars, which are now the subject of a growing scientific literature [4, 5].

For freight, however, elevated and cable-based solutions remain comparatively under-studied, with attention limited mainly to mountain ropeways and a small number of recent proposals for aerial cargo networks in cities [6, 7].

A distinct and less examined concept is the prestressed string-rail overpass carrying automated steel-wheel electric vehicles. Here the guideway is not a flexible rope but a rigid or semi-rigid rail reinforced by a core of pre-tensioned steel wires, which allows large unsupported spans while retaining a hard running surface for conventional steel wheels.

The objective of this paper is to assess, in a structured and transparent way, whether elevated string-rail cargo complexes represent a credible sustainable freight mode, and under which conditions. The contribution is threefold. First, the reported technical parameters of three cargo configurations are consolidated and interpreted. Second, these parameters are compared with established freight modes across a consistent set of techno-economic and environmental criteria. Third, the most promising application niche is identified, together with the main uncertainties that further research must address. The remainder of the paper reviews the relevant background, sets out the assessment method, presents the comparative results, discusses their implications for port and multimodal logistics, and provides final conclusions.

2 BACKGROUND

2.1 Externalities of conventional freight modes

The environmental performance of freight modes differs by more than an order of magnitude. Expressed as specific carbon dioxide intensity, road haulage in Europe is commonly reported in the range of several tens of grams per tonne-kilometre, whereas electrified rail and inland waterway transport are markedly lower [3]. Cost and energy efficiency follow a similar hierarchy: over long distances the cost per tonne-kilometre of moving goods by barge or rail is a small fraction of the equivalent cost by truck, and a single unit of fuel moves a tonne of cargo far further by water or rail than by road [1]. These gaps are the central justification for modal-shift strategies, but they also motivate the search for new modes that combine low operational intensity with route flexibility that rail and water cannot always provide.

2.2 Elevated and cable-based transport

Aerial ropeways are the most mature elevated mode. They are quiet, electrically driven, and able to cross valleys, water and congested areas with a small ground footprint, which has made them attractive for urban passenger transit and for mountainous regions [4, 5]. Their principal limitation is capacity, since

classical gondola and tramway systems are designed around relatively small cabins [4]. Combined freight and passenger ropeways have been examined through simulation and shown to be feasible for specific alpine links, subject to a trade-off between the two flows [6]. More recently, autonomous aerial cable-car networks have been proposed as a way of reducing the externalities of urban freight, with network-design studies reporting substantial cuts in road-transport impacts and a small physical footprint [7].

Case studies of urban cable cars also report reductions in carbon dioxide emissions relative to road-based alternatives [9]. The string-rail concept examined here shares the elevated, electric and low-footprint character of these systems, but replaces the rope with a prestressed rail and uses steel wheels rather than suspended cabins, which in principle allows higher speeds and heavier axle loads.

2.3 The string-rail concept

In the string-rail concept, the track structure consists of anchor supports, intermediate supports and a continuous rail whose core contains a bundle of pre-tensioned steel wires. The pre-tensioning gives the rail high bending stiffness and evenness while keeping material consumption low, so that intermediate supports carry mainly vertical load and can be lighter and more widely spaced than in conventional viaducts [10].

Reported anchor-to-anchor distances reach several kilometres, with intermediate spans of the order of a few hundred metres at demonstration sites. Rolling stock consists of unmanned electric vehicles on steel wheels, running on the rail head under automated control. For cargo, the reported vehicle family includes container and piece-cargo carriers, bulk carriers and continuous-loop systems for loose materials, with individual payloads reported from roughly 1 to 35 tonnes [10]. Because the source of these parameters is manufacturer technical documentation rather than independent measurement, they are treated throughout this paper as reported values requiring verification, and are labelled accordingly.

3 METHODOLOGY

The study is a structured desk-based comparative assessment rather than an experimental or field study. It proceeds in three steps. First, the reported technical parameters of the three string-rail cargo configurations were consolidated from the available technical documentation [10]. Second, four freight modes were selected for comparison: articulated road haulage, conventional electrified rail, inland waterway transport, and the electric string-rail concept. Third, the modes were compared across six criteria selected to reflect both operational performance and sustainability: maximum design speed, indicative throughput, specific carbon dioxide intensity, ground land take, reported capital cost per kilometre, and technological maturity.

Comparative data for the conventional modes were drawn from established secondary sources, including transport-agency statistics and the peer-reviewed literature [1, 3, 4]. Specific carbon dioxide intensity for the electric string-rail case cannot be measured directly, since no full-scale cargo line is in commercial operation. It was therefore estimated using the activity-based approach standardised in ISO 14083 and the GLEC Framework, in which the emissions of a transport leg are the product of the transported mass, the distance and the mission factor [11, 12]:

$$E_{CO2} = m \times d \times EF \tag{1}$$

where E is the carbon dioxide emitted, m is the transported mass in tonnes, d is the distance in kilometres, and EF is the emission factor per tonne-kilometre. For the string-rail case the traction is electric, so EF was derived from the average European electricity mix and treated as grid-dependent. This yields an indicative value comparable with electrified rail rather than a validated figure, and it is

presented as such. Land take and capital cost were assessed qualitatively for the conventional modes and from reported values for the string-rail concept.

All figures use SI units, and abbreviations are defined at first use. The assessment is deliberately conservative: where a reported value could not be corroborated, it is flagged rather than adopted as fact.

4 RESULTS

4.1 Reported configurations and throughput

Table 1 summarises the reported parameters of the three cargo configurations. Two features stand out. The containerised and bulk configurations report the same very high theoretical annual throughput, but at very different design speeds, reflecting the different handling regimes of discrete containers and continuously loaded bulk material. The reported throughput figures should be read as theoretical maxima for a fully utilised line rather than as demonstrated operational values.

Table 1. Reported technical parameters of the three string-rail cargo configurations

Parameter	Container /piece cargo	Bulk cargo	General
Maximum design speed (km/h)	100	36	up to 150
Reported throughput (Mt/year)	up to 100	up to 100	–
Reported capital cost (USD million/km)	from 10	from 3	–
Vehicle payload (tonnes)	1 – 35	1 – 35	1 – 35
Track / rolling stock service life (years)	up to 50 / 25	up to 50 / 25	up to 50 / 25

Source: compiled by the author from reported technical documentation [10]

4.2 System configuration

Figure 1 shows the schematic arrangement of an elevated string-rail cargo complex. Anchor supports at the ends carry the horizontal tension of the prestressed rail, while lighter intermediate supports carry vertical load only.

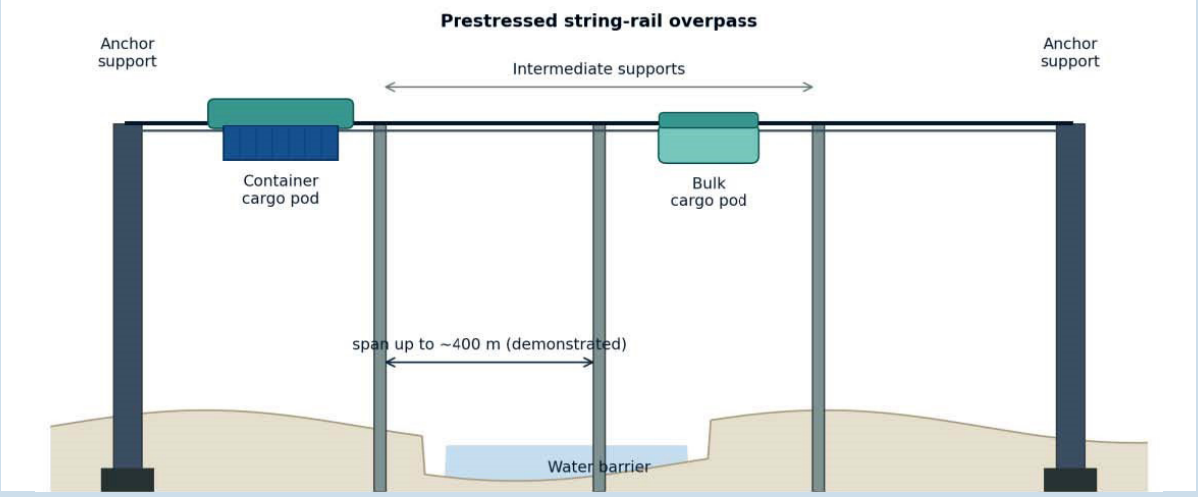


Figure 1. Schematic arrangement of an elevated string-rail cargo complex crossing a terrain and water barrier. Made by authors

Because the guideway is raised, the line can cross water, difficult terrain and existing infrastructure with a footprint limited to the supports, and cargo pods for containers and for bulk material can share the same overpass.

4.3 Environmental and economic comparison

Figure 2 presents indicative specific carbon dioxide intensities for the compared modes. Road haulage is the most intensive, followed by inland waterway and electrified rail. The string-rail estimate, derived from Equation (1) under the European electricity mix, falls close to electrified rail, which is consistent with its electric steel-wheel traction and low aerodynamic and rolling resistance. It should be stressed that this value is an author estimate and is grid-dependent: on a low-carbon grid it would fall further, while on a coal-dominated grid it would rise.

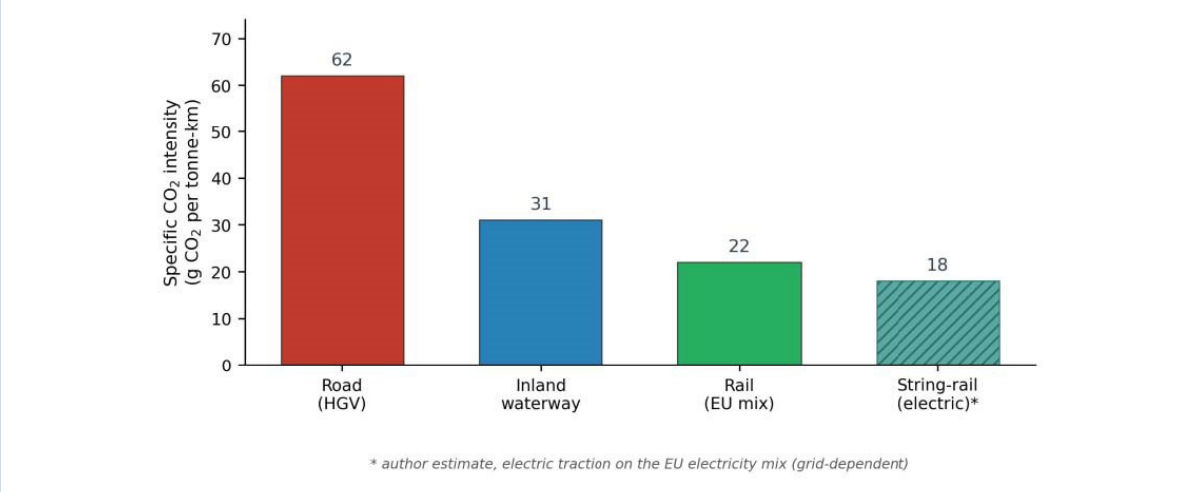


Figure 2. Indicative specific carbon dioxide intensity by freight mode. Made by the author, based on [1, 3] and Equation (1)

Table 2 consolidates the comparison across all six criteria. The string-rail concept is distinguished less by any single dominant advantage than by its combination of low operational intensity, very small land take and the ability to overcome barriers, set against a high reported capital cost for containerised lines and a low level of technological maturity.

Table 2. Comparative assessment of the string-rail concept and conventional freight modes

Criterion	Road (HGV)	Rail (elec.)	Inland waterway	String-rail
Max. speed	high	high	low	medium–high
Throughput	low–medium	high	high	high (reported)
CO2 intensity	high	low	low	low (est.)
Land take	high	high	medium	very low
Capital cost	low	medium–high	medium	high (reported)
Barrier crossing	poor	poor	n/a	strong
Maturity	very high	very high	very high	low

Source: made by the authors

5 DISCUSSION

The comparison suggests that elevated string-rail cargo complexes are unlikely to displace long-haul rail or waterborne freight on the corridors where those modes already perform well. Their advantage lies elsewhere. The very small ground footprint and the ability to cross water, steep terrain and built-up areas point towards a role as a second-level feeder that links nodes which are otherwise costly to connect, rather than as a replacement trunk mode. This mirrors the conclusion reached for aerial cable systems in urban freight, where the benefit is greatest precisely where road access is constrained [7, 9].

For maritime logistics the implication is specific. Port throughput is increasingly limited not at the quay but along the land interface, where hinterland access, storage and the last few kilometres to inland terminals create bottlenecks.

Port regionalisation theory frames this as a shift of the competitive frontier inland, towards integrated corridors and dry ports [13]. An elevated string-rail feeder could connect a marine terminal to an inland logistics zone or an industrial site above existing road and rail, decoupling port-gate flows from urban congestion and reducing the storage that must be held on scarce quayside land. The same elevated principle has been proposed to place terminal structures offshore, over natural depths, which would reduce dredging, although such claims lie well beyond the scope of the present assessment and require independent study.

Several limitations must temper these observations. First, the technical parameters originate from a single manufacturer and have not been independently verified; the reported throughput figures in particular are theoretical maxima. Second, only two demonstration installations are documented, and no full-scale commercial cargo line is in operation, so the concept sits at a low level of technological maturity. Third, the reported capital cost for containerised lines is high relative to some conventional rail, and the low design speed of the bulk configuration constrains its use to short, high-volume shuttles. Fourth, regulatory frameworks and safety certification for automated elevated freight remain immature, which affects insurability and public acceptance. These limitations do not invalidate the concept, but they define the evidence that is still missing.

Future work should therefore prioritise independent measurement. A full life-cycle assessment covering construction materials, operation and end of life would test the environmental claims against the estimates presented here. A multi-criteria decision analysis populated with primary operational data, rather than reported values, would allow a fair ranking against alternatives for a defined corridor.

Finally, a site-specific feasibility study of a port-to-hinterland feeder would be the most direct way to establish whether the theoretical advantages translate into practice.

6 CONCLUSION

This paper assessed elevated string-rail cargo complexes as a candidate sustainable freight mode through a structured comparison with road, rail and inland waterway transport. The concept combines electric steel-wheel traction, giving an estimated operational carbon dioxide intensity close to that of electrified rail, with a very small ground footprint and a strong ability to cross water and difficult terrain. These characteristics position it not as a trunk mode but as a second-level feeder, with a particularly plausible niche linking ports and terminals to inland logistics and industrial sites. The main caveats are the reliance on manufacturer-reported data, the high reported capital intensity of containerised lines, and the low level of technological maturity, with only demonstration installations to date. The contribution of the paper is a transparent, criteria-based framing of where such systems might add value and, equally important, of the independent evidence that must be gathered before the concept can be adopted with confidence.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Connected Reefer Containers for Perishable Cargo Supervision: Multivariable Early Warning of Microclimate Conditions Associated with Accelerated Ripening

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ABSTRACT

Modern refrigerated containers can provide continuous operational and microclimate data during maritime and intermodal transport. In practice, reefer supervision is still mainly based on setpoint tracking, supply- and return-air temperature monitoring, and unit-level alarm thresholds. This paper evaluates a multivariable early-warning approach for connected reefer containers carrying climacteric horticultural products. The approach combines reefer-operating and cargo-microclimate time series and compares a conventional temperature-only baseline with random forest, GRU and LSTM models. Evaluation is performed on a physically informed synthetic demonstration dataset comprising 60 banana voyages and five operating scenarios, using a 2 h input window, a 2 h prediction horizon, voyage-level train/validation/test separation and three repeated random initialisations. Combined-input models substantially outperformed the conventional temperature-only baseline. Among the combined-input models, random forest achieved the highest F1-score (0.924) and the lowest false-alarm rate (0.004), LSTM the highest AUC (0.945), and GRU the longest mean warning lead time (42.5 min). No single model was superior across all criteria. The results support multivariable cargo-condition-oriented supervision while remaining a methodological demonstration that requires validation with measured reefer and postharvest-quality data.

Keywords: connected reefer containers; cold-chain logistics; cargo microclimate; multivariable early warning; time-series modelling; intelligent transport systems

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1 INTRODUCTION

Refrigerated containers are essential transport units for perishable cargo because they maintain controlled thermal conditions during maritime and intermodal movement. In routine operation, reefer supervision is mainly concentrated on the refrigeration unit, setpoint tracking, supply-air temperature, return-air temperature and alarm status. This equipment-centred approach is necessary for detecting technical deviations, but it does not fully describe the cumulative exposure of cargo to temperature, humidity, ventilation and atmospheric conditions during transport.

For climacteric horticultural products, cargo quality is not determined by air temperature alone. Ripening and loss of marketable life are influenced by product temperature, airflow distribution, relative humidity, respiration activity, carbon dioxide and oxygen levels, and ethylene accumulation. Previous work on virtual refrigerated containers has shown that temperature distribution and fruit-quality evolution inside a loaded container are spatially and temporally variable, confirming that return-air temperature alone cannot fully represent product-level conditions [1].

The increasing availability of reefer controller data, cargo sensors, communication modules and edge processing enables a more detailed interpretation of cold-chain transport. Time-series models are suitable for this task because reefer operation and cargo microclimate have delayed responses. LSTM networks have already been applied to temperature prediction in temperature-controlled containers [2], and related recurrent approaches have been used for environmental prediction in cold-chain transport of agricultural products [3]. However, for transport supervision, the main objective is not only to predict temperature, but to identify developing microclimate conditions that may increase cargo-quality risk before a conventional alarm is generated.

Atmosphere-related indicators are relevant for this purpose. Ethylene concentration can provide information on ripening-related processes in controlled-atmosphere transport [4], while information and communication technology solutions increasingly support monitoring and traceability in food supply chains [5]. Multisource sensing studies have also demonstrated the added value of combining environmental and gas-related variables for freshness assessment in cold-chain logistics [6]. These findings indicate that connected reefer containers should be interpreted not only as refrigeration machines, but also as data-generating elements of intelligent freight infrastructure.

This paper evaluates a multivariable early-warning framework for connected reefer containers carrying perishable horticultural products. The study compares conventional temperature-only supervision with random forest, GRU and LSTM models using the same voyage-level validation split. The contribution is threefold: first, it defines a reproducible synthetic-data and target-generation procedure for cargo-condition risk; second, it quantifies the value of combined reefer-operating and cargo-microclimate inputs; and third, it evaluates performance using classification quality, false-alarm behaviour and warning lead time rather than temperature prediction alone.

2 BACKGROUND

A marine refrigerated container is a distributed thermal and airflow system rather than a homogeneous refrigerated volume. Conditioned air is supplied through the floor or air-distribution channels, passes through packaging and cargo spaces, and returns to the evaporator section. Supply-air and return-air temperatures are useful indicators of refrigeration-unit operation, but they cannot fully describe local product temperature, airflow restriction, moisture distribution or the physiological state of the cargo. A loaded reefer container may therefore contain local zones in which cargo exposure differs from the values observed by the unit controller [1].

Conventional reefer supervision confirms whether the refrigeration unit follows the prescribed setpoint and whether alarm thresholds are exceeded. This is technically necessary, but it is not

equivalent to cargo-quality supervision. For climacteric horticultural products, the relevant risk is often cumulative and multivariable. Temperature deviation, insufficient ventilation, humidity imbalance, elevated carbon dioxide, reduced oxygen and ethylene accumulation may interact over time and influence the ripening process [4, 6].

Sequential modelling is suitable for this problem because the reefer-cargo system has delayed responses. A defrost cycle, compressor operating change, ventilation restriction or short thermal disturbance may influence cargo conditions with a time lag. LSTM models have already been applied to temperature prediction in temperature-controlled containers [2], while related recurrent approaches have been used for temperature and relative-humidity prediction in agricultural cold-chain transport [3]. The present study therefore compares recurrent and non-recurrent models for a different operational objective: early warning of multivariable microclimate risk associated with accelerated ripening, rather than temperature prediction alone.

3 METHODOLOGY

The proposed methodology treats the refrigerated container as a connected transport unit that generates operational and cargo-microclimate time series during transport. The objective is to identify a developing multivariable exposure condition before conventional return-air temperature alarms indicate abnormal operation. The method includes five functional stages: data acquisition, communication and storage, preprocessing, temporal modelling and decision-support output.

The data acquisition stage includes setpoint, supply-air temperature, return-air temperature, ambient temperature, compressor operation, defrost events, ventilation status and alarm state, together with relative humidity, cargo temperature, carbon dioxide, oxygen and an ethylene-related indicator. For the synthetic generator, banana transport conditions were centred on a 13.3-13.9 °C setpoint with high relative humidity and controlled-atmosphere ranges consistent with published postharvest guidance [7]. **Figure 1** shows the external monitoring and decision-support architecture used in the study.

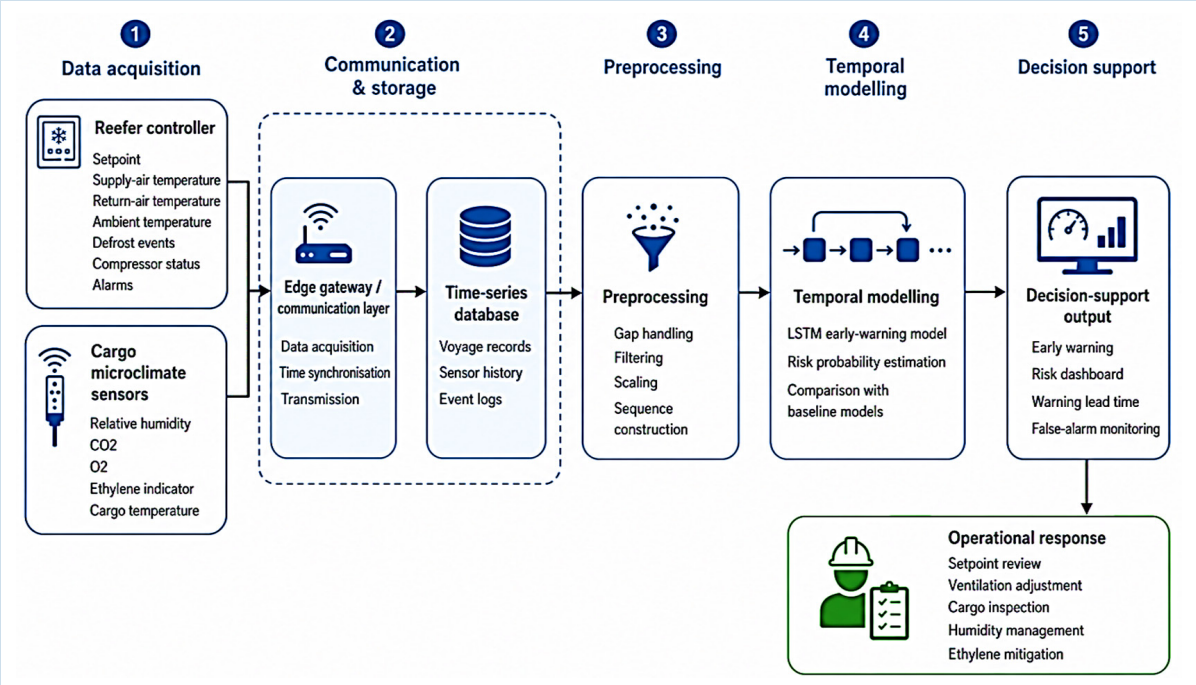


Figure 1. Proposed architecture of the connected reefer-container early-warning system (Made by authors).

3.1 Synthetic data and risk-target definition

Measurements were sampled at 15 min intervals. Each model receives an eight-sample input window (2 h) and predicts whether a risk-positive state will occur within the following eight samples (2 h). A dimensionless exposure index was defined as $E = 0.35z_T + 0.15z_{RH} + 0.15z_V + 0.15z_{CO2} + 0.10z_{O2} + 0.10z_{Eth}$, where $z_T = \max[(T_{cargo} - 14)/1.5, 0]$, $z_{RH} = \max[(RH - 95)/4, (90 - RH)/5, 0]$, $z_V = 1 - v$, $z_{CO2} = \max[(CO_2 - 5)/2, 0]$, $z_{O2} = \max[2.5 - O_2, 0]$ and $z_{Eth} = \max[(Eth - 0.8)/2, 0]$. Here T_{cargo} is the cargo temperature (°C), RH the relative humidity (%), v the ventilation opening as a fraction of its nominal setting (0–1), CO_2 and O_2 the atmosphere concentrations (%), and Eth the dimensionless ethylene indicator. The z terms are normalised exceedances of the reference ranges rather than statistical z-scores, so E = 0 denotes conditions inside the target envelope. A risk-positive state was assigned when the 2 h moving mean of E exceeded 0.09; a sequence was labelled positive if that state occurred anywhere within the 2 h prediction horizon. The input window and future target do not overlap, and voyages are separated before sequence construction, preventing temporal leakage between training and test data. The exposure-index weights and the 0.09 risk threshold were fixed a priori for this methodological demonstration and were not optimised against the validation or test subsets.

The physically informed synthetic dataset contains 60 voyages: 12 for each of the five scenarios in **Table 1**. Voyage duration was 36–37 h, giving 2202 h of data. Baseline setpoints were sampled uniformly from 13.3–13.9 °C, initial relative humidity from 91–94%, CO_2 from 3.5–4.8% and O_2 from 2.6–3.8%. Cargo temperature followed a first-order response, $T(t + \Delta t) = T(t) + \Delta t/\tau_T[T^*(t) - T(t)] + \varepsilon_T$, with τ_T = 1.2–2.0 h; relative humidity used the same form with τ_{RH} = 1.0–2.0 h. Atmosphere-related variables followed first-order balances driven by ventilation and a Q_{10}-type respiration factor $2^{[(Tcargo-13.5)/10]}$. Ambient temperature, response time constants, disturbance onset, disturbance duration and disturbance magnitude were varied independently between voyages. Between-voyage variability was introduced through randomised baseline conditions and scenario timing, while zero-mean Gaussian perturbations represented sensor and process variability (σ = 0.025 °C for cargo temperature, 0.035 °C for supply- and return-air temperature, 0.15% for relative humidity, 0.03% for CO_2, 0.025% for O_2 and 0.02 arbitrary units for the ethylene indicator).

Table 1. Demonstration scenarios used for model evaluation (Made by authors).

Scenario	Operating condition	Purpose
S1	Stable operation: setpoint 13.3–13.9 °C	Baseline behaviour
S2	Thermal forcing +3.3–5.5 °C for 2.5–5.5 h	Thermal early-warning sensitivity
S3	Ventilation reduced to 20–50% for 3–6 h	Operational / atmosphere response
S4	Defrost pulse +0.8–1.4 °C for 0.5–1.0 h	Short transient response
S5	Ventilation 30–60% plus +2.9–4.4 °C forcing for 5–8 h	Delayed corrective-action case

3.2 Model development and validation

Continuous variables were standardised using statistics calculated from the training voyages only; binary operating states were retained as numerical indicators. The 60 voyages were stratified by scenario into 40 training, 10 validation and 10 test voyages; sequences from a voyage were never shared between subsets.

The conventional temperature-only baseline uses the maximum return-air temperature in the 2 h input window as its score and the 16.5 °C alarm threshold for binary classification. Random forest uses the flattened combined-input window with 300 trees, maximum depth 12, minimum leaf size 3 and

balanced class weights. GRU and LSTM use one recurrent layer with 16 hidden units followed by an 8-unit dense layer and 0.2 dropout. Both are trained with Adam (learning rate 0.001), weighted binary cross-entropy, batch size 64, a maximum of 25 epochs and early stopping with patience 4 on validation loss. A probability threshold of 0.50 is used for RF, GRU and LSTM. The three machine-learning models were repeated with random seeds 11, 23 and 37; results are reported as mean ± standard deviation. Performance is assessed by F1-score, AUC, false-alarm rate (FAR) and warning lead time. FAR is the proportion of risk-negative sequences classified as risk-positive, and warning lead time is the interval between the first model warning and the start of the following risk-positive interval, averaged over the held-out test voyages that contain such an interval. All model structures and hyperparameters were fixed before test evaluation; the validation subset was used only for early stopping, while the held-out test subset was reserved for final performance reporting.

4 RESULTS

The revised evaluation uses the fully specified physically informed synthetic generator described above. The purpose remains methodological: to determine whether multivariable time-series inputs can identify a future risk-positive state more effectively than conventional temperature-only supervision, without presenting the synthetic labels as measured biological ripening.

The dataset characteristics are summarised in **Table 2**. The 60 simulated voyages provide 2202 h of 15 min data. With the 2 h input window and 2 h prediction horizon, 7848 sequences were generated. Risk-positive modelling labels represented 16.6% of sequences, while the conventional return-air alarm threshold was exceeded in 3.1% of time samples.

Table 2. Synthetic demonstration dataset and experimental conditions (Made by authors).

Parameter	Value	Unit
Cargo type	Banana	-
Simulated voyages	60	-
Sampling interval	15	min
Total duration	2202	h
Number of sequences	7848	-
Risk-positive modelling labels	16.6	%
Conventional alarm samples	3.1	%

Table 3 reports held-out test performance. The conventional temperature-only baseline achieved an F1-score of 0.450 and an AUC of 0.829, but the 16.5 °C threshold did not provide pre-risk warning. Its false-alarm rate of 0.000 therefore reflects a conservative threshold that responds only after the risk state has developed, which is also visible in its much lower F1-score. Across three random initialisations, the combined-input models achieved markedly higher F1-scores and low false-alarm rates, although the ranking depended on the selected metric.

Combined input refers to reefer-operating and cargo-microclimate variables. FAR denotes false-alarm rate. RF, GRU and LSTM values are mean ± standard deviation over three random initialisations. Warning times are evaluated on the 15 min sampling grid, so an initialisation-independent first-warning sample gives a zero-standard deviation for the GRU lead time.

No single combined-input model dominated all metrics. Random forest achieved the highest F1-score and the lowest FAR among these models, LSTM the highest AUC, and GRU the longest mean warning

lead time. A compact random-forest input ablation gave AUC 0.780 ± 0.001 with thermal variables only, 0.923 ± 0.001 after adding operational states, 0.923 ± 0.001 with relative humidity, and 0.919 ± 0.003 after adding atmosphere-related variables. Thus, most of the incremental information in this synthetic experiment came from operational-state variables rather than from every additional sensor group. Scenario-wise performance is not reported separately because the held-out S1 and S4 voyages contain no risk-positive labels under the present target definition, which leaves scenario-specific AUC undefined for those cases; scenario-level validation is left for a larger study based on measured data.

Table 3. Model-performance summary on the synthetic demonstration dataset (Made by authors).

Model	Input	F1	AUC	FAR	Lead time
Temperature-only baseline	Temperature	0.450	0.829	0.000	0 min
Random forest	Combined	0.924 ± 0.002	0.919 ± 0.003	0.004 ± 0.000	38.3 ± 1.4 min
GRU	Combined	0.911 ± 0.015	0.938 ± 0.004	0.010 ± 0.005	42.5 ± 0.0 min
LSTM	Combined	0.904 ± 0.014	0.945 ± 0.011	0.011 ± 0.007	41.7 ± 1.4 min

Figure 2 shows one held-out S5 voyage. The LSTM warning was issued at 23.00 h, the risk-positive state began at 23.75 h and the conventional return-air alarm occurred at 27.00 h. The representative sequence therefore provides 45 min of pre-risk warning and illustrates that the model output is a decision-support signal rather than a replacement for the unit alarm system.

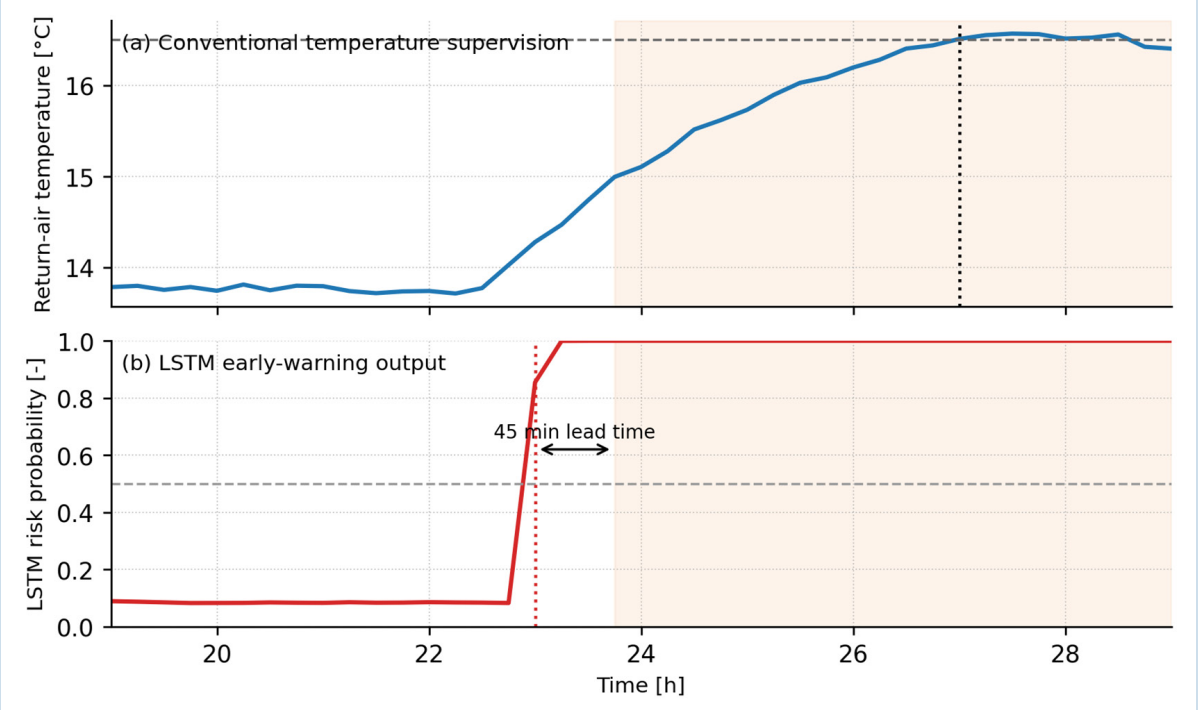


Figure 2. Representative S5 test voyage showing conventional return-air temperature supervision and LSTM early-warning output relative to the risk-positive interval (Made by authors).

These results are interpreted as performance of a reproducible synthetic microclimate-risk experiment, not as validation of biological ripening under commercial transport conditions.

5 DISCUSSION

The revised results confirm that the main contribution is multivariable cargo-condition supervision rather than superiority of a particular algorithm. The input ablation shows that operational-state variables provide most of the gain over temperature-only information in the present synthetic generator, while the additional humidity and atmosphere-related channels do not independently improve random-forest AUC. This prevents attributing unsupported benefit to every sensor group and identifies an important point for validation with measured data.

Model ranking also depends on the performance criterion. Random forest provides the highest F1-score and the lowest FAR among the combined-input models, LSTM the highest AUC, and GRU the longest mean lead time. The title and framing have therefore been revised to emphasise multivariable early warning rather than LSTM alone. LSTM remains relevant because the problem is sequential and because it achieved the highest discrimination, but the results do not support treating it as a universal best model.

The risk-positive target is an operational surrogate derived from future microclimate exposure; it is not a direct measurement of fruit ripeness. The synthetic generator now makes its assumptions, variability, target construction and validation split explicit, but industrial validation still requires measured reefer logs together with cargo-microclimate and postharvest-quality observations. The present results should therefore be interpreted as a reproducible method demonstration rather than evidence of biological prediction accuracy.

In practical reefer operations, the warning should support operator verification rather than autonomous control. A warning could trigger review of controller and ventilation status, controlled-atmosphere performance, sensor consistency and the need for targeted cargo inspection. Any adjustment of setpoint, ventilation or atmosphere must remain commodity-specific and follow the carrier or cargo-handling protocol. This role is consistent with the proposed architecture as an external decision-support layer.

6 CONCLUSION

This paper evaluated a multivariable early-warning approach for connected reefer containers using a fully specified synthetic demonstration of banana transport. A 2 h history was used to predict risk-positive exposure within the following 2 h. Combined-input models outperformed the conventional temperature-only baseline, but no model dominated all criteria: random forest achieved the highest F1-score and lowest FAR, LSTM the highest AUC, and GRU the longest mean warning lead time.

The contribution is therefore the reproducible integration of reefer-operating and cargo-microclimate time series for cargo-condition-oriented decision support, not a claim of validated biological ripening prediction. Future work should replace the synthetic target with measured transport and postharvest-quality data, test sensor-group value under real operating variability, and evaluate how warning thresholds translate into practical operator actions.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Feasibility Assessment of UAV Delivery Logistics in the UTM/U-Space Environment

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ABSTRACT

The increasing use of UAVs in delivery logistics creates the need for a structured assessment of mission feasibility in digitally managed low-altitude airspace. Large-scale low-altitude UAV operations require traffic-management support because they may involve deliveries, BVLOS missions and operations in airspace affected by static and dynamic constraints. The European U-space framework defines mandatory services for UAS operations in U-space airspace, including network identification, geo-awareness, UAS flight authorisation and traffic information. It also allows weather information and conformance monitoring to become mandatory where required by the airspace risk assessment. For UAV delivery missions, feasibility is affected by payload constraints, available energy autonomy and wind-dependent energy consumption. Communication requirements are also part of the operational assessment because 3GPP support for UAS includes C2 communication, remote identification, route-data exchange, route modification and latency requirements. This paper develops a technical-operational framework for assessing the feasibility of UAV delivery missions in the UTM/U-space environment. The framework connects aircraft range, payload requirements, energy reserve, communication reliability and U-space constraints into a structured assessment of delivery scenarios. The proposed approach distinguishes missions that are technically feasible, operationally acceptable and logistically justified from missions limited by energy consumption, communication performance, traffic-management requirements or infrastructure constraints. The paper provides a planning-oriented basis for future evaluation of UAV delivery in rural and island areas.

Keywords: UAV delivery; UTM; U-space; delivery logistics; C2 communication; mission feasibility

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1 INTRODUCTION

Unmanned aerial vehicles (UAVs) are being used more often for delivery tasks where quick response, hard-to-reach locations, or spread-out destinations make traditional last-mile transport less effective. Still, one cannot judge if a UAV delivery mission is possible just by looking at the aircraft's range or the straight-line distance between start and end points. Factors like payload, available energy, weather, communication quality, airspace rules, and regulations all play a role in whether a mission can be carried out safely and effectively [1–3].

This challenge is especially important for beyond visual line of sight (BVLOS) operations. UAS Traffic Management (UTM) systems have been created to help manage low-altitude drone flights at scale [4], and the European U-space framework provides digital services for drone operations in specific airspace. Regulation (EU) 2021/664 lists four required U-space services: network identification, geo-awareness, UAS flight authorisation, and traffic information [5]. These services help decide if a planned route is available and can directly impact whether a mission is possible.

U-space requirements are part of the larger European rules for drone operations. Depending on the mission's details and risks, delivery flights especially BVLOS missions may need to be reviewed under the specific category and its risk framework [6]. Reliable Command and Control (C2) communication is also crucial, since losing or weakening the connection can make a route that might be technically unusable in practice [7].

Previous research has looked closely at single factors like energy use, payload, wind, and communication needs [1]. But in real delivery missions, these factors affect one another. For example, a route might have enough energy but be blocked by airspace rules, while another approved route could use more energy or pass through an area with poor C2 communication.

This leads to the main research question: Which combination of technical, operational, and logistical factors make a UAV delivery mission possible in a UTM or U-space setting? This paper aims to create a comprehensive framework for assessing missions by integrating payload and energy limits, C2 communication, rules and U-space needs, airspace conditions, and the required logistics service.

2 BACKGROUND

Whether UAV delivery can take place in a digitally managed airspace is determined by the way in which the performance of the aircraft interacts with the environment in which the mission is carried out. UTM refers to the general notion of services and procedures designed to enable safe and efficient low-altitude UAS operations [4]. In Europe, U-space is the regulatory framework relating to the offering and use of digital services in designated U-space airspace [5].

The four essential U-space services are especially pertinent to delivery operations. Network identification allows authorised users to obtain information regarding the identity and position of the UAS. Geo-awareness supplies current details on the applicable operational conditions, airspace restrictions, and UAS geographical zones. UAS flight authorisation decides if the requested flight can take place within U-space airspace, and traffic information gives information about the surrounding traffic [5]. As a result, the feasibility of a mission depends not just on whether the aircraft can physically get to its destination, but also on whether the intended flight can be conducted under the applicable airspace conditions.

Energy is one of the primary physical constraints regarding UAV deliveries. Sorbelli et al. show that wind conditions can have a significant effect on the amount of energy needed to carry out a delivery mission and return to the depot [1]. Empirical flight research does likewise confirm that the payload, speed and the various flight phases have an impact on energy demand and consequently on the

effective operational range [2]. Furthermore, Stolaroff et al. prove that both the payload and the characteristics of the aircraft affect the energy performance of commercial package-delivery UAVs [3]. It therefore follows that the nominal range should not be understood as a fixed mission radius.

There is also a constraint that depends on the route. The ETSI/3GPP requirements regarding support for UAS include C2 communication as well as functions connected with remote identification and interaction with UAS traffic management [7]. For the purpose of a delivery mission, general cellular coverage alone is not adequate as a criterion for assessment; it is necessary for the required communication performance to be available on the most important sections of the planned route.

The fact that technical, airspace and communication limitations cannot be assessed separately means that if a route is altered due to U-space or airspace requirements, its distance, its exposure to wind and its communication environment may also be affected. Mission feasibility has to be considered as an iterative problem rather than one that involves only a geometric evaluation of the route.

3 METHODOLOGY

The study presents an analytical framework aimed at evaluating the feasibility of a single UAV delivery mission on the basis of requirements. This framework is obtained by combining requirements drawn from the European UAS and U-space regulatory environment [5], the UAS communication requirements [7] and the results of studies concerning energy-constrained UAV delivery [1].

The framework is designed for use in screening and assessing missions. It does not seek to replace an operational risk assessment, the UAS flight authorisation process or a detailed aircraft performance model; rather, it organises the information needed to establish whether a specific delivery mission is feasible, and if not, to identify the reason.

A mission M is defined by:

$$M = \{O, D, R, U, P, W, C, A, I, S\} \tag{1}$$

where O and D stand for origin and destination, R for the planned route, U for the selected UAS, P for the payload, W for the relevant environmental conditions, C for the communication environment, A for the airspace conditions, I for the required infrastructure and S for the logistics service requirement.

The assessment takes place at three levels in sequence: technical feasibility, operational acceptability and logistical justification. At each level there is a decision gate. A mission only moves on to the next level once the conditions set out at the previous level have been met.

The technical feasibility is evaluated by looking at the payload's compatibility, the available energy, the navigation capability and the C_2 communication.

The requirement related to the payload states that the mass of the cargo and its delivery configuration must stay within the limits set for the selected UAS; furthermore, when considering the payload it is necessary to take into account the energy available since an increase in the mass carried will raise the demand on the propulsion system and reduce the range achievable [2, 3].

The energy criterion is expressed as:

$$E_{req} \leq E_{avail} - E_{res} \tag{2}$$

where E_{req} represents the energy required to complete the mission, E_{avail} the usable energy available at departure and E_{res} the required energy reserve.

The operational profile as a whole, and not just the horizontal cruise distance, should be taken into account when assessing E_{req}. For a given mission, this will cover take-off, the climb, the outbound flight, the delivery or landing manoeuvre, the return or recovery phase and the final landing. Since payload and environmental conditions, especially wind, can cause a mission to become infeasible, they have to be included in the energy model that is selected [1].

The second route-dependent technical requirement concerns navigation and C2. A delivery route can only be considered acceptable if both navigation performance and the necessary C2 communication can be maintained during all mission-critical sections. The exact C2 performance thresholds vary according to the operational concept and the relevant requirements and must therefore be established for the specific operation rather than being substituted by a general latency or coverage figure [7].

Technical feasibility can be represented as:

$$F_T = C_P \cdot C_E \cdot C_N \cdot C_{C2} \tag{3}$$

The binary variables show compliance with the requirements concerning payload C_P, energy C_E, navigation C_N and C2 communication C_{C2}. In the case where any of these criteria is not met, $F_T = 0$ and the mission then needs to be modified by altering the payload, the platform, the route, the departure conditions or the communication solution before it can be assessed further.

The mission, having first been found to be technically feasible, is then evaluated in light of the regulatory, U-space, airspace and infrastructure conditions.

The first thing to do is to determine the relevant regulatory framework; where this is necessary in view of the characteristics and risks involved, the mission has to meet the conditions applicable to the *specific* category as well as the corresponding operational risk assessment and authorisation requirements set out in Regulation (EU) 2019/947 [8]. The proposed framework does not seek to replace this process since regulatory approval is regarded as an input condition for operational acceptability.

When the planned route enters the designated U-space airspace, the flight must comply with relevant U-space requirements. In particular, the mission has to make use of the mandatory services defined by Regulation (EU) 2021/664 and acquire the necessary UAS flight authorisation [5]. Where applicable, operational authorisation under Regulation (EU) 2019/947 and UAS flight authorisation under Regulation (EU) 2021/664 are therefore regarded as separate assessment conditions.

The system uses geo-awareness together with up-to-date information about airspace to determine whether the proposed route is compatible with geographical zones, temporary restrictions and any other relevant airspace constraints. When it is not possible to use the route being requested and an alternative one has to be suggested, then that alternative is regarded as a new technical input and its energy requirement and C2 conditions must be reassessed before the mission can be approved.

Operational feasibility also calls for appropriate physical infrastructure to support departure, handling of the payload, delivery and recovery of the vehicle or the termination of the mission. The infrastructure needed will depend on the method of delivery and could involve a specified landing or delivery site, as well as the possibility of charging or replacing the batteries when repeated operations are involved.

Operational acceptability is expressed as:

$$F_O = F_T \cdot C_R \cdot C_U \cdot C_A \cdot C_I \tag{4}$$

where C_R represents regulatory compliance, C_U U-space compliance, C_A airspace acceptability and C_I infrastructure availability.

The fact that a UAV mission is technically and operationally feasible does not mean that it achieves its logistics objective; it is only on the basis of the final assessment level that it can be said to meet the established service requirement.

The criterion should be established before the mission is assessed. It could involve a maximum delivery time, a delivery time window, shipment priority or the need for a certain platform availability. In the case of a delivery that is time-constrained, the basic condition can be expressed as:

$$T_{delivery} \leq T_{max} \tag{5}$$

where $T_{delivery}$ is the expected mission delivery time and T_{max} the maximum acceptable delivery time.

The framework intentionally separates logistical justification from complete economic viability, since the costs associated with acquiring vehicles, employing personnel, taking out insurance, carrying out maintenance or making investments in infrastructure lie outside the scope of the current mission-level assessment and would need further empirical and financial data.

The final condition is:

$$F_L = F_0 \cdot C_S \tag{6}$$

where C_S denotes compliance with the predefined logistics service requirement.

4 RESULTS

The four different types of mission results that arise from the use of the proposed framework depend on the first assessment level at which the predefined requirements are not met. The framework thus goes beyond providing a simple feasible/infeasible decision since it shows at which level the limiting condition occurs.

A mission is deemed technically infeasible if at least one of the technical requirements pertaining to payload compatibility, available energy, navigation capability, or C2 communication is not met. If all of the technical criteria are satisfied but one or more of the regulatory, U-space, airspace or infrastructure requirements are not fulfilled, the mission is regarded as operationally unacceptable. In cases where both the technical and operational requirements are met yet the predefined delivery or service requirement is not achieved, the mission is considered logistically unjustified. Those missions which meet all three of the assessment criteria are classified as feasible.

A key outcome of the framework is that the classification of a mission does not have to be concluded at the first assessment. In cases where the conditions in U-space or the airspace call for a change in the route, the altered route acts as a new technical input since its energy requirements and C2 communication requirements will be different from those of the original route. It follows that the route-dependent technical criteria must be re-evaluated before the mission can move on to the next assessment levels.

The framework proposed therefore allows the limiting condition to be identified at the technical, operational or logistical level. Since it has not yet been applied to an empirical mission dataset, the results given here should be regarded as qualitative assessment states rather than actual measured mission frequencies, delivery ranges or probabilities of mission success.

5 DISCUSSION

The framework suggested in this paper goes beyond the traditional energy-centered problem of assessing the feasibility of UAV deliveries. Although energy remains a major limiting factor, Sorbelli et al. show that changing wind conditions can affect whether a delivery mission can be carried out successfully [1], while real-flight data indicate that both payload and flight conditions influence energy consumption and range [2] , and an energy-feasible mission is not necessarily operationally feasible in a managed low-altitude airspace environment.

The key feature of the framework is its integration of aircraft capability and operational access at the level of each individual mission. U-space brings about circumstances that may vary during the course of mission planning. For example, geo-awareness information, airspace restrictions or the UAS flight authorisation procedure might result in the originally chosen route becoming unavailable [5]. In such cases, rerouting cannot be regarded merely as an action concerning airspace management since the distance, exposure to wind and C2 conditions may also be affected.

It shows that the shortest route in terms of geometry is not always the most practical delivery route. Although a direct route means the least distance, it could be in an airspace that is unacceptable or in a section with inadequate communication performance. An alternative that covers greater distance might enhance operational or communication acceptability, but would need more energy. On the other hand, a route which includes an adequate energy margin could still fail since the required U-space or regulatory conditions are not met. The various constraints should therefore be taken into account together rather than being optimised separately.

The framework also distinguishes between feasibility and logistical usefulness since it is necessary for a mission to meet the requirements relating to safety, regulatory compliance and aircraft performance even if it fails to achieve the service objective which was the reason for using a UAV. For instance, a considerable need for route changes might keep the mission technically and operationally feasible but at the same time offset the intended time benefit. That is why the framework treats the logistics requirement as a separate final check rather than supposing that every UAV mission which can be carried out is also operationally useful.

This method is especially appropriate when evaluating rural and island delivery situations, since physical accessibility and the degree of spatial separation could make UAV transport a viable option. Yet the current study does not show that UAV delivery is generally feasible or better in these areas, and to reach such a conclusion it would be necessary to have case-by-case empirical data regarding routes, wind conditions, terrain, UAS geographical zones, communication coverage, aircraft performance and the existing infrastructure.

The following limitations should therefore be acknowledged. The first is that the framework has not yet been tested on actual delivery missions. The second is that the binary gate structure oversimplifies factors which are in fact continuous or probabilistic, such as wind conditions, energy margin and communication reliability. The third point is that while the framework determines whether a mission is feasible it does not optimise fleet size, hub location, scheduling or economic performance.

Future research should therefore apply the framework to a case study that is defined in terms of geography, using the actual specifications of UAVs together with meteorological, airspace and communication data that have a spatial reference. This approach would enable the proportion of missions falling into the different mission outcome categories to be determined and would show which constraints most frequently prevent the execution of a delivery.

6 CONCLUSION

It is impossible to judge whether UAV delivery is feasible within a UTM/U-space environment just on the basis of the nominal range of the aircraft or the distance of the route. A mission can only be considered feasible if the aircraft's performance, communication requirements, regulatory requirements, current airspace conditions and desired logistics service are all met at the same time.

The paper puts forward a three-level assessment framework made up of technical feasibility, operational acceptability and logistical justification. Technical feasibility looks at the payload, energy, navigation and C2 requirements. Operational acceptability examines the relevant regulatory and U-space requirements, airspace availability and infrastructure, and logistical justification assesses whether the mission meets the predefined delivery requirement.

The key result of the framework is that there is a feedback effect between these assessment levels; specifically, if a route is altered as a result of U-space or airspace conditions, this will affect energy consumption and C2 performance and thus mean that a renewed technical assessment is required. It cannot therefore be assumed that the shortest or theoretically achievable route is the one that is feasible.

The framework offers a structured approach to determining which constraint was responsible for the failure of the mission and sets the different categories of missions as technically infeasible, operationally unacceptable and logistically unjustified. The following stage should involve quantitative validation based on actual mission, meteorological, communication and airspace data, especially in the case of delivery operations in rural and island areas.

Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, analysis, interpretation, and conclusions were developed and verified by the author(s), who remain fully responsible for the content.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Optimization of Delivery Vehicle Allocation and Routing Using Free Open-Source Tools: A Case Study of Express Parcel Delivery in Rijeka, Croatia

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ABSTRACT

This paper presents a mathematical modelling framework for optimising delivery vehicle allocation and routing in parcel logistics, addressing the Vehicle Routing Problem (VRP) through free, open-source software tools. Two complementary models were implemented in Python using the Google OR-Tools library: a vehicle allocation model minimising the number of active vehicles, and a routing model based on the Pickup and Delivery Problem with Time Windows (PDPTW). Queueing theory models (M/M/1, M/M/S and M/G/1) were additionally applied to validate fleet-sizing decisions from a service-level perspective. The methodology was tested on a case study of SwiftExpress parcel delivery in the city of Rijeka, comparing an urban and suburban delivery area against experience-based dispatcher solutions. Queueing analysis confirmed the VRP-derived fleet sizes. The results demonstrate that free, open-source optimisation tools can deliver measurable operational and economic improvements for small and medium-sized logistics operators without software licensing costs.

Keywords: vehicle routing problem; fleet allocation; queueing theory; Google OR-Tools

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FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Express parcel delivery is one of the fastest-growing segments of the logistics industry, driven by the expansion of e-commerce, accelerated urbanisation and rising customer expectations for short delivery lead times. Efficient operation of such systems requires the combined application of several complementary mathematical disciplines: the assignment of vehicles to routes is modelled as a Vehicle Routing Problem (VRP), while the stochastic nature of customer arrivals and service-time variability is described through queueing theory. Together, these two approaches provide a complete picture of the operational system: VRP determines optimal routes for given resources, while queueing theory quantifies service levels and supports fleet-sizing decisions under varying load scenarios.

Real system data were obtained from SwiftExpress Logistics, a regional courier company operating parcel pickup and delivery services. For reasons of commercial confidentiality, the express-delivery operator is referred to throughout this paper under the pseudonym SwiftExpress Logistics. Daily allocation of delivery vehicles and route planning is, in most regional postal networks, still performed manually by dispatchers relying on experience rather than quantitative methods. This approach does not guarantee an optimal solution and often results in fleet over-utilisation, increased fuel costs and delivery delays. While large logistics companies rely on expensive proprietary routing software, small and medium regional operators can rarely afford such solutions. Free, open-source tools such as the Google OR-Tools library offer a competitive alternative with zero licensing cost.

The purpose of this research is to demonstrate that free software tools (Python and Google OR-Tools) combined with mathematical optimisation models can achieve a significant improvement in the efficiency of delivery vehicle allocation and routing compared with an experience-based dispatcher approach, and that this improvement can be independently confirmed through queueing-theory analysis of the resulting fleet configurations. The specific research contributions of this paper are: (i) implementation of two complementary mathematical models (vehicle allocation and vehicle routing) adapted to a real express-delivery operational process; (ii) a fully free, open-source implementation in Python using Google OR-Tools, empirically validated on realistic delivery data for the city of Rijeka; (iii) joint application of three queueing models (M/M/1, M/M/S, M/G/1) to independently validate VRP-derived fleet sizes from a service-level perspective, including quantification of the effect of service-time variability on queue length; and (iv) a quantitative comparison against dispatcher solutions demonstrating the operational and economic value of the proposed methodology.

2 BACKGROUND

The Vehicle Routing Problem (VRP) was first formally introduced by Dantzig and Ramser (1959) as the truck dispatching problem, and has since become one of the most studied problems in operations research and computer science. Numerous variants extend the basic Capacitated VRP (CVRP) to reflect real operating conditions, including VRP with Time Windows (VRPTW), VRP with Deliveries and Pickups (VRPDP), Multi-Depot VRP (MDVRP) and Dynamic VRP (DVRP) (Toth and Vigo, 2014). The present study uses a VRPTW formulation extended with pickups, which corresponds to the operational reality of express parcel delivery. Classical construction heuristics such as the Clarke and Wright savings algorithm (1964) remain the basis of many modern solvers, while exact branch-cut-and-price methods achieve optimal solutions only for moderately sized instances (Pecin et al., 2017). Google OR-Tools, an open-source constraint-programming and metaheuristic solver, has been benchmarked against commercial solvers such as Gurobi (Vidal et al., 2020). Applications of VRP models to postal and parcel-delivery networks have been reported for delivery network optimisation in Croatia (Tabak and Kljak, 2009; Švehla et al., 2016) demonstrating that mathematical allocation models consistently outperform dispatcher-based solutions. Queueing theory provides a complementary analytical frame for service-level analysis and fleet dimensioning in systems with stochastic demand (Zenzerović, 2003). This paper combines both perspectives within a single case study.

3 METHODOLOGY

3.1 Case-study area and data

The city of Rijeka was selected as the case-study area for its geographic diversity, combining a dense urban core with a lower-density suburban hinterland. Two delivery areas were analysed: an urban zone (Rijeka city centre, Kantrida, Sušak, Turnić, Trsat) and a suburban zone (Opatija, Kastav, Viškovo, Kostrena, Bakar). **Table 1** summarises the main characteristics of the two areas. The urban area is almost eight times denser than the suburban area (7.1 vs. 0.9 customers/km^2), and the average inter-customer travel time is more than twice as long in the suburban area (14.7 vs. 6.3 minutes), which directly affects fleet-sizing outcomes.

Real operational data of SwiftExpress could not be obtained in a form suitable for academic analysis, which is a common limitation in logistics research involving commercially sensitive data. Therefore, customer data (locations, service types, time windows and parcel masses) were generated using a Monte Carlo simulation. Arrival rates follow a Poisson process with a time-of-day-dependent intensity reflecting morning (8:00-10:00) and afternoon (13:00-15:00) peaks. Service times follow a log-normal distribution to avoid negative values.

Table 1. Delivery area characteristics

Characteristic	Urban area	Suburban area
Number of customers	85	42
Number of deliveries	64	28
Number of pickups	21	14
Avg. inter-customer travel time (min)	6.3	14.7
Total area (km^2)	~12	~45
Customer density (customers/km^2)	7.1	0.9
Vehicle capacity (kg)	1490	1490
Driver working time (h)	8	8

Source: authors' elaboration based on simulated data, direct observation and SwiftExpress specifications

3.2 Mathematical formulation

The proposed solution consists of two connected mathematical models, both grounded in operations-research formulations and adapted to the operational constraints of the delivery process.

Vehicle allocation model. This model assigns customers to vehicles in the available fleet, minimising the number of activated vehicles subject to capacity, time-window and working-time constraints. Let $V=\{1,\ldots,m\}$ denote the set of available vehicles, $L=\{1,\ldots,n\}$ the set of customer locations, and $L_0=L\cup\{0\}$ the set of locations including the depot (node 0). Parameters include the travel time t_{ij} between locations i and j, the time window T_i for service at location i, the average service (loading/unloading) time st, the delivery and pickup parcel masses D_i and P_i, the vehicle capacity q, and the total driver working time R. Decision variables are $x_{ik}\in\{0,1\}$ (1 if customer i is assigned to vehicle k), $y_k\in\{0,1\}$ (1 if vehicle k is active), the service-start time a_{ik} and the cumulative load m_{ik} of vehicle k after serving customer i. The objective function minimises the number of active vehicles:

$$MinZ = \sum_{k=1}^{m} y_k \tag{1}$$

subject to constraints ensuring that: each customer is assigned to exactly one vehicle; a vehicle is marked active if it serves at least one customer; the cumulative parcel mass on any vehicle never exceeds capacity q; the initial load equals the total mass of parcels to be delivered; every customer is served within its time window; and the total operating time of each vehicle does not exceed the driver working time R.

Vehicle routing model. After allocation, the routing model determines the optimal visiting sequence within each vehicle's route. The model follows a Vehicle Routing Problem with Deliveries and Pickups (VRPDP) formulation extended with time windows (Wassan and Nagy, 2014), where the binary variable x_{ij} equals 1 if the vehicle travels directly from customer i to customer j. The objective function minimises total driving time:

$$Min\ Z = \sum_{i,j=0}^{n} x_{ij}(t_{ij} + s_t) \tag{2}$$

subject to constraints requiring that: customers with earlier time windows are served first when feasible; every customer is served within its designated time window; total route duration does not exceed the driver working time; and the service-start time at location j is a function of the service-start time and travel time from the preceding location i. Both models were implemented in Python 3 using the Google OR-Tools constraint-programming solver (Google OR-Tools Documentation, 2024).

3.3 Queueing theory models

To independently validate the fleet sizes obtained from the VRP models, three complementary queueing models were applied (Hillier and Lieberman, 2021), described using the standard Kendall notation A/B/S/K//D. The key parameters are the arrival rate λ (requests/h), the service rate per server μ (requests/h), the number of channels (vehicles) S, and the utilisation factor $\rho=\lambda/(S\cdot\mu)$. System stability is $\rho<1$.

The M/M/1 model (single channel, exponential inter-arrival and service times) was applied to the single-vehicle suburban scenario. Its performance measures are:

$$L_Q = \frac{\rho^2}{1-\rho} \tag{3}$$

$$W_Q = \frac{\rho}{[\mu(1-\rho)]} \tag{4}$$

The M/M/S model extends this to S parallel identical channels and was applied to the two-vehicle urban scenario, using the Erlang-C formula to obtain the probability of waiting $C(S, A)$, where $A=\lambda/\mu$ is the offered load:

$$W_Q = \frac{C(S,A)}{S\mu - \lambda} \tag{5}$$

$$L_Q = \lambda \cdot W_Q \tag{6}$$

Because real service times rarely follow an exponential distribution, the M/G/1 model was additionally applied using the empirically measured variance of service time (σ^2) via the Pollaczek-Khinchine (P-K) formula (Hillier and Lieberman, 2021):

$$L_Q = \frac{\rho^2 + \lambda^2\sigma^2}{[2(1-\rho)]} \tag{7}$$

The P-K formula shows that greater variability of service times (higher σ^2) increases queue length even at the same average utilisation ρ. This is directly relevant to delivery logistics, where service-time heterogeneity (e.g. ground-floor vs. fifth-floor deliveries) lengthens customer waiting.

3.4 Comparison methodology

For each delivery area (urban and suburban), two solutions were compared: the experience-based dispatcher solution and the mathematical-model solution. The comparison used the following key performance indicators (KPIs): number of activated vehicles, total operational (driving and service) time, vehicle capacity utilisation (%), number of time-window violations, and solver computation time (s). Queueing-model outputs (ρ, L_Q, W_Q) were additionally computed for both the dispatcher and optimised fleet configurations to provide a service-level cross-check of the VRP results.

4 RESULTS

In the urban area with 85 customers the dispatcher solution used three vehicles, while the mathematical model allocated only two, redistributing customers into a more balanced load (43 and 42 customers per vehicle, vs. the dispatcher's 29, 31 and 25). **Table 2** summarises the comparison of results for urban and suburban area.

Eliminating the third vehicle reduced total operational time by 119 minutes (~2 hours) despite each remaining vehicle working longer individually, and increased average capacity utilisation from about 44% to 70%. At an assumed driver cost of €12/hour, the time saving alone corresponds to roughly €6,000 per year, and the combined saving from fleet reduction is estimated at approximately €30,000 per year for the urban area, which is a conservative estimate excluding fuel and vehicle-wear savings.

Table 2. VRP results comparison – urban and suburban area

Indicator	Dispatcher		Mathematical model	
	Urban	Suburban	Urban	Suburban
Activated vehicle	3	2	2	1
Total operational time (h:mm)	13:40	7:50	11:41	6:47
Avg. capacity utilisation (%)	44.0	12.7	70.7	21.0
Time-window violations	2	0	0	0
Fleet saving (%)	-	-	33.3	50.0
Operational-time saving (%)	-	-	14.6	13.4
Solver computation time (s)	-	-	8.4	3.1

Source: Made by authors

In the suburban area with 42 customers the dispatcher used two vehicles, while the model showed that all 42 customers could be served by a single vehicle within the 8-hour working-time limit (6:47 total operational time).

The combined parcel mass (312.6 kg) uses only 21% of the 1490 kg vehicle capacity, indicating that in the suburban area the binding constraint is not payload but the number of stops and total driving time. Eliminating return paths and optimising the route, OR-Tools reduces total operational time to an actual 6:47 (407 minutes), which is noticeably below the eight-hour limit.

Queueing analysis, presented in **Table 3**, supports the VRP results. The dispatcher's three-vehicle configuration (M/M/3) has ρ=0.585 (vehicles idle 41.5% of the time) with negligible waiting (W_Q=2 min), whereas the optimised two-vehicle configuration (M/M/2) achieves ρ=0.877 with W_Q=24.5min, which is an operationally acceptable service level combined with substantially better vehicle utilisation.

Table 3. Urban queueing-model comparison

Indicator	Dispatcher (S=3)	Optimised M/M/2 (S=2)	M/G/2 (S=2, real σ)
ρ – utilisation	0.585	0.877	0.877
L_Q – avg. in queue	0.47	5.81	10.1
W_Q – waiting (min)	2	24.5	85.5
System stability	Yes	Yes	Yes
Economic efficiency	Low (ρ=0.585)	High	High

Source: Made by authors

The single-vehicle M/M/1 configuration (**Table 4**) yields ρ=0.907 (stable but close to saturation), with W_Q~78 min, indicating that a second vehicle should be held in reserve for days when demand exceeds approximately 7.5 requests/h (e.g. holiday peaks). This is a simple, queueing-theory-derived operational trigger that dispatchers can monitor without further computation.

Table 4. Suburban queueing-model comparison

Indicator	Dispatcher (S=2)	Optimised M/M/1 (S=1)
ρ – utilisation	0.453	0.907
L_Q – avg. in queue	0.24	8.85
W_Q – waiting (min)	2.1	77.7
System stability	Yes	Yes (near limit)
Economic efficiency	Low (ρ=0.453)	High

Source: Made by authors

It can be seen that the mathematical model consistently outperforms the dispatcher approach across every KPI: fleet size, total operational time, capacity utilisation and time-window compliance, in both delivery areas, confirming the findings of comparable studies (Švehla et al., 2016). **Tables 3** and **4** summarize the queueing-model cross-check for the urban and suburban areas respectively, each comparing the dispatcher baseline against the corresponding optimised configuration, where S denotes the number of vehicles (parallel service channels) assumed in each configuration.

The comparison highlights a non-linear relationship between the number of vehicles and waiting time, consistent with the mathematical structure of the Erlang-C formula: at high utilisation (ρ~0.9) with a single channel, queues grow sharply, whereas adding a channel drops ρ below 0.5 and further channels yield insignificant additional benefit. The M/G/2 result further shows that, for the same mean service time and utilisation, higher service-time variability (σ=11min, coefficient of variation V=1.49) increases L_Q by 62% relative to the M/M/2 assumption of exponential service times. This is empirical confirmation of the Pollaczek-Khinchine relationship, and a practical argument for standardising the delivery process (mobile scanners, pre-sorted parcels) to reduce service-time variability without adding vehicles.

OR-Tools, with a 30-second search limit, produced solutions within 3-9 seconds for the analysed instances (85 and 42 customers). This is consistent with OR-Tools that reaches solutions within 1-3% of optimal in under 10 seconds (Pecin et al., 2017). Vidal et al. (2020) further report that OR-Tools achieves solution quality equal to or better than the commercial Gurobi solver for compute budgets up to 60 seconds, at zero licensing cost, making it well suited to a system such as SwiftExpress Rijeka, which requires solutions once per day within seconds.

5 DISCUSSION

The results provide converging evidence, from two independent analytical frameworks (VRP optimisation and queueing theory), that experience-based dispatcher decisions systematically over-provision the delivery fleet. In both delivery areas, dispatcher solutions correspond to queueing configurations with ρ well below the economic efficiency threshold (ρ~0.45-0.59), meaning vehicles are idle for a large share of the working day, while the optimised configurations operate at ρ~0.88-0.91, close to but safely below the stability limit of ρ=1. This convergence between two conceptually different models strengthens confidence in the fleet-sizing recommendations beyond what either method could support alone.

From a practical standpoint, eliminating one vehicle per area is estimated to save an amount that far exceeds the cost of implementing the proposed software solution, whose licensing cost is zero. The elimination of time-window violations (from two occurrences to zero) also has commercial value beyond the measured KPIs, since missed time windows in express delivery typically trigger contractual penalties and erode customer trust.

The methodology is particularly relevant for small and medium-sized regional delivery operators that cannot justify the cost of commercial routing software, since it relies exclusively on free, open-source components while achieving solution quality within a few percent of commercial and exact solvers for realistic problem sizes. The main limitations of the study are the use of simulated rather than directly observed operational data (mitigated through calibration against published aggregate statistics), the absence of parcel-volume constraints, and a static, single-day planning horizon that does not capture intraday demand dynamics.

It should also be noted that the specific fleet-size recommendations are conditional on the calibrated simulation assumptions described in Section 3.1 (Poisson arrival intensity, log-normal service-time distribution, and randomly generated customer locations and time windows). The two recommended configurations differ in the operational margin they leave: the suburban single-vehicle solution operates at ρ=0.907, close to the ρ=1 stability limit, so a moderate increase in demand or service time would be enough to push the queue toward instability, whereas the urban two-vehicle solution (ρ=0.877) retains somewhat more headroom. The suburban recommendation is therefore more sensitive to the underlying assumptions than the urban one and both could be re-verified with available directly observed operational data.

6 CONCLUSION

This paper demonstrated that combining free mathematical optimisation tools (Python and Google OR-Tools) with queueing theory can substantially improve the efficiency of delivery vehicle allocation and routing in real logistics systems. Applied to a case study of SwiftExpress parcel delivery in Rijeka, the proposed approach reduced the required fleet by 33.3% (urban) and 50.0% (suburban), cut total operational time by 14.6% and 13.4% respectively, and eliminated all time-window violations observed in the dispatcher solutions. Queueing-theory analysis (M/M/1, M/M/S, M/G/1) independently confirmed the VRP-derived fleet sizes as an efficient balance between service level and vehicle utilisation, and quantified the impact of service-time variability on queue length (a 62% difference in L_Q between M/M/2 and M/G/2). Future research should extend the models to include parcel-volume constraints alongside mass, and a dynamic VRP (D-VRP) formulation. Further work should also test larger instances and extend the queueing analysis to models with finite waiting capacity and priority disciplines.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Simulation-Based Evaluation of Urban Freight Delivery Flows: A Case Study of Rijeka, Croatia

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ABSTRACT

Urban freight transport significantly influences traffic conditions, environmental sustainability and the overall quality of life in city centres, and growing demand for goods distribution has intensified the need for evidence-based delivery planning. This study applies traffic microsimulation, using the PTV VISSIM platform, to assess and compare four urban freight delivery scenarios for the historic city centre of Rijeka, Croatia: the existing delivery system (status quo); routing of all delivery vehicles through the D404 entrance, reproducing the access pattern of a single urban consolidation centre; an equal split of delivery vehicles between the western and eastern entrances, reproducing the access pattern of two centres; and a liveability scenario in which the Riva corridor is closed for general traffic and reserved for pedestrians and delivery vehicles. Input data were drawn from traffic counts provided by Rijeka promet d.d. and from carrier and business-operator surveys, covering delivery locations, frequency, vehicle types, loading and unloading duration, and the freight-vehicle share of total traffic. Each scenario was simulated in 20 replications over an 11-hour period. Concentrating delivery access at one entrance produced results close to the status quo, with a local increase at that entrance; splitting access between two entrances increased queue lengths and carbon monoxide emissions at most intersections; and the liveability scenario improved conditions in the southern city centre while shifting pressure northward. The findings support traffic microsimulation as a decision-support tool for urban freight policy and indicate that splitting delivery access between two entrances is unfavourable for Rijeka.

Keywords: urban consolidation centre; traffic microsimulation; PTV VISSIM; last-mile delivery; liveability; city logistics

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Urban freight transport and last-mile delivery are essential to city-centre functioning, yet they impose disproportionate pressure on historic networks not designed for today's delivery volumes. Delivery vehicles are estimated to account for around 18% of urban road traffic while contributing 40% of transport-related energy consumption and 20-30% of vehicle-kilometres travelled in cities [1]. This pressure manifests as congestion at intersections, elevated local emissions, delivery-point scarcity, and growing tension between freight accessibility and pedestrian-oriented "liveability" objectives such as street pedestrianisation.

Ex-ante evaluation of freight measures is therefore valuable to city authorities and carriers prior to physical implementation. Traffic microsimulation quantifies the effects of alternative delivery configurations at intersection and street level, without the cost of a real-world pilot. Alternative delivery configurations also include urban consolidation centres (UCCs), facilities from which last-mile deliveries to a defined area are consolidated and redistributed, and access-restriction measures. Compared with strategic or tactical freight-demand models, microscopic tools such as PTV VISSIM represent vehicle-by-vehicle interactions, signal control and queue formation in sufficient detail to support operational planning.

The historic centre of Rijeka, Croatia, illustrates these challenges, with a narrow street network, dense delivery destinations and a pedestrian-oriented waterfront street (Riva). Our own earlier work on this case established the empirical foundations for scenario evaluation, collecting traffic-count and carrier-survey data [2] and ranking the same scenario set by stakeholder preference using a multi-actor multi-criteria approach [3]. The former study notes explicitly that scenario effectiveness "must be verified through simulations"; this paper reports the corresponding microsimulation results.

This paper reports a PTV VISSIM microsimulation of four Rijeka delivery scenarios: status quo, two delivery-entry reallocations reproducing the access pattern of one or two UCCs, and a liveability scenario closing Riva Street to all but delivery vehicles. The research question is: how do these configurations change queue lengths and carbon monoxide (CO) emissions in the network relative to the status quo, and how do the simulated outcomes relate to previously reported stakeholder preferences for the same scenarios? The contribution is twofold: quantified microsimulation evidence for the Rijeka scenarios, and an explicit contrast between simulated performance and stakeholder rankings. Section 2 reviews relevant literature; Section 3 describes the methodology; Section 4 presents results; Section 5 discusses findings; Section 6 concludes.

2 BACKGROUND

2.1 Urban freight transport and city logistics

Urban freight movements are disproportionately burdensome relative to their vehicle share, contributing significantly to urban traffic, energy consumption and vehicle-kilometres travelled [1], motivating extensive research into consolidation, kerbside management and access restriction. For Rijeka, the empirical groundwork for the present study derives from the authors' earlier work, which profiled delivery practices through entry-point counts and carrier/business surveys and proposed five conceptual scenarios as a foundation for future simulation [2], and ranked an almost identical scenario set by stakeholder preference using multi-actor multi-criteria analysis (MAMCA) [3]. Neither study reports simulated traffic or environmental outcomes for these scenarios.

2.2 Traffic microsimulation in urban freight research

Microsimulation approaches to urban freight vary in scale, software and validation rigour. Commercial platforms such as PTV VISSIM have been applied to real, monitored networks [4], alongside custom cellular-automata models [5], open-source simulators on synthetic networks [6], large-scale dynamic assignment across metropolitan networks [7], and disaggregate agent-based platforms [8]. Validation rigour differs sharply: while some studies report a formal GEH statistic against field counts [15], others validate only through travel-time or visual comparison [4, 5]. Validation reporting therefore differs widely across the field, a limitation that also applies to the present study (Section 5).

2.3 Urban consolidation centres, delivery bays and access-management measures

A recurring finding is that consolidation does not automatically improve network-wide performance and that its benefits are often highly localised. In Rotterdam, combining UCCs with zero-emission-vehicle transition cut emissions by 89-91% within the restricted zone but only 8-9% city-wide, while total vehicle-kilometres travelled rose slightly (+0.25%) owing to the extra consolidation leg [9]. Introducing UCCs for last-mile delivery similarly reduced vehicle-time concentration at the original depot by 59-60% while increasing it locally around the new centres [6]. A life-cycle assessment of a Brussels consolidation facility found transport-emission savings partly offset by the facility's own embodied and operational carbon [10], and a Melbourne siting study showed that the number and location of facilities, not their mere existence, determine outcomes [11]. Together, these findings support the proposition that adding consolidation facilities does not straightforwardly improve performance. Delivery-bay availability, dwell time and kerbside operations are a further determinant of urban traffic performance: optimised delivery-area location and number reduced double-parking-related congestion in Grenoble [12] and in Querétaro, where traffic performance at 80% bay-demand fulfilment differed significantly from the baseline, whereas 90-100% fulfilment did not [13]. Dedicated delivery bays raised travel speed on a Fez commercial street [14], and, counter-intuitively, tolerating illegal parking near loading zones reduced network-level congestion in one study, at the cost of unmodelled local externalities [5]. Access-restriction and liveability measures are similarly reported to concentrate benefits locally while potentially displacing traffic elsewhere. Examples are Rotterdam's zero-emission zone [9] and the pedestrianisation scenarios proposed for Rijeka [2, 3].

Few studies combine a microsimulation of a real historic city-centre network, built on field-collected traffic and carrier data, with a direct comparison of a status-quo baseline, one- and two-entry delivery reallocations and a liveability measure, together with an explicit confrontation of simulated performance against stakeholder preferences for the same scenario set, as available for Rijeka through the MAMCA study [3]. This paper addresses that gap.

3 METHODOLOGY

3.1 Study area

The simulation covers the historic city centre of Rijeka, Croatia, accessed through seven monitored entry points: R6 (Krešimirova St.), R38 (Vukovarska St.), R40-41 (1. Maja St.), R46-47 (Laginjina St.), R24-25 (Franje Račkog St.), R20-21 (Strossmayerova/Križanićeva St.), and R89 (state road D404). **Figure 1** shows their location within the network.

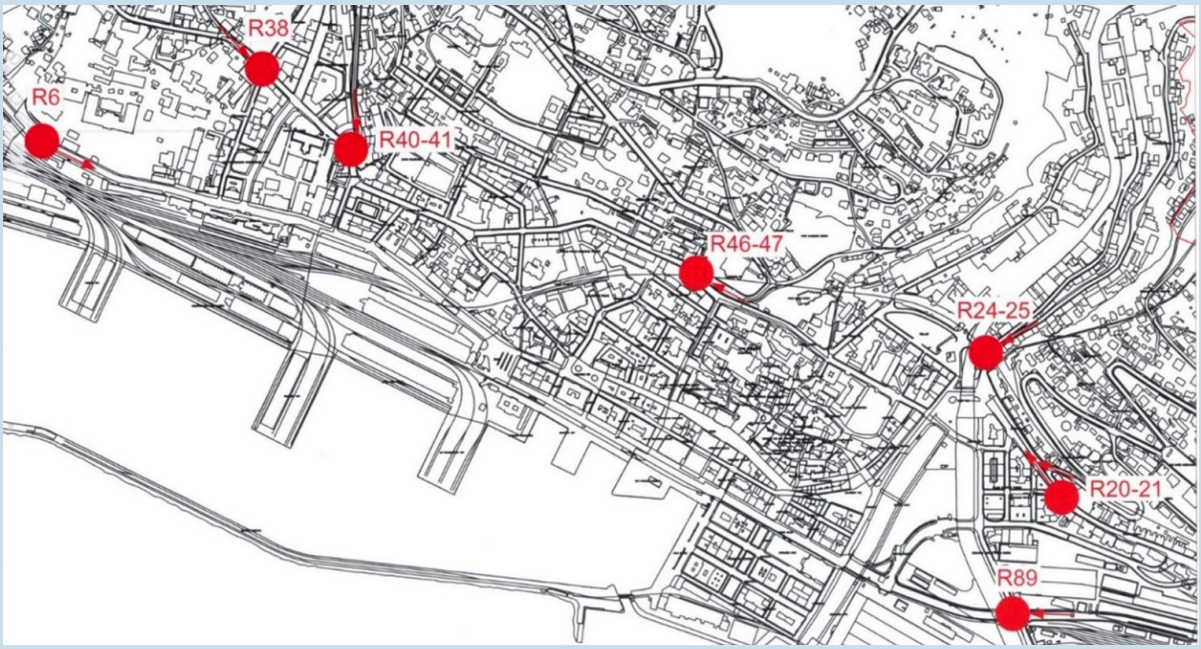


Figure 1. Entry points to the Rijeka city-centre network

Source: Rijeka promet d.d.

3.2 Input data

Inputs combine vehicle-count data from the local traffic operator, Rijeka promet d.d., with carrier and business-entity questionnaire surveys. Counts at all seven entries were entered in 15-minute intervals across the simulation horizon. The status quo scenario served as the comparison baseline. Total vehicle volume, delivery-point numbers and total delivery-vehicle numbers were held constant across all four scenarios, with only the entry-point distribution varying by scenario. The delivery-vehicle share was estimated from the carrier survey: surveyed carriers (11 carriers, ≈50% of those delivering to the centre) operated 358 delivery vehicles collectively, as also reported for the same area [2], and reported an average of 2.15 deliveries per vehicle per day, implying approximately 770 delivery trips per day. In the model, delivery vehicles were represented as a 2% share of the vehicles entering at each entry point, using the VISSIM heavy goods vehicle (HGV) class.

3.3 Simulation model

The model was built in PTV VISSIM Academic Licence 2020 (SP07), a microscopic platform representing private traffic, freight vehicles, public transport, pedestrians and cyclists and their interactions within one model. Development comprised: entering entry-point volumes and turning-movement-based routes, setting the delivery-vehicle share, configuring delivery points as modified parking-lot objects with defined access rules and dwell time, signal groups entering and control programs (119 signals, 22 controllers), placing measurement nodes and queue counters at intersections and principal streets, and defining travel-time sections between entries and selected delivery points. Turning proportions were measured individually per intersection from peak-hour counts (e.g., Strossmayerova St.: 35% right turn, 65% left turn).

3.4 Scenario design

Four scenarios were simulated (**Table 1**). In all scenarios, total vehicle volume and the total number of delivery vehicles was unchanged and only delivery-vehicle routing across entries was modified,

isolating the effect of delivery-flow reorganisation from overall demand change. The two reallocation scenarios reproduce the access pattern that one or two UCCs would create at the city-centre boundary. Transfer and consolidation of loads, changes in fleet size and the additional transport leg to a consolidation centre were not modelled; the results therefore describe the effect of delivery-entry reallocation, not the overall benefit of consolidation.

Table 1. Overview of the four simulated delivery scenarios.

Scenario	Delivery-vehicle routing configuration
Status quo	Delivery vehicles distributed across all seven city-centre entry points, reflecting current conditions.
One-entry reallocation (one-UCC access pattern)	All delivery vehicles routed exclusively via the R89 entry – eastern part of the network.
Two-entry reallocation (two-UCC access pattern)	Delivery vehicles split (50% each) between R6 – western entry and R89 – eastern entry.
Liveability	Riva Street closed to all but delivery vehicles; R6 also closed consequently, with volumes rerouted via the R38.

Source: Made by authors

An additional variant combining one UCC with an eco-friendly vehicle fleet had been envisaged, but the VISSIM licence used did not support an explicit eco-vehicle class, so this variant was not simulated. Vehicle composition by entry and scenario is given in **Table 2**.

Table 2. Vehicle composition by scenario and entry points.

Scenario	Entry point	Cars (%)	Delivery vehicles (%)
Status quo	All seven entries	98	2
One-UCC	R89	77	23
One-UCC	Remaining six entries	100	0*
Two-UCC	R6	94	6
Two-UCC	R89	87	13
Two-UCC	All entries, outside delivery hours	100	0

*No delivery-vehicle share was modelled at the remaining entries, since flow was routed exclusively through R89.
Source: Made by authors.

3.5 Model validation

During model development, the simulated flows of the status-quo network were compared with field counts collected by the authors. The location-level comparison was not retained in a reportable form, so no quantitative goodness-of-fit statistic (such as GEH) is reported. Because all scenarios were simulated on the same network with the same total demand, the results are interpreted as relative differences between scenarios rather than as absolute predictions of traffic conditions.

3.6 Performance indicators and simulation procedure

The simulation ran stochastically over 39,600 s (06:00 – 17:00), with no separate warm-up period; results were collected in hourly evaluation intervals. Each scenario was replicated 20 times. The required number of replications for 95% confidence and 10% relative deviation was estimated per parameter as:

$$n = \left(\frac{t \cdot s}{\bar{x} \cdot \varepsilon}\right)^2 \quad (1)$$

where t is the two-sided value for 95% confidence, s is the standard deviation, $\bar{x}$ is the mean of an indicator across replications, and $\varepsilon = 0.10$ is the accepted relative deviation.

The average requirement across parameters was 3.25 replications, so 20 replications exceeded the minimum. Comparison across scenarios used VISSIM's Scenario Management function. Indicators reported here are entry-point vehicle counts, CO emissions (g) at intersections and on the busiest streets, and queue length (m) at intersections. Delivery-point behaviour used a bay-selection decision point ~50 m upstream and a Blocking Time Distribution of 10-30 minutes based on survey data (e.g., delivery point 25-1: 60% occupancy, ≈7 of 11 observed hours). **Table 3** summarises key parameters.

Table 3. Key simulation parameters.

Parameter	Value
Software	PTV VISSIM Academic Licence 2020 (SP07)
Network	Rijeka city centre; 7 monitored entry points
Simulation horizon	39,600 s (06:00 – 17:00)
Vehicle-input interval	15 minutes
Traffic signal / controllers	119 / 22
Delivery-vehicle share	2% of entering vehicles (≈770 delivery trips/day: 358 vehicles × 2.15)
Delivery-point dwell time	10-30 minutes (Blocking Time Distribution)
Replications per scenario	20

Source: Made by authors

4 RESULTS

This section reports simulation outcomes for entry-point vehicle counts, CO emissions and queue length. Values are averages across replications; the dispersion reported in the simulation output is given in brackets (**Table 4**).

4.1 Vehicle flow, emissions and queues

Average vehicle counts at the two reallocation entries changed as intended. At Krešimirova (R6), the count fell from 152.2 in the status quo to 148.9 under the one-entry scenario and rose to 160.7 under the two-entry scenario; at D404 (R89), it rose from 57.9 to 75.9 and 66.0, respectively. Under the liveability scenario, the Krešimirova count fell to 4.9 following the closure of R6.

Differences between the one-entry scenario and the status quo were small at all seven intersections (CO emissions −3.8% to +4.9%; queue length −8.4% to +5.6%) and smaller than the reported dispersion in every case (**Table 4**).

Table 4. CO emissions and queue length at intersections by scenario

Intersection	Status quo	One-entry	Two-entry	Liveability
CO emissions (g)				
Jadranski trg	155.5 (14.0)	163.1 (14.3)	166.7 (19.1)	53.7 (5.5)
Market entrance	78.3 (5.5)	75.6 (6.6)	93.1 (9.7)	1.0 (0.5)
Market exit	241.5 (14.0)	249.2 (15.8)	253.1 (30.4)	75.9 (6.4)
Medico	265.6 (10.7)	255.5 (9.6)	268.7 (16.9)	317.5 (12.7)
Strossmayerova	165.8 (6.3)	171.1 (7.4)	186.9 (20.3)	178.8 (6.1)
Kalvarija	267.7 (15.7)	265.1 (15.2)	294.7 (31.1)	274.9 (16.0)
Guvernerova palača	55.5 (5.6)	53.8 (5.4)	59.2 (7.2)	63.6 (5.7)
Queue length (m)				
Jadranski trg	56.9 (6.3)	57.3 (9.2)	64.7 (10.3)	59.1 (10.7)
Market entrance	25.5 (3.0)	23.9 (2.9)	34.1 (6.3)	31.4 (8.5)
Market exit	30.2 (4.8)	31.9 (5.2)	64.1 (10.4)	32.5 (5.8)
Medico	30.6 (3.7)	30.3 (3.1)	49.9 (8.5)	34.2 (4.6)
Strossmayerova	45.0 (4.4)	43.4 (4.1)	54.1 (8.1)	47.4 (4.7)
Kalvarija	75.8 (10.7)	71.8 (9.9)	74.1 (11.6)	116.5 (19.1)
Guvernerova palača	16.1 (2.2)	14.8 (1.5)	16.7 (3.8)	20.2 (8.1)

Source: made by authors, based on simulation output

The two-entry scenario produced the highest CO emissions at five of the seven intersections and the longest queues at five of seven, with the largest relative increases in queue length at the market exit (+112%) and at Medico (+63%) compared with the status quo.

The liveability scenario recorded the lowest CO emissions in the southern network, notably at the market entrance (1.0 g compared with 78.3 g in the status quo), but higher emissions further north, with the highest single value at Medico (317.5 g). Queue lengths increased at all seven intersections, most at Kalvarija (116.5 m, +54%).

Among the busiest streets, Adamićeva St. and Riva St. recorded the highest CO emissions (366.6 g and 307.8 g in the status quo). Splitting delivery access between two entries increased emissions in Adamićeva St. to 520.8 g. Under the liveability scenario, emissions in Riva St. fell to 6.0 g, while they rose in Adamićeva St. (423.0 g, +15%) and Pomerio–Guvernerova St. (351.8 g, +35%). On the D404 section, CO emissions increased under the one-entry scenario (231.5 g compared with 211.2 g).

5 DISCUSSION

Concentrating all delivery vehicles at the D404 entry produced intersection-level results close to the status quo, while vehicle counts and CO emissions increased locally at D404 itself. The pattern of concentrated pressure at the single access point mirrors evidence that UCCs reduce congestion at the original depot while increasing it locally around the new centre [6], and that consolidation benefits are often concentrated locally rather than network-wide [9].

The two-entry scenario, by contrast, increased queue lengths and CO emissions relative to both the status quo and the one-entry scenario at most intersections. Splitting delivery flow between two entries increased delivery-vehicle penetration at both simultaneously, spreading rather than reducing network exposure. This is consistent with evidence that facility number and location, not mere existence, determine UCC outcomes [11], and with Rotterdam's finding of large local but marginal city-wide benefit alongside a small vehicle-kilometre increase from the extra consolidation leg [9]. Together, these findings support the proposition that adding UCCs does not automatically improve traffic performance. Because consolidation itself was not modelled, the present results concern the access pattern associated with one or two UCCs, not the overall benefit of consolidation.

Spatial redistribution is clearest in the liveability scenario, which improved conditions in the southern city centre while transferring queuing and emissions to the north, especially around Kalvarija and Adamićeva Street. A comparable compensatory pattern, where a targeted measure produces increased traffic outside the target zone, has been reported for a central-business-district morning-peak delivery restriction [8], reinforcing that access restrictions displace, rather than eliminate, freight pressure unless paired with measures in the receiving area.

A central contribution here is the explicit contrast between simulated performance and stakeholder preference. Our own MAMCA study of the same case [3] found all four stakeholder groups jointly ranked the two-UCC scenario highest (26.80%) and the status quo lowest (9.51%), with one-UCC scoring lowest among the reorganisation scenarios (18.03%). This is not an error in either study but evidence that stakeholder preference and simulated performance are complementary, not equivalent. MAMCA weighting emphasised organisational/technical criteria such as customer coverage and delivery-point access, which two centres could plausibly be expected to improve in principle, whereas simulation measures the realised network-level consequences of splitting the same delivery volume between two entries. Stakeholders also evaluated the consolidation concept as a whole, whereas the simulation tests only the access pattern it would create. A comparable distinction, between the behavioural determinants of UCC adoption and short-run operational outcomes, has been reported for Stockholm city hubs, where efficiency gains materialised only with delay and required policy support [15]. Operational efficiency, environmental performance and stakeholder preference thus need not produce the same ranking of urban freight measures.

For planners, the results indicate that concentrating delivery access at D404 left intersection conditions in the model largely unchanged but would require delivery-point capacity at D404 to be expanded or better managed. Where a two-centre configuration is pursued for customer-coverage or access reasons valued by stakeholders, this should be paired with targeted traffic management at the affected entries. The liveability measure should not be considered in isolation from complementary traffic management in the northern city centre.

Limitations include the absence of a reportable quantitative validation (Section 3.5), the representation of consolidation only through its delivery-access pattern, single-city scope and limited transferability, reliance on survey and short-window traffic-count inputs, echoing sample-representativeness limitations reported for the same area [2], the inability to model an eco-friendly fleet within the VISSIM licence used, precluding simulation of the environmentally optimised variant proposed elsewhere [2], [3], restriction of environmental output to CO, limiting comparability with studies reporting a wider pollutant set [4, 9], and the absence of a formal economic or stakeholder-implementation assessment alongside the simulation.

Future research should model consolidation explicitly, including transfer at the centre and the additional transport leg, combine this microsimulation evidence with stakeholder-adoption and policy-incentive modelling [15], extend the model to an eco-friendly-vehicle scenario, broaden environmental indicators to NOx, particulate matter and CO2, and test explicit off-peak delivery time-window scenarios, given the demand-side/supply-side timing mismatch identified for the same case-study area [2].

6 CONCLUSION

This paper used PTV VISSIM microsimulation (20 replications per scenario) to evaluate four delivery configurations for Rijeka's historic centre: status quo, two delivery-entry reallocations reproducing the access pattern of one or two UCCs, and a liveability scenario closing Riva Street to all but delivery vehicles. Concentrating delivery access at one entry (D404) produced results close to the status quo, with a local increase at that entry. Splitting access between two entries increased queue lengths and CO emissions at most intersections relative to both other scenarios. The liveability scenario improved southern conditions while transferring queuing and emissions pressure north, especially around Kalvarija Street.

The scientific contribution is twofold: quantified microsimulation evidence for the Rijeka delivery scenarios, and a direct comparison of these outcomes with previously reported stakeholder preferences, showing that the access pattern of the two-centre configuration preferred by stakeholders performed least favourably at most intersections. This underscores the value of combining quantitative simulation with stakeholder evaluation in urban-freight decision-making. Practically, the findings advise against splitting delivery access between two entries without accompanying traffic management, and support a phased approach to Riva Street pedestrianisation accompanied by northern-network traffic management.

The study is limited by its single-city scope, survey- and time-limited inputs, the inability to model an eco-friendly fleet, the absence of a reportable quantitative validation, the representation of consolidation only through its access pattern, and its restriction to CO emissions and queue length. Future research should model consolidation explicitly, broaden the pollutant set, test off-peak delivery scenarios, and integrate stakeholder-adoption dynamics with the operational evidence generated here.

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Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, analysis, interpretation, and conclusions were developed and verified by the authors, who remain fully responsible for the content.

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IV. Logistics, Supply Chains, Ports and Freight Transport

Last-Mile Delivery Solutions for Sustainable Urban Logistics

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ABSTRACT

The rapid growth of e-commerce, rising customer expectations, and increasing pressure to decarbonise urban freight transport have made last-mile delivery one of the most challenging segments of logistics systems. Traditional delivery models, largely based on dispersed home deliveries and conventional vehicle fleets, contribute to traffic congestion, greenhouse gas emissions, failed delivery attempts, and inefficient use of urban space. In response, last-mile delivery solutions have emerged as an important pathway towards more sustainable urban logistics. Last-mile delivery solutions improve the environmental and operational performance of urban logistics systems. Attention is given to parcel lockers, urban micro-hubs, cargo bikes, electric delivery vehicles, and digital route optimisation tools. When supported by adequate urban infrastructure, these last-mile solutions offer measurable potential to curb vehicle kilometres travelled, tailpipe emissions, and first-attempt delivery failures, though their real-world efficacy varies across spatial settings and operational constraints. Empirical evidence demonstrates that parcel lockers and micro-hubs reduce city-centre traffic pressure by consolidating deliveries into single access points, provided customer trips remain non-motorised. Similarly, deploying cargo bikes, electric fleets, and algorithmic routing achieves measurable tailpipe emission reductions and route flexibility, subject to local charging infrastructure, payload thresholds, and curb accessibility. However, their effectiveness depends on urban context, infrastructure availability, regulatory support, and consumer acceptance. The paper contributes to the growing discussion on sustainable urban logistics by providing a synthesised overview of last-mile delivery models and their relevance for the transition towards more resilient, low-emission, and service-oriented urban freight systems.

Keywords: last-mile delivery; urban logistics; sustainable freight transport; parcel lockers; micro-hubs; cargo bikes; route optimisation

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FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Research and policy interest in urban logistics have significantly grown over the past years. Urbanisation is one of the main factors driving this growing tendency: by 2050, 70% of people and 90% of GDP will be attributable to urban areas. Consequently, addressing urban freight logistics systematically is essential to prepare transport networks for future demand [1].

Numerous definitions of last mile logistics exist, yet a common view is that it concerns the last stretch of the supply chain from the last distribution centre to the recipient's preferred destination point. The last mile is often described as one of the most expensive, inefficient, and polluting parts of the supply chain. Efficiency depends on multiple factors, such as consumer density and time windows, congestion, fragmentation of deliveries, and shipment size and homogeneity. Last mile logistics cause various externalities, especially greenhouse gas emissions, air pollution, noise, and congestion. Therefore, a better understanding of the last mile is required to enhance its economic, environmental, and social sustainability [2].

Conventional urban last-mile delivery paradigms rely predominantly on fossil-fuelled, internal combustion engine light commercial vehicles performing dispersed, direct-to-door deliveries. This operating model produces substantial negative externalities [3].

From an infrastructural perspective, the proliferation of individual delivery couriers exacerbates street-level congestion, double-parking, curb obstruction, and conflict with vulnerable road users such as pedestrians and cyclists. Moreover, traditional home deliveries suffer from an intrinsically high rate of first-time delivery failures which triggers secondary and tertiary delivery attempts, multiplying vehicle kilometres travelled and operational overheads [4].

With urban logistics expanding under tighter environmental regulations like the European Green Deal and local SUMPs, conventional direct-to-door delivery models are becoming unsustainable. Some last-mile delivery solutions are parcel lockers, urban micro hubs, cargo bikes, electric vehicles, and advanced digital route optimisation tools [5].

2 BACKGROUND

Urban spatial constraints, shifting retail patterns, and environmental degradation collectively define the operational reality of metropolitan freight networks. As demographic concentration intensifies municipal density, public road infrastructure remains largely static, creating chronic spatial competition between commercial operators, public transit, and private commuters [1]. Within this framework, modern distribution networks experience structural friction: consumer demand increasingly shifts toward shorter delivery windows, dynamic order tracking, and smaller shipment batches [2].

The systemic reliance on internal combustion vehicle fleets further translates into distinct economic and public health penalties [3]. At the policy level, European sustainability agendas and local authorities are actively restructuring urban access through low-emission zones, dynamic curb pricing, and stringent freight regulations [5]. These institutional pressures render the traditional courier paradigm economically unviable, forcing logistics service providers to rethink fleet composition. To reconcile economic viability with environmental compliance, modern urban logistics tends to move toward decentralised nodes, zero-emission transport modes, and algorithm-driven operational integration [2, 5].

3 METHODOLOGY

This paper adopts a thematic narrative overview methodology to examine and synthesise operational models of sustainable last-mile delivery within urban environments. Targeted narrative synthesis was

selected to critically evaluate the technological maturity, operational trade-offs, spatial niches, and environmental boundaries across five established delivery solutions.

Literature identification was conducted across three primary scientific databases: Scopus, Web of Science and Google Scholar, with a primary temporal focus on peer-reviewed research and institutional reports published between 2014 and 2024. The search targeted academic contributions in the fields of transport geography, urban logistics, operations research, and sustainable supply chain management. Key search terms combined core thematic components, such as: "last-mile delivery" or "parcel lockers". To maintain analytical focus, retrieved publications were screened according to explicit eligibility criteria: empirical case studies or validated simulation models reporting measurable operational metrics, economic and environmental life-cycle evaluations, focus on metropolitan spatial dynamics and inner-city access constraints.

The resulting evidence base comprises 13 sources ([1–13]), categorised into two analytical tiers based on:

1) Macro-Contextual and Theoretical Frameworks ([1–5]): United Nations demographic forecasts [1], peer-reviewed systematic frameworks [2, 3, 5], and established city logistics literature [4] establish baseline definitions, urban growth projections, regulatory paradigms (e.g., European Green Deal, SUMPs).
2) Operational and Empirical Field Studies ([6–13]): Eight dedicated empirical and modelling studies evaluate the five interventions: automated parcel lockers in dense urban networks [6], micro-hub spatial architectures and transferability [7, 8], cycle logistics selection [9, 10], electric commercial vehicle fleet adoption constraints and total cost of ownership [11, 12], and dynamic AI/IoT route optimisation algorithms [13].

The selected literature was specifically chosen due to its direct thematic alignment, empirical rigor, and proven relevance, thereby ensuring an accurate foundation for this paper.

4 RESULTS

Last-mile delivery solutions improve urban logistics systems and its segments. Attention is given to parcel lockers, urban micro-hubs, cargo bikes, electric delivery vehicles, and digital route optimisation tools. Additional solutions, such as delivery drones and autonomous delivery vehicles, were deliberately excluded from this study due to the specific scope of the paper.

4.1 Parcel lockers

Last mile deliveries are a primary driver of commercial traffic, and heavy traffic of commercial vehicles in the whole city area. Owing to the specific nature of e-commerce, operations in the B2C sector have predominantly relied on home deliveries. In recent years remarkably interesting and popular solution became the parcel lockers as the efficient last mile delivery system. Parcel lockers are unattended delivery machines, located at chosen, mostly attended places. It is a system of reception boxes, which enable users to receive and send parcels 24 hours a day, 7 days a week.

The process of collecting a parcel via parcel locker begins when the customer selects a preferred locker location or is assigned the nearest available terminal. After placing the order, the customer receives an email confirmation, while full tracking visibility remains available throughout transit. Within a few business days, the parcel is delivered to the designated terminal, prompting an automated SMS and email notification with an access code. To complete retrieval, the customer visits the machine, inputs the code, and collects the parcel from the designated compartment. This collection process typically requires only a few seconds. To ensure the safety of both the senders as

well as consumers, parcel lockers are placed in the monitored locations (e.g., petrol stations, 24h car parks, supermarkets). A distinguishing feature of parcel lockers in comparison to the traditional courier services is a significant reduction in the number of supplies and the lack of drop deliveries resulting from the absence of the recipient. Parcel lockers are usually sited in public places, therefore enabling users to collect shipments at their convenience, often while doing other things, such as shopping or refuelling the car. With the selection of appropriate locations, parcel lockers can provide not only significant economic benefits, but also, or even primarily, they can have a positive impact on the reduction of pollutants emitted into the environment.

The most important aim of parcel lockers implementation is to reduce the number of deliveries in the city area, including failed deliveries and the subsequent return of goods by couriers and postal services. It helps to reduce unnecessary vehicle mileage with associated energy use and congestion impacts. An additional value of parcel lockers is that people can pick up their packages whenever they want within the specified time frame; they do not need to worry about whether someone will be at home to receive the package, and this convenience certainly has a positive impact on users [6].

4.2 Urban micro hubs

The meteoric rise of urban deliveries elevates the importance of sustainable urban freight solutions. Despite the benefits that online shopping brings, increasing urban freight traffic has dramatic consequences for city, country, and company sustainability goals, including climate impact, air quality, road safety, liveability, and congestion. Among several proposed last-mile delivery solutions are micro hubs, which appear to reduce delivery emissions and congestion. Micro hubs, sometimes called 'micro-distribution' facilities or 'micro-depots,' are last mile consolidation and distribution nodes located in or next to urban neighbourhoods. Micro hubs depart from the well-defined concept of Urban Consolidation Centres, which emerged as a popular logistics strategy for decreasing emissions and minimising congestion in densely populated pedestrian, commercial, or historical zones and improving the quality of life in urban areas and city centres. Micro hubs present an important opportunity to improve urban freight sustainability and efficiency, and they represent one step to manage the challenge of multi-sector collaboration [7].

Micro hubs are transport provider-owned and led initiatives, located near the end receivers. By optimising load distribution within a delivery zone, micro hubs aim to reduce total vehicle trips in urban areas. The activities of micro hubs include logistical setups and parcel handling in the city. Micro hub facilities tend to support delivery through a variety of environmentally friendly modes, such as light-duty electric vehicles, electric cargo bicycles with pedal assistance or without, and/or by foot or handcarts [8].

4.3 Cargo bikes

One of the significant side-effects of growing urbanisation is the constantly increasing amount of freight transportation in cities. This is performed by conventional vans and trucks and causes a variety of problems such as road congestion, noise nuisance, and pollution. Yet delivering goods to residents is a necessity. Sustainable concepts of city distribution networks are one way of mitigating difficulties of freight services. Especially in urban areas, there is an enormous potential for consolidation and coordination of distribution flows, since typically lesser amounts of freight need to be delivered to spatially dispersed locations [9].

Cargo bikes are becoming an immensely popular and sustainable solution when it comes to parcel distribution in urban areas. A cargo bike is defined as a modified bicycle with a cargo box, enabling it to transport a variety of goods and loads. One of the possible ways to achieve sustainable urban freight transport is by considering cargo bikes. Parcel distribution by cargo bikes becomes an easier and

ecologically friendly solution. With the minimal level of noise, zero-emission pollution, and adequate payload volume, postal and logistics companies are trying to move away from traditional delivery modes (gas and diesel-powered vehicles) to this more sustainable way [10].

4.4 Electric delivery vehicles

The rising demand for last-mile delivery has led to a considerable number of fossil-fuelled vehicles on the road, contributing to environmental issues such as traffic congestion, greenhouse gas emissions, noise and air pollution. Using fossil-fuelled vehicles also leads to high delivery costs arising from traffic congestion, fuel consumption, and high vehicle maintenance expenses. The growing volume of goods in last-mile delivery and tight delivery deadlines, necessitate faster delivery options. These last-mile delivery challenges have provided motivation to look for alternatives to fossil-powered vehicles, making electric vehicles (EVs) increasingly popular in recent years due to their attractive features [11].

An electric vehicle is powered exclusively by electric motors, using energy stored in batteries. In urban freight operations, electric vehicles offer substantially lower running and maintenance costs due to superior energy efficiency and the absence of internal combustion engine wear [12].

The potential economic impacts of electric vehicles include creating new manufacturing, maintenance, and charging infrastructure jobs. The potential social impacts of electric vehicles include improved air quality and reduced noise pollution, contributing to better health outcomes and a higher quality of life. While electric vehicles offer numerous benefits, the uptake is hindered by various limitations. Among the limitations is the scarcity of critical materials used in electric vehicle batteries and electronic equipment. In addition, the disposal of electric vehicle batteries raises significant environmental concerns due to toxic materials [11].

4.5 Digital route optimisation tools

In the field of modern logistics management, the optimisation of distribution routes is a key factor to improve efficiency and reduce costs. With the rapid development of e-commerce and the increasing expectations of consumers for fast delivery services, logistics companies are faced with a huge challenge of how to effectively manage transportation costs and time while ensuring service quality. In this context, logistics distribution route optimisation has become crucial. The traditional logistics distribution model usually relies on experience and simple planning algorithm, which are inadequate for managing large-scale and dynamic logistics needs.

The complexity of modern logistics systems requires more efficient and intelligent methods to deal with the planning and optimisation of distribution routes. This demand has spawned research interest in using artificial intelligence (AI) and Internet of Things (IoT) technologies to enhance logistics distribution route optimisation. Artificial intelligence technologies, especially machine learning and deep learning, can predict logistics needs, optimise inventory management, and improve the efficiency of distribution paths by analysing historical and real-time data. At the same time, IoT technology provides a wealth of real-time data by tracking goods and vehicles in real time, which can be used to optimise delivery routes, reduce delays, and improve customer satisfaction in delivery [13].

5 DISCUSSION

A comparative evaluation demonstrates that each solution exhibits specific operational trade-offs and spatial niches [2, 5]. In terms of spatial suitability, automated parcel lockers and micro-hubs excel within high-density residential and commercial corridors [6, 7], cargo bikes uniquely master narrow, pedestrianised historical centres [9, 10], and electric commercial vans effectively serve broader suburban-to-urban distribution rings [11, 12]. However, each model introduces operational constraints:

lockers reduce delivery trips but can be offset by personal motorised collection travel [6], micro-hubs incur a transshipment penalty and high urban real estate costs [7, 8], cargo bikes face strict payload limits and weather dependency [9, 10], electric fleets require robust charging infrastructure and grid capacity [11, 12], and algorithmic route planning remains vulnerable to physical curb blockages [4, 13].

Consequently, achieving maximal sustainability in urban freight requires systemic complementarity rather than isolated deployment [2, 5]. An integrated, multi-tier delivery architecture enables line-haul electric vans to supply decentralised urban micro-hubs [7, 11], while cargo bikes execute quiet, zero-emission final drops in pedestrian cores [8, 9]. Concurrently, automated parcel lockers absorb fragmented residential deliveries to preclude failed courier attempts [6], and dynamic route optimisation algorithms continuously coordinate fleet flows and dispatch schedules across the entire metropolitan network [13].

Table 1. Comparative synthesis of sustainable last-mile delivery solutions.

Solution	Suitable Context	Operational Limitations	Observed Findings vs. Modelled Integration	Ref.
Automated Parcel Lockers	Dense residential zones, transit nodes	Curb competition, capacity limits, fixed CAPEX	Observed: High first-attempt success. Modelled: Net emissions drop relies on walking/cycling pickup.	[6]
Urban Micro-Hubs	Historical cores, Low Emission Zones	Real-estate costs, zoning, handling friction	Observed: Lower van-km in core zones. Modelled: Requires multi-carrier neutral consolidation.	[7, 8]
Cargo Bikes	Flat/pedestrian cores	Payload volume/ weight caps, weather sensitivity	Observed: Shorter curb dwell times. Modelled: Van-as-a-hub algorithmic re-supply synchronization.	[9, 10]
Electric Vehicles	Suburban-to-urban trunk corridors	Charging downtime, grid caps, winter range loss	Observed: Zero direct tailpipe emissions. Modelled: TCO parity highly dependent on purchase subsidies.	[11, 12]
Digital route optimisation	Mixed-fleet dynamic metropolitan routes	Data latency, fragmented carrier systems	Observed: 10–20% mileage and fuel reduction. Modelled: Real-time multi-modal re-routing under curb restrictions.	[13]

Source: Made by the authors based on the referenced literature

6 CONCLUSION

This paper evaluates the operational challenges of urban last-mile logistics and the necessity of transitioning from fragmented, direct-to-door deliveries powered by internal combustion engines. Automated parcel lockers mitigate first-attempt delivery failures by decoupling parcel drop-offs from recipient presence through continuous self-service access, though their net environmental benefit depends on non-motorised customer collection. Urban micro-hubs shift consolidation closer to delivery zones in dense districts, serving as intermediate transshipment platforms for low-emission modes, provided additional handling overheads and urban space costs remain controlled. Cargo bikes demonstrate high spatial manoeuvrability within pedestrianised areas and narrow street grids, reducing curb-space friction on small-load deliveries, within the physical boundaries of payload capacity and weather conditions. Electric delivery vehicles eliminate localised tailpipe emissions and lower operating noise in dense corridors; however, their life-cycle carbon abatement is fundamentally linked to the regional electricity generation mix and charging infrastructure availability. Digital route

optimisation tools replace static dispatching with data-driven planning, responding dynamically to traffic fluctuations while remaining subject to physical curb side access constraints. As every urban environment presents distinct spatial, infrastructural, and regulatory parameters, sustainable last-mile logistics depends on strategically selecting and synergistically integrating operational models tailored to the specific urban context.

Use of AI tools: AI-assisted tools were used to support literature synthesis, structural organisation, and language refinement. All analytical perspectives, conceptual syntheses, interpretations, and conclusions were formulated and critically reviewed by the authors, who remain fully responsible for the content.

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V. Smart Mobility, Rail and Evidence-Based Transport Planning

The Strategic Role of Night Trains in Sustainable Transport

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ABSTRACT

This paper compares several studies on the environmental impact of the railway sector, focusing on night-train operations. It examines the economic challenges of operating them, including high fixed and operating costs and competition from more carbon-intensive transport modes such as aviation and road travel. Although night trains offer clear environmental advantages, their long-term viability remains constrained without stronger policy support, structural reforms, or public investment. The paper investigates the overall sustainability and feasibility of revitalising European night trains through central research questions and objective areas such as environmental impact and infrastructure balance, potential for modal shift & EU emission reductions, economic viability & policy reforms and social, regional and macroeconomic contributions.

Keywords: night trains; overnight rail renaissance; modal shift; GHG emissions; carbon footprint

1 INTRODUCTION

The overarching aim of the research is to evaluate the viability, decarbonisation potential, and overall sustainability of night trains as a low-carbon alternative to aviation and road travel in Europe. The transport sector is carbon-intensive; for example, air travel alone contributes 3.5% of anthropogenic global climate impact. Using normalisation to aviation fuel use, the contribution of global aviation in 2011 was calculated to be 3.5% of the net anthropogenic ERF (effective radiative forcing) of 2.290 mW m^2 (the standard scientific unit measuring the rate of net energy/heat trapped in Earth's atmosphere per square metre due to human activities) [16]. The road sector has a profound, multifaceted influence on the environment, driving environmental degradation through construction, maintenance, and vehicle operation. It accounts for a significant share of global greenhouse gas (GHG) emissions, roughly 25–30% of energy-related emissions and is the dominant source of noise and air pollution in urban areas [6]. Upstream emissions incurred during fossil fuel extraction and electricity generation are not included, and the combustion of biofuels is treated as non-emitting on a net basis. [7]. In contrast, rail is the least emission-intensive motorised transport mode, producing only 0.4%–2% of total GHG emissions in the transportation sector while holding a significant modal share. This data was directly obtained from scientific and official reports on emissions in the transport sector. However, agencies such as the International Energy Agency (IEA) and the European Environment Agency (EEA) calculate this percentage by measuring total sector emissions which are greenhouse gas emissions (in CO_2 equivalent) produced by the entire transport sector (road, air, maritime, and rail transport). Also, by measuring rail emissions from diesel consumption in diesel locomotives, which are calculated along with emissions from power plants generating electricity for electric trains. Rail emissions are divided by total transport emissions and multiplied by 100. Rail transport is 3-10 times less CO_2-intensive than road or air transport. Comparisons regarding emission intensity (between 3 and 10 times lower) are calculated using a standardised unit of emission intensity, which measures the grams of CO_2 emitted to transport one unit over a distance of one kilometre [10]. Numerous initiatives are underway to decarbonise transport; however, the goals of the Paris Agreement strongly imply a need to drastically reduce greenhouse gas emissions. Recent attention has focused on shifting travel demand to trains, either through high-speed or night trains, to reduce the carbon footprint of long-distance travel [5]. High-speed trains can compete with flights on trips up to 800 kilometres (km) [22], but their potential use is limited for longer trips. Night trains could play a relevant role for such longer trips. However, the potential to shift longer trips from flights to night trains has been questioned, as night train services have struggled to grow beyond niche markets, and many night train connections have been abolished in recent decades [12]. This paper draws upon several primary data sources, institutional databases, and scientific research studies to ground its conclusions: International Energy and Aviation Organizations (International Energy Agency (IEA) and International Civil Aviation Organization (ICAO)), European rail research initiatives, European Union frameworks and electrification data, operator and industrial market reports and consumer and academic literature. The source material relies primarily on 2019 real-world data as its baseline reviewed period for quantitative modelling and emissions comparisons, incorporates metrics from 2021 and 2023 and evaluates scenario projections for 2030 (target for doubling night train capacity and ordering initial rolling stock) and 2050 (the EU target deadline for transport carbon neutrality and technological limits of battery-electric aviation).

2 MAJOR INFLUENCE ON THE ENVIRONMENT

The European Commission named 2021 the European Year of Rail, which was expected to boost train adoption in Europe, including a night-train renaissance. An action plan that was developed was aimed at rendering cross-border train services more affordable, which includes making the ticketing system more customer-friendly and helping operators to upgrade their rolling stock [8]. New companies entered the market, such as European Sleeper and Midnight Trains, and then Austrian ÖBB, which

has expanded its fleet and is offering new direct train connections linking major European cities. According to 2019 data from the International Energy Agency (IEA), the actual GHG emissions from planes were 28 times higher than those of long-distance passenger trains, including night trains [1]. The figure was calculated by standardising a few critical variables according to equation 1.

$$Emissions\ per\ Passenger/km = \frac{Total\ Energy\ Consumed \times Emission\ Factor\ Energy\ Source}{Average\ Vehicle\ Occupancy} \quad (1)$$

Table 1. A summary table outlining the key environmental differences between a conventional aircraft, an aircraft powered by sustainable aviation fuel (SAF), and an electric night train

Impact category	Conventional-fuel aircraft	100% sustainable aviation fuels – aircraft	Electric night train
CO_2 emissions on the route)	High (~88–285g per passenger-km)	Similar direct emissions (80% reduction over lifecycle))	Zero (on-track; depends on grid cleanliness)
Contrails	Maximum impact (creates cirrus clouds that warm the planet)	Reduced impact (by ~26–45%), but still present	None (operates on the ground)
High-altitude [NO_x]	High	Present (due to engine combustion process	None
Overall climate impact ratio	28 times more harmful than a night train	16 times more harmful than a night train	Baseline (Cleanest choice)

Source: Made by authors

By choosing international train services instead of short-haul flights, travellers can reduce their carbon footprint by more than ten times, with trains emitting an average of 25 g of equivalent per passenger-kilometre compared to 263 g for planes [11]. The calculator assumes greenhouse gas emissions of ¼ tonne CO_2 equivalent per passenger per hour flying which is derived by calculation from fuel consumption per flight. Then there are non-effects, meaning that even if "sustainable aviation fuels" were used on a larger scale, flying would remain multiple times more climate-damaging than rail travel due to emissions that aircrafts have which are non-CO_2 pollutants at high altitudes that amplify total global warming [1].

Rail can produce green energy, considering that European rail is already largely "green," with approximately 81% of train-kilometres in the EU powered by electricity [8]. Reflecting towards environmental efficiency, it is necessary to mention that High-speed trains (HST) produce less noise and air pollution per passenger-kilometre than road transport [18].

3 REDUCING EU EMISSIONS BY INTRODUCING NIGHT TRAINS

While rail is generally more sustainable, the construction of new high-speed (HSR) rail lines is costly and has a huge environmental impact. Additionally, energy consumption for trains increases in a higher proportion than the rise in speed, meaning faster trains require significantly more power. High-speed rail projects also involve large land use, creating "barrier effects" in territories and causing landscape intrusion [18]. For these reasons, the sources suggest that upgrading existing main lines to allow for speeds of 160 to 230 km/h may be a more environmentally balanced solution than building

entirely new high-speed infrastructure [1]. Where high-speed lines already exist, suitable night trains should be able to take advantage of them. Many national operators (such as those in Sweden, Austria, and the Netherlands) use 100% renewable energy or emission-free hydropower to run their fleets. Using these green fuel sources helps the industry move closer to the goal of achieving carbon neutrality by 2050 [14, 1]. If rolled out on a European scale, night trains as an alternative to short and medium-haul flights (up to 3,000 km), could prevent 3% of total gross EU GHG emissions [1]. The 3% figure comes from a specialised modelling study conducted by Back-on-Track.eu, the researchers mapped out specific scenarios based on real-world European transit data. The study analysed actual EU aviation data from 2019, identifying all short-haul (500–1,500 km) and medium-haul (1,500–3,000 km) flights. These are distances perfectly suited for an overnight train journey [1]. While the airline industry regularly refers to "green" flying, no real pathway exists to make this happen. The capacity to produce "sustainable aviation fuels" is vanishingly low. Short-haul flights are particularly inefficient because emissions during take-off and landing are at their highest. Replacing these flights with night trains can significantly lower the carbon footprint of long-distance travel [14, 11].

Table 2. Key statistical projections, targets, and figures regarding the potential environmental and operational impacts of expanding the European night train network

Category	Statistics/ Numbers	What does it represent?
Potential passenger shift	32%	Share of all air passengers in the EU who would switch from flying to a night train.
Citizen willingness	70% (7 out of 10)	Share of Europeans who, in surveys, would prefer a night train under reasonable conditions.
Aviation reduction	26%	Percentage by which total greenhouse gas emissions from aviation would decrease.
Reduction in total transport	8.6%	Reduction in greenhouse gas emissions across the entire transport sector.
Reduction in total EU emissions	3%	By which absolutely all greenhouse gas emissions in the European Union would decrease.
Route distance	500–1,500 km	Optimal distance at which trains most effectively replace flights.
Maximum distance:	up to 3,000 km	Upper limit of the distance is considered in Study scenarios.
Railway network expansion	300 lines	target number of night routes in Europe, up from the current ~150
Passenger growth:	3x (tripling)	Expected growth in night train passenger numbers within 7 years of network expansion.
Environmental advantage:	up to 28x	How much less harmful night trains are to the climate per passenger on average compared to airplanes.

Source: Back.On-Track.eu

Emissions data per person for aeroplanes, trains, and automobiles depend on many factors, such as the energy source used to fuel the engines, passenger capacity, and distance covered [19], [4]. To calculate the carbon footprint per passenger-km (gCO_2/pkm), aviation organizations like the International Civil Aviation Organization (ICAO) use a standardised four-step formula and calculators estimate total fuel consumption based on the aircraft model and the distance between airports [2]. While an aircraft emits around 340 gCO_2/pkm over a distance of 500 km, modern European electric trains (such as the

TGV in France or the ICE in Germany) emit only about 15 to 30 gCO_2/pkm, thanks to the high share of renewable energy sources in the European electricity grid while passenger cars, on the other hand, emit 111 g CO_2/pkm [5, 9]. This data showcases that rail transportation is far more environmentally sustainable than air travel and automobiles [18], [20]. While night trains have a lower "packing density" (fewer berths per coach compared to seats in day trains), their higher average capacity utilisation, often estimated at 70% to 80%, and lower speeds balance this out to maintain favourable emission levels [1]. Unlike high-speed rail (HSR), which often requires the "huge environmental impact" of constructing entirely new lines, night trains typically run on existing conventional infrastructure.

This reduces the environmental burden in several ways, such as avoiding the massive emissions associated with the creation and maintenance of new high-speed tracks [14], because they use existing lines that are often unfenced and conventional; night trains minimise new land clearing and division of local ecosystems; and also, their lower speeds compared to HSR also result in a lower rate of collisions with wildlife.

4 NIGHT TRAINS SUSTAINABILITY ACHIEVEMENT

Night trains achieve sustainability through a triple-bottom-line approach, balancing environmental, social, and economic components to offer a viable alternative to more polluting modes of transport. Europe is reviving night trains after decades of neglect and major line closures. One of the main arguments used by companies and public authorities is that they are more practical, comfortable, and environmentally friendly. This study examines the environmental, economic and social aspects of night trains in Europe to assess their overall sustainability. It also analyses the strengths and weaknesses of night train services, as well as the opportunities and threats facing the sector, taking into account their reliance on existing railway infrastructure. From the environmental perspective, the study focuses on the impacts of emissions, energy use, noise and vibrations and land use. As for the economic aspects, the main issues are operational costs, employment, and pricing. Social issues addressed are travel time, quality, comfort, and safety. Given the broad geographic and thematic scope, this study provides a general overview based on the relevant literature. The main sources examined are scientific, technical and policy reports on cross-border night trains in Europe. The results indicate that, while night trains are clearly sustainable from an environmental point of view, significant economic challenges need to be overcome to make them competitive with other alternatives. Social aspects, being somewhat subjective, may be solved more easily with adequate information and awareness-raising. Overall, it can be concluded that night trains are a viable and sustainable form of transport, once the economic challenges are addressed [14].

Socially, night trains are evolving from a niche product of nostalgia into a practical tool for modern mobility [21]. Passengers see night travel as highly efficient because most of the journey time is spent sleeping, allowing them to arrive rested in city centres early in the morning [13]. Night trains reconnect geographically remote regions to economic centres, serving mid-sized cities often bypassed by high-speed rail [21]. Public demand for night trains is rising, driven by the "flygskam" (flight shame) movement, as 7 out of 10 Europeans say they would choose night trains over planes if the offer were reasonable [16]. It is also necessary to improve comfort by modernising rolling stock with private suites and "mini cabins" that cater to updated social preferences for privacy and safety [13]. To achieve economic sustainability, the industry seeks a sustainable business model through strategic reforms [14]. Achieving economic sustainability requires policy shifts, such as applying 0% VAT on international rail tickets (matching aviation) and reducing Track Access Charges (TAC), which currently account for up to 88% of operating costs [1]. The finding that track-access charges (TAC) account for up to 88% of costs is based on extensive economic and academic research into the European transport sector. European Union railroad sector analysed data from 28 European Union countries found that these fees are the main driver of infrastructure costs for railway operators.

Unlike daytime trains, where passengers frequently board and disembark at intermediate stops (causing fluctuations in occupancy), night trains primarily connect distant major cities (e.g., Vienna–Paris or Split–Zürich). Most passengers travel from the starting station to the final destination, allowing the train to maintain consistently high occupancy (70%–80%) along the entire route [1]. With such high occupancy, the train's environmental efficiency per passenger-kilometre (g CO_2/pkm) improves further, making it by far the greenest alternative to evening and morning flights.

5 CONTRIBUTIONS OF NIGHT TRAINS TOWARDS NATIONAL ECONOMY INCREASE

Night trains contribute to national and regional economies by serving as strategic tools for spatial planning, enhancing business productivity, and driving significant industrial investment. Rather than just being a niche transport mode, they are increasingly viewed as a "vector of transition" that reconnects territories and creates new economic opportunities [21]. Night trains play a vital role in national economic growth by connecting geographically remote or peripheral regions to central economic hubs [1]. In countries like Sweden and Finland, night trains are used to connect isolated northern regions to national economic centres. In Italy, they provide a strong link between the southern parts of the country and the industrialised north [15]. Regional centres that lack their own airports (such as Dresden, Leipzig, or Münster in Germany) benefit particularly from business travel enabled by night trains [15]. Unlike point-to-point air travel, night trains can serve multiple intermediate destinations along a single route, bringing economic potential to cities that would otherwise be bypassed by high-speed rail [15].

For the professional sector, night trains offer a unique economic advantage by maximising usable time and reducing indirect costs for businesses. Passengers can take advantage of the night to rest and then "work as normal" when arriving at their destination early the next morning [17]. Many distant metropolises lack early-morning flight or day-train arrivals (often not arriving before noon). Night trains fill this gap, which can lead to a direct increase in productivity for these regions [1, 15]. By travelling overnight, businesses and individuals save on the cost of hotel stays and evening flights [5]. Revitalising the night train industry would drive substantial activity in European manufacturing and engineering. Doubling the number of night trains in the EU by 2030 would unlock massive investment potential. It would require an investment of approximately €2 billion for just the initial 1,000 carriages. A full-scale rollout to replace medium-haul flights could require over 2,500 new night trains, representing a total order volume of roughly €97 billion [1]. The figure of 97 billion euros for 2,500 trains derives from dividing the total amount by the number of trains yields an average cost of approximately 38.8 million euros per night train. Modern night trains—featuring sleeping cars, advanced safety systems, and high-speed technology—are extremely complex and expensive to manufacture. The system boundaries primarily cover the direct costs of procuring railway vehicles (rolling stock) but exclude broader supporting infrastructure. This assessment includes trainset production, the costs associated with the design, materials, and assembly of the trains themselves (locomotives and carriages, including sleeping cars, couchette cars, and dining cars). Then technology and homologation which are costs of equipping trains with systems for cross-border operations (such as ERTMS/ETCS signalling) to enable travel across multiple countries and the unit price which is estimated cost and ranges from approximately 35 to 40 million euros per modern train (depending on the number of carriages in the trainset). It is recommended that European factories manufacture rolling stock to maximise local economic benefits and standardise pricing [1]. Night trains act as a catalyst for sustainable tourism, which is a major component of many national economies. Partnerships between rail operators and Destination Management Organisations (DMOs) can create integrated holiday packages that include travel and local accommodation, boosting regional tourist revenue [3]. They are particularly effective for seasonal travel to high-volume tourist regions, such as the Alps or the Mediterranean, where they compete effectively with cars [1].

The night train industry is more labour-intensive than daytime rail or low-cost aviation, contributing to specialised job creation. Night trains require more personnel for specialised tasks such as security, bed preparation, and breakfast service [14]. Beyond on-board staff, the industry supports significant technical roles, including engineers, mechanics, and station staff needed for complex overnight turnaround [14]. While not always reflected in direct ticket prices, night trains provide a massive economic benefit to society by reducing "externalities." Shifting passengers from aviation to rail significantly reduces the social costs associated with emissions and air pollution [1, 14]. Night trains utilise existing conventional infrastructure during off-peak hours when it is otherwise underused, increasing the economic return on existing national rail assets without requiring the costly construction of new high-speed lines [1, 14].

6 CONCLUSION

Night trains represent a viable and sustainable form of long-distance transport, provided that key economic and regulatory challenges are addressed. The comprehensive evidence from the sources indicates that night trains are a vital "vector of transition" for sustainable mobility in Europe, offering the most climate-friendly alternative to medium and long-distance aviation. While their environmental benefits are undisputed, their long-term success depends on addressing significant economic hurdles and aligning services with evolving social preferences for comfort and privacy. By running on existing conventional lines, they avoid the high environmental costs and habitat fragmentation associated with building new high-speed infrastructure; they have a minimal infrastructure footprint. The weakest aspect of night trains is their high cost, which currently makes them less competitive than heavily subsidised low-cost airlines. High Track Access Charges (TAC) can account for up to 88% of operating costs, and a severe lack of specialised rolling stock prevents rapid market expansion. This percentage represents the upper limit (worst-case scenario), not a fixed average for every line. On most standard lines, the TAC averages between 10% and 30% of operating costs, but it rises towards 88% under specific, extreme conditions. According to EU directives, infrastructure managers (such as SNCF Réseau in France or DB InfraGO in Germany) must charge a minimum cost of rail wear. However, on high-speed and high-frequency lines, states have the right to add so-called "markups" (additional levies) if they judge that the market can bear it. When a private or open operator (so-called open-access operator, like European Sleeper) wants to run a night train on that line, it pays the full, penalizing price, which drastically inflates the cost. While an aircraft flies over three countries without paying per-km transit fees, a night train physically travels along the tracks of each country. Since night trains have a significantly lower passenger capacity per carriage (as beds take up much more space than seats), the operator faces a massive, fixed track cost that must be spread across a very small number of passengers [1]. There is a growing public demand to revive night trains, driven by climate awareness (the "flygskam" movement) and the desire for time-efficient travel. Travellers prioritise comfort, privacy, and morning arrival times, and studies show that many "mode shifters" are willing to choose trains over planes if the offer includes private suites or "mini cabins" [15]. While environmental "greens" are a core segment, the larger market of "pragmatists" is highly sensitive to ticket prices, meaning competitive pricing is the main driver for shifting demand from flights [11].

In summary, based on the sources, it can be concluded that night trains are clearly a sustainable and viable from an environmental and social standpoint [14]. However, to move beyond a niche market and reach their full potential, significant political intervention is required to solve the economic challenges of high infrastructure fees and rolling stock scarcity.

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V. Smart Mobility, Rail and Evidence-Based Transport Planning

From Service Standards to Infrastructure Needs: A Transferable Model for Suburban and Regional Railway Network Planning

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ABSTRACT

This paper proposes a service-standard-led method for planning local, suburban, and regional passenger railway networks. Instead of deriving future services primarily from the constraints of existing railway infrastructure, the proposed method first defines the desired level of service in terms of frequency, connectivity and accessibility. These objectives are then translated into a hierarchical operational passenger transport network with clearly defined service standards, from which the corresponding infrastructure requirements are derived. Central Croatia is used here as a case study. The existing railway service is analysed using selected indicators related to passenger service frequency, direct connections, opportunities for coordinated transfers, and timetable structure. It is then compared with a proposed hierarchical network of regional, suburban, and local passenger services based on the integrated clock-face timetable concept. A schematic network diagram is used as both a technical and graphical representation of the proposed line hierarchy, stopping patterns, service structure, and coordinated transfer opportunities. The main scientific contribution is the development of a planning framework that links desired public transport outcomes and citizens' mobility needs with operational service design and long-term railway infrastructure requirements. Under this approach, infrastructure development is guided by a carefully designed passenger service network intended to meet the mobility needs of most of the population, rather than by existing infrastructure constraints alone. The proposed method should be transferable to other metropolitan and polycentric regions with comparable geographical structures and passenger mobility needs.

Keywords: integrated clock-face timetable; passenger railway service; public transport; service standards; passenger offer; transport planning

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FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

In medium- and low-density regions, high-frequency railway services are often not feasible. Therefore, railway passenger services should be planned around regular headways and coordinated transfers that provide acceptable interchange times and a wider range of reachable destinations. Such an approach can improve accessibility even where individual line frequencies remain moderate.

One of the main problems in planning of railway systems in Croatia, and similar countries, is that railway planning has often followed an infrastructure-first or sequential logic. Such an approach often neglects organisation, timetable integration and the overall usability of the passenger services, therefore creating limited network effects with services that offer uneven travelling possibilities on different parts of the network. Such systems become unattractive and often underutilised.

These problems can be reduced by timed-transfer or pulse systems, in which services meet at selected nodes within planned interchange windows, allowing passengers to transfer between several lines with short and predictable waiting times [1-4].

The current passenger railway timetable used in the Croatian railway network is not organised as nationwide timed transfer system or integrated clock-face timetable [5].

This paper proposes a new methodology for transforming an existing railway infrastructure network into a categorised, layered and connected public transport service network that offers high-quality standardised passenger services. Such a structured network can offer an all-day, uniform, sustainable mobility service. The core of this planning tool is a planning method that proposes modelling of lines supported by defined graphical model. Such model offers a visual method to adequately monitor and evaluate accessibility and service standards at every part of the network by combining a mathematical approach with precise methodology driven by graphical depiction of the network and its characteristics. This depiction of network is based on Henry Charles Beck design of the London's underground railway system schematic map in 1933. Beck was an electrical engineer that made such a map similar to an electrical scheme. The method was successful and such a design has been used around the world until this day [7].

The main geographical scope of this article is the region of Central Croatia. This region includes the Croatian capital Zagreb and its surroundings.

The main goal of this article is to propose a methodology for developing a hierarchical operational model for regional, suburban and local railway passenger services by combining the design of integrated clock-face timetable, proper classification of the passenger services, establishing proper nodes as transit centres and using the methods of designing a schematic public transport network maps to support this process.

2 LITERATURE REVIEW

Friesen et al. [8] wrote about this problem and noted that such approach leads to strict constraints for the timetable and reduces the options to adjust the timetable to the transportation demand which possibly changes between the infrastructure planning and the actual operation.

Because of the long planning periods and their long-life cycle, railway infrastructure has to be outlined long ahead. At present, the infrastructure is being designed while only little about the intended operation is known. Hence, the timetable and the operation are adjusted to the infrastructure. Since space, time and money for extension measures of railway infrastructure are limited, each modification has to be done carefully and long lasting and should be appropriate for the future unknown demand [8].

The public transportation planning process is traditionally subdivided into a number of steps which are assigned to either the strategic, the tactical, or the operational planning phase [9]. According to

Huisman et al. [10], the strategic phase encompasses a time horizon of two to ten years before implementation and includes infrastructure decisions and line planning. The timetabling problem is often allocated to the tactical phase (approximately one year before implementation).

Tosstorff et al. [11] have also determined that Railway timetabling in Europe is shifting towards passenger-centred, connection-optimised network timetables with synchronised stops at major nodes.

Vuchic gives his overview of, as he calls it, timed transfer system. A *timed transfer system* (TTS) is a network consisting of transit lines and one or several *transit centres* (or focal points of the network) at which TUs from all intersecting lines arrive simultaneously, allowing easy passenger transfers in all directions [1].

Services on the line are scheduled for such arrivals and simultaneous dwell times, which are as long as is needed to allow passengers to transfer and then TUs to depart. For this type of operation, travel times between the transit centres and scheduled headways have a certain relationship.

Walker [2] also talks about the importance of pulse systems, or timed transfer systems, and their contribution in planning a logical public transport system. Finger et al. [6] discuss the need to plan regular interval timetables and the amenities that such system offers for passengers and high-quality passenger services in general. Hesse [3] offers theoretical background and the explanation behind the Deutschlandtakt project that aims to establish integrated clock-face timetables for the entire Germany beyond 2030.

The proposed hierarchy also follows the general public transport categorisation between local, accelerated and express services, where different stopping patterns balance accessibility and travel speed [12].

Schematic public transport maps are commonly used as passenger information tools, but their relevance can also be translated to transport planning sector too. Unlike conventional cartographic maps, which aim to represent the transport system in its geographical context as faithfully as possible, schematic maps primarily represent the structure of the network and its connectivity. For this reason, these maps can deliberately be used to simplify, exaggerate or displace geographical elements in order to emphasise links, adjacency, relative position, transit centres or interchange terminals and even other attributes that are more important for understanding the public transport network than exact geographical accuracy [7].

In the Rijeka, Croatia, metropolitan-region concept, schematic representation was used to support the design of a suburban railway service concept and to communicate the relationship between lines, stations and integrated timetable logic [4]. Similarly, the Ludbreg public transport study used a schematic network map to present an integrated local bus and rail concept, in which line colours, numbering, the central transfer hub and clock-face timetable logic helped explain the proposed system structure [15].

In Croatia, passenger railway services are not currently organised as a nationwide regular-interval timetable, timed transfer system or integrated clock-face timetable. Mlinarić et al. [13] worked on the idea to implement “Integraler Taktfahrplan” or ‘Integrated Fixed–Interval Timetable’ in central Croatia due to the lack of implementation of such system in Croatia. Brezina et al. [5] also discuss capacity problems that lead to unattractive timetables for passengers, stating that low speed and insufficient train frequencies made passenger services uncompetitive.

3 METHODOLOGY

The main geographical scope of this article is the region of Central Croatia. This region includes the Croatian capital Zagreb and its surroundings, as well as the network of medium and small sized cities placed around 100 kilometres around Zagreb including cities: Varaždin, Čakovec, Koprivnica, Križevci,

Bjelovar, Kutina, Sisak, Karlovac and Krapina. This region was chosen because most of these cities gravitate towards Zagreb, because railway network forms logical connecting corridors among those cities and it overlaps, except for the Karlovac County and Bjelovar-Bilogora County, with two statistical regions on NUTS 2[1] level called The City of Zagreb and Northern Croatia [14]. This area also represents the study area where examples of all-day service, connectivity and accessibility have been tested.

For this paper the existing timetable of the HŽ Putnički prijevoz d.o.o.[2] will be used [16]. HŽ Putnički prijevoz is the only passenger railway service operator on the railway network in central Croatia [17]. Public railway passenger services are provided under Public Service Contract no. 1/2019/DP-HŽPP, concluded between the Republic of Croatia, the Ministry of the Sea, Transport and Infrastructure, and HŽ Putnički prijevoz d.o.o. for the period 2019–2028 [18]. Therefore, for the purposes of this study, HŽ Putnički prijevoz d.o.o. official timetable for 2025/26 will be used for the research.

In order to propose services that are more competitive with a personal car in terms of speed, a range of properly categorised railway services should be offered.

The proposed network for central Croatia is designed by using a service-standard-led procedure. Instead of starting from the existing network and its possible limitations, which could limit the development of the passenger service, the procedure starts from the passenger standards set in advance. Main service standards set here are all-day operations, regular headways, clear hierarchy, direct connections on main corridors, and harmonised transfers at selected nodes.

The first step is the definition of the operating working hours of the system plus the basic headways for each service. The model proposed here will be operating from approximately 05:00 to 24:00 hours on each workday.

The second step is the classification of nodes in the network. Nodes are classified according to their position and the network characteristics. InterCity nodes are the nodes at the highest level, served by InterCity, high-speed (if existing), regional, suburban and local railway passenger services. Regional nodes are important nodes on the regional level, and they are served by regional, suburban and local railway passenger services. Suburban and local nodes are served only by suburban and local railway passenger services.

The third step is the definition of the railway passenger service categories. Three basic railway passenger service categories are defined here: InterCity, regional and suburban/local services.

The fourth step is the application of the node stopping rules. Regional trains stop only at national and regional nodes, while suburban and local trains stop at all nodes on their routes.

The fifth step is the design of the schematic network model. The proposed lines are drawn as a layered schematic network in which each service layer is represented by line types, different colours and clearly defined nodes of different categories. The system is being drawn with a similar logic that was proposed by Henry C. Beck in 1933 by drawing a schematic map of London's underground. The purpose of this schematic map is not only to illustrate the proposed system, but to also support the process of planning the entire public transport network by showing line hierarchy, node hierarchy, stopping patterns, nodes for entering and leaving the system, nodes with transfer possibilities and the level of coverage of different parts of the network with services.

[1] To reference countries' regions for statistical purposes, the EU has developed a classification known as NUTS (Nomenclature of territorial units for statistics). NUTS divides each EU country into 3 levels: NUTS 1: major socio-economic regions, NUTS 2: basic regions (for regional policies) and NUTS 3: small regions (for specific diagnoses) [14]

[2] HŽ Putnički prijevoz d.o.o. or HŽPP d.o.o. is short for: Hrvatske željeznice Putnički prijevoz d.o.o., which is the full name of the company. Translation to English: Croatian Railways Passenger Transport Ltd

Table 1. The set of indicators proposed to determine improvements when the six-step method is being used.

Indicator	Meaning	Application
Frequency improvement	Difference between existing and proposed departures	Varaždin directions
Service-span improvement	Difference between first and last usable departure	Varaždin node
Headway regularity	Variation of departure intervals, expressed through CV	Four directions from Varaždin
Transfer improvement	Number of favourable 5–15 min transfer options	Varaždin node

Source: made by authors

The sixth step is finding and planning the nodes for transfers and placing them into the network. These nodes are placed on the places where lines of the same or different categories intersect.

To evaluate the new approach and new method of planning, several indicators have been developed to monitor the difference in contrast to currently used timetables. These indicators can be observed in **Table 1**.

4 EVALUATION OF RESULTS

The six-step procedure described in Section 3 was applied to the Central Croatia case study.

In the first step the working hours of the system are defined, and it was set that operating hours of the system start roughly at 5:00 hours and terminate around 24:00 hours in the night.

In the second step all of the nodes, meaning stops and stations, for passenger operations were determined and categorised. Most of the nodes were categorised as local or suburban meaning they are only served by local and suburban trains and skipped by higher categories of trains.

In the third step the categories of trains were chosen. The first category, meaning the first and the lowest level of service was set to be local trains in low-density areas and suburban trains in medium and high-density areas. These trains are designated with the letter S. The second category, meaning the second, medium level, are regional trains. These trains are designated with the letter R. It should be pointed out that the scope of this article does not include InterCity or high-speed trains.

In the fourth step stopping rules were fully determined, based on steps two and three.

In the fifth step the design of the schematic network model was completed. The lines were drawn as diagonal lines passing through main regional or InterCity nodes. The main corridors were covered by regional train lines (R) and suburban/local lines (L/S). Other corridors were only covered by local lines (L). The map can be observed in **Figure 1**.

In the sixth step, by using the schematic network map and the predetermined service standards, the role of the nodes in the network was checked and they were given proper categories.

The schematic map reveals no gaps in service on main corridors, which are all covered by regional and local/suburban service. Also, all the stations and stops are covered by services, and the standard is almost equally distributed across the network. During the designing process of the schematic map, it was easily discovered when some corridors or nodes did not have adequate coverage with service. With additional redesigning, all the gaps were covered.

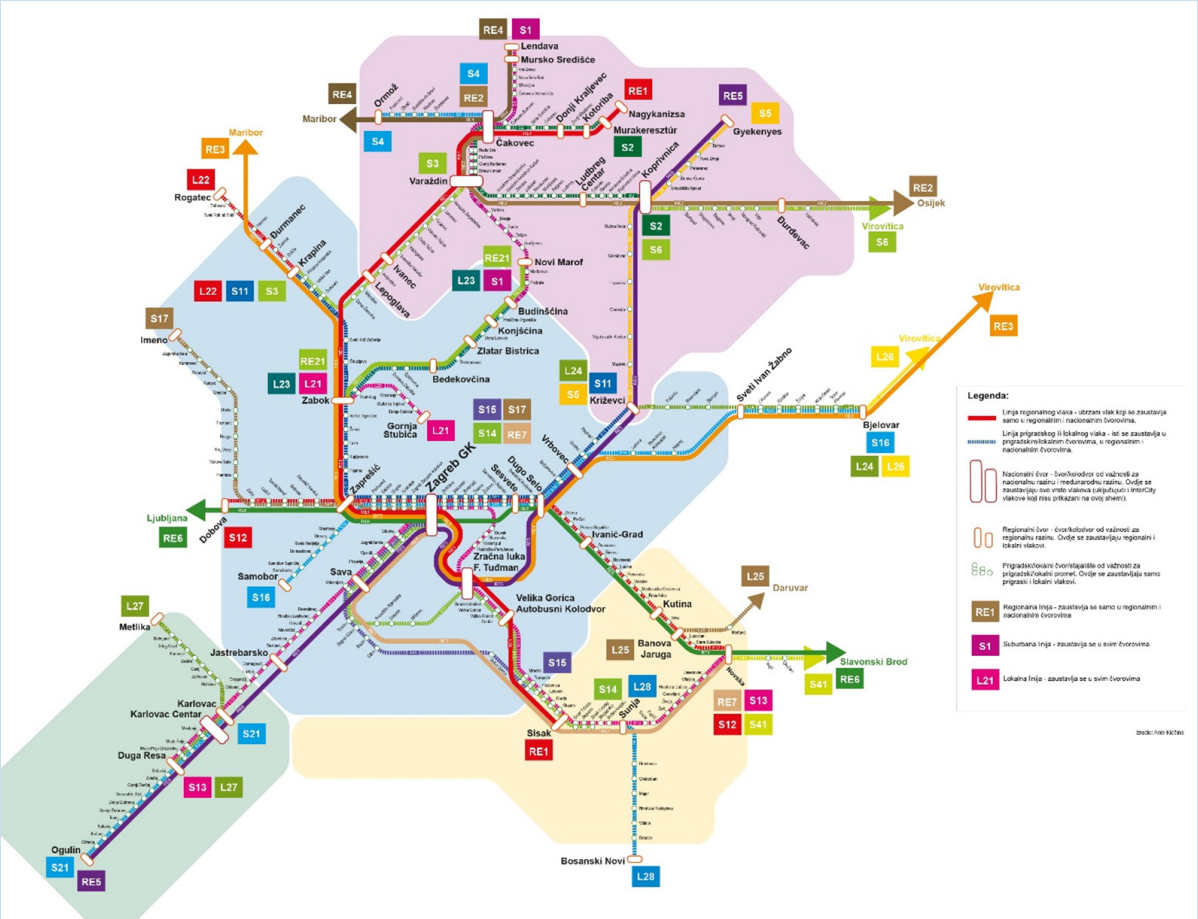


Figure 1. A proposed schematic passenger railway service network map, with regional (R), local (L) and suburban (S) passenger train lines in the region of central Croatia. Source: made by authors

Parts of the missing railway infrastructure were also detected using this approach. A service that could extend to the Zagreb Airport F. Tuđman (Zračna luka F. Tuđman) is currently not possible due to the lack of the railway infrastructure connecting the airport with the rest of the network. But this operational concept and the schematic map support the idea of connecting the Zagreb airport with railway links that should make them part of the railway network.

The headways for all the lines in the network were also determined and they are the following:

- Regional trains (R), 60-minute headways
- Suburban trains (S) that serve Zagreb Glavni kolodvor or Zračna luka F. Tuđman (Zagreb airport), 30-minute headways
- Suburban trains (S) that do not serve Zagreb Glavni kolodvor or Zračna luka F. Tuđman (Zagreb airport), 60-minute headways
- Local trains (L), 60-minute headways

To test potential improvements of the new approach in planning of the railway service using integrated clock-face timetable combined with the schematic network map one railway node in the network was chosen, and that node is Varaždin. Varaždin is the seat of the County, it is an urban node in the TEN-T network, and it is a regional centre in economy, education, health care and tourism. The railway network from the Varaždin railway station extend into four directions: Čakovec, Koprivnica, Zabok and Golubovec.

The improvements of the new proposed timetable are shown in **Table 2**.

Table 2. The comparison of main categories between the existing railway passenger timetable and the new proposed system for Central Croatia.

Indicator	Existing timetable	Proposed model	Improvement
Service span, Varaždin	17 h 12 min	19 h 00 min	+1 h 48 min
Departures within 05:00–24:00	41	model-based hourly service	increase
Local/suburban departures, four directions	39	80	41
Regional departures, four directions	2	80	78
CV Čakovec direction	0.58	0.00	fully regular
CV Koprivnica direction	0.43	0.00	fully regular
CV Zabok direction	0.09	0.00	fully regular
CV Golubovec direction	0.53	0.00	fully regular
Favourable transfer opportunities	39	up to 240	substantial increase

Source: made by authors

The results show that the proposed service-standard-led model offers improvements of the passenger railway service on three levels. At the network level, the new proposed integrated model offers 1,506 two-way daily departures through the entire network.

Varaždin railway node, meaning Varaždin railway station was taken as an example here, and on a level of a node, several more improvements are visible. The new proposed model shows improvements in service span. It also shows improvements in regularity of headways, eliminating irregularities completely once the integrated clock-face timetable was hypothetically implemented. Finally, the transfer-node analysis compared the existing timetable with the new proposed timetable shows a substantial increase in transfer possibilities. The number rose from 39 up to 240 possibilities in favour of integrated clock-face timetable concept.

5 CONCLUSION

This paper proposed and tested a service-standard-led method of planning regional sustainable mobility based on planning of regional, suburban and local passenger railway services. The purpose of this method was to reverse the usual infrastructure-first planning logic and to place emphasis on adequate high-quality passenger railway service standard. So, instead of adapting the future passenger railway timetable according to the constraints of the existing network, the proposed approach first defined the desired level of high-quality service in terms of service span, even headways, service hierarchy, node hierarchy, stopping patterns and adequate transfer opportunities. These service standards were then transferred into a schematic operational network diagram, which was used to identify service, corridor, node and transfer gaps.

The method was applied to the case of Central Croatia. The proposed model defined an all-day railway passenger service spanning from approximately 5:00 to 24:00 hours, with regular 60-minute headways on regional, local and non-core suburban lines, and 30-minute headways on the suburban lines that serve two central nodes, Zagreb Glavni kolodvor and Zagreb Airport.

The detailed evaluation of the Varaždin railway node, which was chosen as a node to test the categories for evaluation, showed that proposed model improved several selected indicators which were set to measure the quality of railway passenger services. The proposed service span was longer than the one in the existing timetable, the number of departures was largely increased, and the use of integrated clock-face timetable eliminated the irregularity of headways. The analysis of transfer possibilities showed that integrated approach could substantially increase the number of needed transfer possibilities in Varaždin node, with transferability of such approach to different nodes in the proposed network, and also other similarly designed networks too.

Using the approach where a schematic network map was designed proved that this step was an important part of the proposed method. The main purpose of the map was not only a pre-trip information tool for passengers, but also a planning tool displaying line hierarchy, node hierarchy, stopping patterns, service layers and transfer-node logic. When gaps in service, coverage and transfer possibilities were discovered on the map, the redesigning process was applied, and gaps were eliminated.

The results also show how operational service planning can support the identification of infrastructure needs. If the desired operational concept cannot be operated on the existing infrastructure, the gap between the proposed operational model and the current infrastructure becomes visible. This is especially relevant for missing links, capacity limitations or transfer option gaps at both railway nodes and corridors. Therefore, infrastructure development can be guided by the requirements of a planned high-quality passenger-service network.

This method should be considered as a strategic and methodological evaluation tool rather than a full design method for timetables and other operating elements. Before launching the results that were obtained by the proposed method, a full-scale study covering timetable calculations, turnovers for the rolling stock and personnel, investment costs, full cost-benefit analysis and interaction with freight railway transport must be completed.

Nevertheless, the proposed method provides a transferable framework for early-stage railway network planning in metropolitan and polycentric regions where regular, connected and passenger-oriented railway services are both needed and desired.

Use of AI tools: AI-assisted tools were used to support the search for data, structural organisation and language refinement. All scientific content, analysis, interpretation, and conclusions were developed and verified by the author(s), who remain fully responsible for the content.

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V. Smart Mobility, Rail and Evidence-Based Transport Planning

Expert and User Perceptions of Multimodal Public Transport Attributes: A Comparative Analysis for Stated Preference Design

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ABSTRACT

Stated preference (SP) experiments are the standard tool for modelling mode choice, but their validity depends on which attributes are presented to respondents, and experts usually make this choice. This paper asks whether transport experts and public transport users weigh the same attributes in the same way, and whether users can be treated as a single average respondent. Within the MOBIUS project, an identical online questionnaire was completed by 32 transport experts and 67 Zagreb residents. Respondents rated 33 attributes of urban and multimodal transport on a 1-10 scale and selected the seven attributes they consider most important. Experts and users agree strongly on the overall ordering of the attributes (Spearman $\rho = 0.76$). However, all eight attributes with a significant difference after multiple-testing correction are rated higher by users, and most of them are experiential attributes such as crowding, perceived safety and trust in digital services. Among users, concordance is weak (Kendall's $W = 0.14$), and hierarchical clustering separates two groups of similar size, which differ mainly in how demanding they are about operational attributes, while demographic variables cannot predict group membership (AUC = 0.69). Based on these results, the 33 attributes are assigned to six tiers, which gives a set of 16 candidate attributes for the SP design and five core attributes that should appear in every choice task.

Keywords: stated preference; public transport; mode choice modelling; attribute selection

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1 INTRODUCTION

The shift towards sustainable urban mobility depends on getting people to choose public and multimodal transport over the private car. To design services and policies that support this shift, planners need to know which service attributes drive travel choices. The standard tool for this is the stated preference (SP) experiment, in which respondents choose between hypothetical travel alternatives described by a set of attributes [1-3]. The validity of an SP study depends heavily on which attributes are chosen and presented, because a choice task can only represent a handful of attributes before it overloads the respondent [4]. In practice, the selection of attributes is usually made by experts. If experts and travellers weigh attributes differently, an expert-built SP design risks measuring what modellers consider important rather than what users experience.

This study examines that risk directly. Within the MOBIUS research project, the same online survey was given to two groups, transport experts and users, to compare how they rate 33 service attributes. The study sets out to answer two main questions: how well experts and users agree on the importance of these attributes and whether user preferences are consistent enough to treat users as a single, average respondent, or whether segmentation is required.

This paper is organised into six sections. Section 1 introduces the problem and sets out the research question. Section 2 reviews the relevant literature on attribute selection for SP studies, the expert-user gap and user segmentation. Section 3 describes the survey instrument, the two samples and the analysis, while in Section 4 we present the results. Section 5 discusses these findings together with the study's limitations. Finally, in Section 6 we set out the attribute tier framework and present the conclusions.

2 BACKGROUND

Attributes for a stated preference study are typically chosen by experts, whose priorities need not match those of the travellers whose behaviour is being modelled. This section reviews how attributes are selected for choice experiments and what is known about the gap between expert judgment and user preferences.

2.1 Stated preference and attribute selection

Stated preference methods are a standard way to study travel behaviour when revealed data are unavailable [1], [3]. A recognised constraint is respondent burden, as the number of attributes in a choice task grows, response quality falls, so most designs keep to roughly five to eight attributes per choice task [4]. This makes attribute selection a decisive step. The range of possible public transport attributes is large and spans several dimensions, from operational performance to comfort and information [5, 6]. With the development of multimodal and Mobility-as-a-Service (MaaS) concepts, the number of relevant attributes has expanded further [7].

This study compiled the 33 attributes examined from a structured literature review [2]. Attributes reported across several sources were retained and organised into five thematic categories. The list was intentionally kept broad, instead of reducing it to a handful of attributes in advance, so that the comparison between experts and users can show which attributes an SP design should keep. The full inventory and its five categories are presented in Section 3.1.

2.2 Aligning expert-driven design with user preferences

Public transport service-quality research has produced a substantial body of work on how travellers rank the attributes of a public transport (PT) service [8, 9]. A useful way to organise these attributes is to separate systemic ones, which describe the network at the planning scale (cost, transfers, ticketing, service structure), from experiential ones, which describe the journey as the traveller feels it (crowding,

waiting, information availability, etc.). Both dimensions matter for how a service is perceived, and both need to appear in any SP attribute list intended to reflect real mode-choice behaviour.

Whether experts and users rank the attributes in the same way is hard to judge from the existing literature. Most comparisons use different tools to survey experts and users. Experts are usually interviewed or asked open-ended questions, while travellers answer standardised rating scales. Any difference between the two sides therefore reflects the two instruments as much as the two sets of priorities. Studies that use the same instrument for both groups, item by item, are rare, and we did not find one at the attribute level in the recent literature. This study is designed to close that gap.

The second aim concerns users alone. Any mean ranking of the 33 attributes assumes that users think broadly the same way. That assumption does not always hold. When users disagree among themselves, the mean profile hides distinct preference groups and segmentation is needed [10, 11]. This study asks whether users from the Zagreb area form distinct preference groups, and whether those groups can be recovered from the demographics a modeller usually has. Together, the two aims define the structure of the results in Section 4.

3 METHODOLOGY

This study is based on single online questionnaire administered to two independent samples, transport experts and Zagreb residents. The attribute set and its thematic structure, the recruitment and composition of the two samples, and the statistical procedures used to compare them are set out in this section.

3.1 Survey development

An online questionnaire was developed to measure how respondents rate 33 selected attributes of urban and multimodal transport. For every attribute, two response formats were combined. The first is a Likert-type rating on a 1-10 scale, which captures how important each attribute is for the respondent. The second is a forced-choice TOP7 selection, where each respondent chose the seven attributes they consider most important overall. This dual-scale design was used because the two formats answer different questions. The Likert scale shows how important each attribute is on its own, while the TOP7 selection shows which attributes a respondent would prioritise when forced to choose.

The 33 attributes were selected from prior literature on service quality and multimodal integration [2, 5, 6] and grouped into five thematic categories: operational (8 attributes), multimodality (5), service quality (6), contextual (7) and psychological (7). The full attribute list and their group assignments are given in **Table 1**.

Table 1. 33 public transport attributes grouped into five thematic categories

Thematic group	N	Attributes
Operational	8	total travel time; total travel cost; number of transfers; travel-time reliability; waiting time; in-vehicle time; service frequency; access/egress time
Multimodality	5	integrated ticketing; service integration; Park-and-Ride availability; Mobility-as-a-Service; ease of transfer
Service Quality	6	crowding level; travel comfort; perceived safety; real-time information; service reliability; ease of use

Thematic group	N	Attributes
Contextual	7	trip purpose; day of week; time of day; weather conditions; spatial accessibility; time pressure; travel companions
Psychological	7	environmental concern; habitual behaviour; trust in digital services; comfort preferences; affordability; access for people with disabilities; perceived complexity

Source: made by authors

The survey was distributed online via SurveyMonkey, and it was identical for both samples. In this way, any observed differences should reflect differences in perceptions and not in the measurement instrument.

3.2 Samples and recruitment

Two samples were surveyed in the same period. Experts (N=32) were recruited through the MOBIUS project network and professional contacts in academia, transport consulting and public administration. Areas of expertise reported by experts include stated-preference survey design, discrete choice modelling, multimodal transport, PT planning, sustainable urban mobility planning, behavioural research and applications of machine learning.

Users (N=67) are residents of the Zagreb area recruited through the authors' personal and professional networks. The following demographic variables were collected for each respondent: age group, employment status, education, car access, familiarity with digital travel apps, travel frequency and usual modes used. **Table 2** gives a compact profile of both samples.

Table 2. Sample profile: experts (N = 32) and Zagreb public transport users (N = 67). Values are n (%). Mean number of transport modes used per user: 1.64 (SD 0.48).

Experts (N = 32)	n (%)	Users (N = 67)	n (%)
Region		**Age group**	
Regional (CRO, SRB, MKD)	19 (59.4)	18–35	36 (53.7)
International	13 (40.6)	36+	31 (46.3)
Affiliation		**Employment**	
University/research	28 (87.5)	Employed	43 (64.2)
Other	4 (12.5)	Student	17 (25.4)
Experience		Retired	7 (10.4)
> 10 years	25 (78.1)	**Car access**	
≤ 10 years	7 (21.9)	Has car access	51 (76.1)
		No car access	16 (23.9)
		Travel frequency	
		Daily	50 (74.6)
		Less than daily	17 (25.4)

Source: made by authors

3.3 Statistical methods

All analyses were run in SAS OnDemand for Academics. Prior to performing comparisons, a one-sample t-test against the scale midpoint (5.5) was used to check that each attribute was rated as more than neutral in each sample.

The first part of the analysis measures how much experts and users agree. Overall agreement is summarised by Spearman's rank correlation (ρ) between the two mean rankings of the 33 attributes, which ranges from -1 (opposite rankings) through 0 (unrelated) to +1 (identical rankings). Attribute by attribute, the two samples are compared with a non-parametric test for two independent samples (Mann–Whitney U) applied to each of the 33 attributes. Because many tests are done at once, the p-values are adjusted so that the expected number of false positives stays under control via the Benjamini–Hochberg correction [12]. The same adjustment is used everywhere in the study where a family of tests is run together. Within each sample, we also measure how much respondents agree with one another on the ranking using Kendall's coefficient of concordance (W), which runs from 0 for no agreement to 1 for perfect agreement.

The second part looks at whether users can be treated as one group. Users are grouped by the pattern of their 33 standardised ratings using hierarchical clustering (Ward's method), and the number of groups is chosen from a standard cluster-fit criterion. Whether group membership can be predicted from what a modeller usually knows about a person (age, employment status, car access, travel frequency, use of digital travel apps and number of modes used) is then tested in two ways: one variable at a time with contingency-table tests, and all variables together in a logistic regression with a small-sample correction. The overall predictive quality of the joint model is reported as an area-under-the-curve (AUC), which ranges from 0.5 (no better than chance) to 1 (perfect prediction).

4 RESULTS

The results address two questions in sequence. The first is how closely experts and users agree on the importance of the 33 attributes, examined both at the level of the overall ranking and attribute by attribute. The second is whether users can be treated as a single group at all, tested through the internal concordance of their ratings and a cluster analysis of their response profiles.

4.1 Alignment between experts and users

Before comparing the two samples, we checked that respondents used the 1-10 scale to distinguish attributes. In both samples, 30 of the 33 attributes were rated significantly above the neutral midpoint of 5.5 after the Benjamini-Hochberg adjustment. Two of the three exceptions are the same in both samples (environmental concern and travel companions), while the third differs: trust in digital services for experts and accessibility for people with disabilities for users.

Overall, the two samples agree strongly on the ordering of the 33 attributes. The rank correlation between the two mean rankings is Spearman $\rho = 0.76$ ($p < 0.001$), meaning a stated preference design seeded from the expert ranking would reproduce most of the user ranking. Four of the five top-rated attributes are shared by both samples (total travel time, service reliability, travel time reliability and service integration), only in a different order: total travel time is first for experts (mean 9.06) and service reliability first for users (9.22). At the level of five thematic groups, only service quality differs significantly between samples (users +0.71 higher than experts), while the other four groups are aligned.

The disagreements sit at the level of individual attributes. Of the 33 attributes, 8 have a significant gap after the adjustment (**Table 3**). What is interesting is that all 8 gaps run in the same direction: users rate the attribute higher than experts. If the direction were random, 8 out of 8 gaps on the same side would occur with a probability of about 0.4%, so the asymmetry is systematic rather than incidental. The three largest gaps are trust in digital services (+1.76), spatial accessibility (+1.22) and crowding level (+1.01).

Table 3. Attribute-level comparison of Experts and Users, sorted by absolute difference |Δ| in descending order. Δ = Mean(User) − Mean(Expert). Mann–Whitney U test per attribute with Benjamini–Hochberg FDR correction over 33 tests. TOP7 columns give the percentage of respondents in each sample who selected the attribute in their forced-choice TOP7 set. Significance codes: ** p < 0.01, * p < 0.05, (.) p < 0.10, ns not significant after FDR. Group abbreviations: Op = Operational, Mm = Multimodality, SQ = Service Quality, Con = Contextual, Psy = Psychological.

Attribute	Group	Mean E	Mean U	Δ (U−E)	Sig.	TOP7 E %	TOP7 U %
Trust in digital services	Psy	6.03	7.79	+1.76	**	6.3	4.5
Spatial accessibility	Con	7.31	8.54	+1.22	**	15.6	11.9
Day of week	Con	6.25	7.37	+1.12	*	0.0	3.0
Crowding level	SQ	7.34	8.36	+1.01	*	3.1	46.3
Comfort preferences	Psy	7.00	7.97	+0.97	*	6.3	13.4
Accessibility (disabilities)	Psy	7.16	6.22	-0.93	ns	15.6	1.5
Real-time information	SQ	7.97	8.79	+0.82	*	21.9	22.4
Total travel cost	Op	7.97	7.21	-0.76	ns	53.1	40.3
Ease of use	SQ	7.44	8.18	+0.74	ns	9.4	10.4
Perceived safety	SQ	7.97	8.70	+0.73	*	15.6	43.3
Trip purpose	Con	7.31	8.00	+0.69	ns	25.0	9.0
Service integration	Mm	8.38	9.01	+0.64	*	46.9	43.3
Affordability	Psy	7.28	7.91	+0.63	ns	3.1	9.0
Environmental concern	Psy	5.63	6.18	+0.55	ns	3.1	4.5
Weather conditions	Con	7.09	7.61	+0.52	ns	12.5	13.4
Service reliability	SQ	8.72	9.22	+0.51	(.)	40.6	25.4
Time of day	Con	7.09	7.60	+0.50	ns	0.0	1.5
Travel comfort	SQ	7.41	7.87	+0.46	ns	15.6	22.4
Park&Ride availability	Mm	6.88	6.45	-0.43	ns	3.1	6.0
In-vehicle time	Op	7.44	7.10	-0.33	ns	15.6	20.9
Total travel time	Op	9.06	8.79	-0.27	ns	81.3	74.6
Ease of transfer	Mm	8.22	8.46	+0.24	ns	21.9	20.9
Access and egress time	Op	7.66	7.49	-0.16	ns	18.8	7.5
Travel time reliability	Op	8.69	8.85	+0.16	ns	53.1	46.3
Number of transfers	Op	7.56	7.72	+0.15	ns	43.8	37.3
Waiting time	Op	8.25	8.40	+0.15	ns	31.3	52.2
MaaS	Mm	7.44	7.58	+0.14	ns	12.5	4.5
Integrated ticketing	Mm	8.00	8.13	+0.13	ns	40.6	19.4
Service frequency	Op	8.44	8.57	+0.13	ns	43.8	49.3
Travel companions	Con	5.94	5.87	-0.07	ns	3.1	6.0
Habitual behaviour	Psy	7.25	7.21	-0.04	ns	15.6	4.5
Time pressure	Con	7.84	7.84	-0.01	ns	12.5	3.0
Perceived complexity	Psy	6.88	6.88	+0.01	ns	9.4	0.0

Source: made by authors

The forced TOP7 selection shows the same pattern, but more sharply. The clearest example is crowding level, picked by only 3.1% of experts but by 46.3% of users, a gap of 43 percentage points and the largest single-attribute difference in the dataset. Perceived safety and waiting time show smaller versions of the same pattern (15.6% vs 43.3% and 31.3% vs 52.2%). The two forced TOP7 sets share four attributes and differ on three. The expert-only picks are systemic (integrated ticketing, number of transfers, total travel cost), while the user-only picks are experiential (crowding, perceived safety, waiting time). Together, these results describe an alignment that is strong overall but systematic in its exceptions: experts and users mostly agree, and when they do not, experts consistently rate the experiential attributes lower.

4.2 User heterogeneity

Within the user sample, agreement on the ranking of the 33 attributes is weak (Kendall's W = 0.136, compared with 0.230 among experts), so the mean profile discussed in previous section hides substantial variation between individual users. To see whether that variation is structured, users were grouped by the pattern of their 33 standardised ratings using hierarchical clustering, and the fit criterion pointed clearly to a two-cluster solution.

The two clusters are similar in size, with 37 users (55%) in Cluster 1 and 30 (45%) in Cluster 2. The two clusters differ in the level of their ratings more than in the shape of the profile. Cluster 1 rates almost every attribute at or above the overall user mean, while Cluster 2 rates almost every attribute below it. The separation is not uniform, though. It is largest on the operational and multimodality attributes and smallest on the contextual and accessibility attributes. Cluster 1's five largest positive deviations from the sample mean are integrated ticketing (+1.33), access/egress time (+1.32), number of transfers (+1.31), in-vehicle time (+1.22) and waiting time (+1.11 rating points), and Cluster 2's five largest negative deviations fall on the same five attributes (from −1.37 to −1.63). Cluster 2 comes closest to the overall mean on accessibility for people with disabilities, spatial accessibility, time of day and weather conditions. We therefore refer to Cluster 1 as "demanding" users, who place a high value on operational precision, and to Cluster 2 as "tolerant" users, who rate the same operational attributes markedly lower. The names are descriptive only and summarise the two mean profiles.

Whether cluster membership can be predicted from what a modeller usually knows about a person was tested next. Univariate contingency-table tests on five demographic variables (age, employment status, car access, digital app use, travel frequency) returned only one significant result: employment status (Fisher's exact p = 0.038). Retirees are over-represented in the tolerant cluster (20% vs 3%). A joint model with all six predictors (the five demographic variables and the number of modes used) returned no significant predictor, and its overall discrimination is modest (AUC = 0.687). A simpler model with employment alone gave a better fit statistic (ΔAIC = 11.6) but slightly lower discrimination (AUC = 0.646). The practical implication is direct: two distinct preference groups exist among Zagreb users, but observable demographic characteristics cannot reliably identify which group a user belongs to. If a stated preference design is to represent both groups, it must draw on direct measurement of attribute preferences rather than on demographic proxies.

5 DISCUSSION

Overall, the two samples agree strongly on the ranking of the 33 attributes (ρ = 0.76), so expert consultation remains a defensible starting point for attribute selection. Where they disagree, the disagreement is systematic. Most of the eight significant gaps fall on the experiential side of the distinction introduced in Section 2.2: experts view the network from a planning perspective, users from the journey perspective. Crowding is the clearest single case, picked in the forced TOP7 by 3.1% of experts and 46.3% of users. The direction of the crowding and safety gaps is consistent with the service-quality literature, where comfort- and safety-related attributes are among the strongest drivers of user satisfaction [8, 9].

The heterogeneity results carry a comparable message. Given the sample size and the fixed set of 33 attributes, the two-cluster solution should be regarded as exploratory, and a larger and more diverse sample may produce different groups. Nevertheless, the clear separation on operational attributes indicates that users can be meaningfully distinguished by how demanding they are about the core service attributes. What matters for design is that observable characteristics such as age, employment, car access, digital app use and travel frequency cannot reliably identify which group a user belongs to. Stratifying a sample by demographics will not recover the two preference groups. This is in line with attitude-based segmentation studies, which find that travel behaviour segments cut across socio-demographic groups [10, 11]. For SP design, this means that experiential attributes such as crowding should be retained in the choice tasks even when experts rate them lower. Since user preference groups cannot be identified from demographics, heterogeneity should be addressed at the modelling stage rather than through sampling quotas.

The study's main practical contribution is the attribute-selection framework, shown in **Table 4**, which assigns the 33 attributes to six tiers by combining the mean ratings of both samples, the size and significance of the expert–user gap, and the forced-choice (TOP7) selection frequencies. Five core attributes should appear in every choice task, two are flagged as points of critical disagreement that an expert-only inventory would overlook, four are user-driven and five are expert-driven, while fifteen are secondary and two can be dropped. The recommended active set for a stated preference design is the union of the first four tiers, sixteen attributes in total. Because a single choice task can carry only five to eight attributes without overloading respondents, we suggest keeping the five core attributes in every task and rotating a small number of user-driven and expert-driven attributes across experiments. A further fourteen attributes show high rating dispersion (the "Latent" column in **Table 4**) and are better captured through attitudinal scales alongside the choice experiment than through variation within the choice task itself.

Table 4. Stated Preference attribute-selection framework: the 33 attributes assigned to six tiers. Δ = Mean(User) − Mean(Expert). Tiers combine the mean ratings of both samples, the size and significance of the expert–user gap, and the forced-choice (TOP7) selection frequencies given in Table 3. The "Latent" column flags attributes with a rating standard deviation above 2.3 in either sample, i.e. candidates for attitudinal-scale measurement.

Rank	Tier	Attribute	Group	Mean E	Mean U	Δ (U−E)	Sig.	Latent
1	**Core**	Total travel time	Op	9.06	8.79	−0.27	ns	N
2		Travel time reliability	Op	8.69	8.85	+0.16	ns	N
3		Service frequency	Op	8.44	8.57	+0.13	ns	N
4		Waiting time	Op	8.25	8.40	+0.15	ns	N
5		Ease of transfer	Mm	8.22	8.46	+0.24	ns	N
6	**Critical disagreement**	Crowding level	SQ	7.34	8.36	+1.01	*	N
7		Spatial accessibility	Con	7.31	8.54	+1.22	**	N
8	**User-driven**	Real-time information	SQ	7.97	8.79	+0.82	*	N
9		Comfort preferences	Psy	7.00	7.97	+0.97	*	N
10		Day of week	Con	6.25	7.37	+1.12	*	Y
11		Trust in digital services	Psy	6.03	7.79	+1.76	**	N
12	**Expert-driven**	Service reliability	SQ	8.72	9.22	+0.51	(.)	N
13		Integrated ticketing	Mm	8.00	8.13	+0.13	ns	Y
14		Total travel cost	Op	7.97	7.21	−0.76	ns	Y
15		Trip purpose	Con	7.31	8.00	+0.69	ns	N
16		Accessibility (disabilities)	Psy	7.16	6.22	−0.93	ns	Y

Rank	Tier	Attribute	Group	Mean E	Mean U	Δ (U−E)	Sig.	Latent
17		Service integration	Mm	8.38	9.01	+0.64	*	N
18		Perceived safety	SQ	7.97	8.70	+0.73	*	N
19		Time pressure	Con	7.84	7.84	−0.01	ns	N
20		Access and egress time	Op	7.66	7.49	−0.16	ns	Y
21		Number of transfers	Op	7.56	7.72	+0.15	ns	Y
22		Ease of use	SQ	7.44	8.18	+0.74	ns	N
23		In-vehicle time	Op	7.44	7.10	−0.33	ns	Y
24	**Secondary**	MaaS	Mm	7.44	7.58	+0.14	ns	Y
25		Travel comfort	SQ	7.41	7.87	+0.46	ns	N
26		Affordability	Psy	7.28	7.91	+0.63	ns	N
27		Habitual behaviour	Psy	7.25	7.21	−0.04	ns	Y
28		Time of day	Con	7.09	7.60	+0.50	ns	N
29		Weather conditions	Con	7.09	7.61	+0.52	ns	Y
30		Park&Ride availability	Mm	6.88	6.45	−0.43	ns	Y
31		Perceived complexity	Psy	6.88	6.88	+0.01	ns	Y
32	**Drop**	Travel companions	Con	5.94	5.87	−0.07	ns	Y
33		Environmental concern	Psy	5.63	6.18	+0.55	ns	Y

Source: made by authors

Several limitations should be noted. The sample sizes (32 experts, 67 users) are sufficient to detect systematic patterns, but they limit the power of the joint predictor model, which is why a small-sample correction was needed. The user sample is drawn from a single city, and the magnitude of the crowding gap in particular is likely inflated by Zagreb peak-hour tram conditions, although the direction of the gap is a common finding in the PT literature. The findings should therefore be generalised with caution, as cities with different network structures, service levels or user populations may show different expert-user gaps, particularly on experiential attributes. The expert sample is also dominated by academic researchers (87.5%), so the views of practitioners from operators and public administration are under-represented. Self-reported importance ratings are best treated as an input to stated preference experiments, and not as a substitute for revealed choice data. Finally, the two-cluster solution depends on the 33-attribute set, and a different inventory of attributes could produce a different segmentation.

6 CONCLUSION

This study compared how 32 transport experts and 67 Zagreb residents rate the importance of 33 attributes of urban and multimodal transport, with the aim of informing attribute selection for a stated preference experiment. Experts and users agree strongly on the overall ordering of the attributes, so expert judgement remains a defensible basis for attribute selection. Where the two groups disagree, the disagreement is systematic rather than incidental: all eight significant attribute-level gaps run in the same direction, with users rating the more experiential attributes higher than experts do. Users, in turn, cannot be treated as a single average respondent: concordance among them is weak, and their ratings resolve into two preference groups of similar size (55% and 45%). These groups cannot be recovered from the characteristics a modeller normally observes, as no demographic variable predicts group membership with useful accuracy. Taken together, the findings indicate that expert consultation is necessary but not sufficient, and that user preferences must be measured directly rather than inferred from observable characteristics.

The study's main practical contribution is an attribute-selection framework (**Table 4**) that assigns the 33 attributes to six tiers and identifies a core active set of sixteen attributes for the stated preference design, with five attributes recommended in every choice task. This provides a concrete, empirically grounded starting point for the stated preference experiment planned in the next phase of the project.

Future work within the MOBIUS project will use this framework as the input to the SP experiment and to a discrete choice model estimated on the resulting data, and will test whether the tiers and the two preference groups remain stable over time. The wider message is simple: experts and users largely agree, but the systematic exceptions are precisely the attributes that users experience most directly, and no demographic shortcut can substitute for measuring what users actually prefer.

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V. Smart Mobility, Rail and Evidence-Based Transport Planning

Assessing the Impact of Real-Time Passenger Information Systems on Perceived Bus Transport Service Quality: A Narrative Literature Review

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ABSTRACT

Real-Time Passenger Information (RTPI) systems are increasingly implemented in public transport with the aim of improving service quality, reducing passenger uncertainty, and increasing the attractiveness of bus transport. This study reviews the effects of RTPI systems on passenger perception through a narrative literature review of eight empirical studies, purposively selected as relevant and recent bus-specific evidence published between 2013 and 2025. The synthesis follows the principles of Synthesis Without Meta-analysis (SWiM), given the heterogeneity of study designs and outcome measures. The studies cover passenger information displays, mobile applications, web platforms, SMS services, and combined information systems. Reported outcomes were classified into perceived or self-reported waiting time, passenger satisfaction, reliability perception and trust-related outcomes, and behavioural outcomes such as ridership. All three studies examining waiting-time-related outcomes reported reductions, but the measures differed (self-reported, perceived, and hypothetical) and are not directly comparable. All three studies examining satisfaction, all three examining reliability perception and trust-related outcomes, and all four examining behavioural outcomes reported positive associations, although only one of the three reliability/trust studies directly measured trust and two relied on indirect indicators. The benefits depend on the accuracy of the information provided and on the quality of the underlying service. RTPI therefore appears to be a valuable but not stand-alone measure for improving perceived bus service quality; the conclusions are limited by purposive study selection and unweighted vote counting.

Keywords: real-time passenger information; public transport; bus services; passenger satisfaction; waiting time

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1 INTRODUCTION

Public transport (PT) systems are a backbone of sustainable urban mobility, yet their attractiveness relative to the private car depends strongly on service reliability and on how uncertainty is managed from the passenger's point of view. One of the most persistent sources of dissatisfaction among bus passengers is uncertainty about vehicle arrival time, which inflates the perceived burden of waiting well beyond its objective duration; an early and influential study using bus-stop surveys found that access to mobile real-time arrival information brought passengers' perceived waiting time much closer to the actual measured time [1]. Real-Time Passenger Information (RTPI) systems – delivered through electronic displays at stops, mobile applications, web platforms and SMS services – have been implemented worldwide as a comparatively low-cost measure to reduce this uncertainty and to improve the perceived quality of bus services.

Although the underlying prediction technologies (GPS-based automatic vehicle location, GTFS-realtime feeds) are now mature and widely deployed, the empirical evidence on how RTPI actually affects passenger perceptions remains scattered across disciplines, cities and methodologies, ranging from controlled behavioural experiments to large-scale satisfaction surveys and simulation-based studies [2]. This heterogeneity makes it difficult for transport planners and policy makers to draw a coherent, evidence-based picture of what RTPI can, and cannot, deliver.

This paper addresses this gap through a narrative literature review of eight empirical studies examining the effects of RTPI on bus passengers' perceptions, purposively selected as the most relevant bus-specific evidence meeting explicit eligibility criteria (Section 3.2), published between 2013 and 2025. The review focuses on four outcome categories that recur throughout the literature: (i) perceived or self-reported waiting time, (ii) passenger satisfaction, (iii) reliability perception and trust-related outcomes, and (iv) behavioural outcomes such as ridership. Because the identified studies differ substantially in design, sample, RTPI technology and reported metrics, a quantitative meta-analysis was not appropriate; instead, the review adopts a structured narrative synthesis following the Synthesis Without Meta-analysis (SWiM) reporting guideline. This review complements the earlier literature review by Brakewood & Watkins [2], which is used here as background rather than as one of the included studies, in three respects: it focuses exclusively on bus services rather than on transit in general; it adds evidence published after that review (three of the eight included studies were published in 2020–2025); and it applies an explicit, structured vote-counting synthesis that separates perceptual/self-reported outcomes from behavioural ones and directly measured outcomes from indirect indicators. The objective of the study is to assess, on the basis of the identified evidence, the extent to which RTPI systems are associated with improvements in the perceived quality of bus transport services, and under what conditions their benefits may be limited.

2 BACKGROUND

Perceived service quality is a well-established determinant of public transport patronage. Classic quality-attribute frameworks identify information provision as one of the core dimensions shaping passenger satisfaction, alongside reliability, comfort, safety and personnel behaviour [3]. Passengers systematically overestimate the time they have spent waiting when no information is available, a bias quantified in one of the earliest empirical studies of wait-time perception at bus stops [4]; subsequent research examined the effects of dynamic at-stop real-time information displays on customers [5].

A parallel line of research has examined mobile- and web-based real-time information. The OneBusAway system, which distributes real-time arrival data through a website, phone line, SMS and native mobile applications, was found to be associated with more transit trips among its users [6], and

panel-data analyses have examined traveller responses to real-time bus-arrival information [7]. Evaluations of city-wide systems have linked RTPI to ridership: a study of a citywide real-time bus information system in Chicago attributed a modest but measurable ridership gain to its introduction [8], and complementary work on the same system suggested that part of this effect operates through psychological mechanisms rather than through time savings alone [9]. A recent quasi-experimental study of a multi-feature transit app in San Antonio found a positive effect on bus ridership on infrequent routes but not on frequent ones [10]; because the app is not an RTPI system alone and the outcome is ridership only, this study does not meet the eligibility criteria in Section 3.2 and is used here as background.

RTPI has also been linked to a broader set of perceptual outcomes. An earlier before–after evaluation of OneBusAway users, which is included among the primary studies in Section 4, associated real-time information with higher satisfaction, perceived personal safety and ridership frequency, while showing that inaccuracies in the underlying data can partly offset these gains [11]. Modelling work has examined how different strategies of using real-time information affect travel outcomes [12], and passengers adapt their behaviour to service unreliability more generally [13]. Studies of stop and station amenities have shown that real-time departure information signs, together with shelters and benches, reduce perceived waiting time [14], and a two-wave university survey examined how RTPI affected community perceptions of the bus service's environmental and traffic-reduction role [15]. Finally, research on passengers waiting at bus stops in Shijiazhuang, China suggests that waiting-time perception is also shaped by smartphone use for travel-irrelevant activities, a factor distinct from RTPI [16].

Review-level evidence summarising the passenger benefits of real-time information generally reports reduced perceived waiting time, increased satisfaction and other passenger benefits [2]. However, the practical magnitude and consistency of these effects have rarely been synthesised across studies using bus-specific data and an explicit, transparent synthesis method, which motivates the present review.

3 METHODOLOGY

3.1 Review approach

This is a narrative literature review, not a systematic review: the included studies were purposively identified and screened against the explicit eligibility criteria in Section 3.2, rather than through an exhaustive, reproducible database search. Because the eligible studies differ substantially in design, sample and reported outcome metrics (minutes, percentages, ordinal satisfaction scores, sentiment classifications), their effect estimates could not be meaningfully combined in a quantitative meta-analysis. For this reason, the synthesis follows the principles of Synthesis Without Meta-analysis (SWiM) [17]. SWiM was chosen because it provides a transparent structure for (i) grouping studies by outcome category, and (ii) reporting each study's direction of effect using a standardised vote-counting procedure alongside a narrative description of the reported effect sizes, which is well suited to outcomes reported in incompatible units across studies. Because the review is narrative and the selection purposive, a PRISMA 2020 flow diagram is not reported; the consequences of this are discussed in Section 5.

3.2 Search strategy and eligibility criteria

Candidate studies were identified through searches of academic databases and repositories covering the research literature on transport (e.g., Scopus, Web of Science, ScienceDirect, and the Transportation Research Board repository), using combinations of the terms "real-time passenger information",

"real-time transit information", "RTPI"/"RTI", "bus", "waiting time", "passenger satisfaction" and "reliability perception". These searches were exploratory: search dates, database-specific search strings and numbers of records identified and screened were not systematically recorded, and the authors no longer have institutional access to some of these databases, so the search cannot be fully reproduced. Studies were included if they: (i) empirically examined an RTPI system (display, mobile application, web platform or SMS) as a bus-specific intervention; and (ii) reported a passenger-level outcome related to waiting time, satisfaction, reliability/trust, or associated travel behaviour, measured through passenger surveys, experiments, or system data directly reflecting the information passengers received. Studies that examined broader transit applications in which RTPI was only one of several features, studies based primarily on modelling or simulation rather than passenger-level empirical evidence, and studies addressing outcomes outside these predefined categories were retained as contextual background but excluded from the primary synthesis. Literature-review papers, such as [2], were likewise used for background and discussion but were not counted among the included studies, to avoid double-counting the evidence they summarise.

Applying these criteria to the literature identified through the search described above, and re-screening the studies cited in Section 2 against the same criteria, yielded eight primary studies (**Table 1**). For example, Bian et al. [10] examined a multi-feature transit application rather than RTPI as a distinct intervention, with ridership as the only outcome; Fonzone and Schmöcker [12] modelled RTPI usage strategies on an idealised network rather than evaluating empirical passenger-level outcomes; McCord et al. [15] examined perceptions of transit's environmental and traffic-reduction role, an outcome outside the four categories used here; and Wang et al. [16] examined waiting-time perception in relation to smartphone use for travel-irrelevant activities rather than RTPI itself. In total, the twenty-six references cited in this paper comprise the eight primary studies in **Table 1** and a further eighteen studies discussed as background (Section 2) or as excluded context (above). This split reflects which passenger-level outcome each study reported, not the direction of its findings: studies were not excluded for reporting a null or negative effect, but for not measuring perceived or self-reported waiting time, satisfaction, reliability/trust-related outcomes, or associated behaviour as defined in this section. Two further studies were excluded from the primary synthesis for related reasons, although both remain informative as context: an evaluation of an electronic bus-arrival display system assessed prediction accuracy using vehicle-location data rather than a passenger-level outcome [18], and a simulation study of RTPI-based trip-planning strategies used one year of empirical GPS/GTFS data rather than passenger-reported outcomes [19]; both are discussed further in Sections 4 and 5. Because the underlying search was not exhaustive, additional studies meeting these criteria may exist beyond the eight identified here; this is stated as a limitation in Section 5.

A substantially larger number of studies addressing RTPI and passenger perception exist in the wider literature; the eight primary studies were retained because they most directly matched the predefined eligibility criteria and, wherever possible, are recent, so as to reflect the current generation of RTPI technology (GPS-based vehicle tracking, GTFS-realtime feeds, smartphone applications). The included studies were published between 2013 and 2025 (five in 2017 or later, three in 2013–2016; see **Table 1**). One of the eight included studies is a non-peer-reviewed working paper reporting preliminary results. However, it is retained because it directly compares perceived with measured waiting time, and it is flagged with an asterisk in **Table 1** and **Table 2**, and discussed further in Section 5.

3.3 Data extraction and synthesis

For each included study, the following information was extracted: location and RTPI channel, study design and sample size (where reported), the outcome(s) measured and whether they were direct or indirect, and the key reported effect (**Table 1**). Results were then summarised using a standardised vote-counting method across four outcomes: perceived or self-reported waiting time, satisfaction, reliability perception and trust-related outcomes, and behavioural outcomes such as ridership, mode share or

Table 1. Characteristics of the eight included studies

Study	Location	RTPI channel and design (sample size)	Outcome(s) measured (type)	Key reported effect
Brakewood, Macfarlane & Watkins (2015) [20]	New York City, USA	Mobile app and web; natural experiment / panel regression of route-level ridership (n/a – route-level data)	Ridership (behavioural)	Ridership up to +2.3% on the busiest routes (≈340 trips/route/weekday)
Henriquez-Jara, Arriagada & Tirachini (2025) [21]	13 cities, Chile	Mobile app; survey, discrete choice and sentiment analysis (n = 3,681)	Satisfaction (direct)	70% of satisfied users valued waiting-time information; effect depends on objective service reliability
Macedo et al. (2021) [22]	Portugal and Sweden	Mobile apps, information panels, web; cross-sectional survey (n = 655)	Perceived usefulness of RTI type/platform (direct); predictability (indirect)	82% valued arrival/departure info most (vs. 73% trip planning); 87% reported a positive association with travel experience
Cullen & Ahuja (2017) [23]*	Mid-sized North American city (three bus corridors)	Displays and mobile apps; mixed methods: stated-preference survey (n = 850) plus revealed-preference data; preliminary results, preprint	Perceived vs. measured waiting time (direct); bus mode share (behavioural)	Perceived wait 23–28% shorter than measured; actual waits identical; mode share up ($p < 0.01$)
Lu et al. (2018) [24]	London, UK	Countdown displays, app, web, SMS; stated-preference discrete-choice experiment (n = 1,690 completed interviews)	Value of waiting time (stated, hypothetical)	Expected wait 6.3→4.5 min; value-of-waiting multiplier 2.2→0.8 depending on channel
Brakewood, Barbeau & Watkins (2014) [25]	Tampa, Florida, USA	Mobile app and web; randomised field experiment (n = 217: 107 control, 110 treatment)	Self-reported usual waiting time; satisfaction (direct)	Usual wait about 2 min shorter than control; less frustration and anxiety
Deng & Chen (2021) [26]	Xi'an, China	Mobile app; cross-sectional survey (n = 660)	Trust (direct); route choice (behavioural)	Trust depends on accuracy and timeliness; higher accuracy linked to more route switching
Gooze, Watkins & Borning (2013) [11]	Seattle, Washington, USA	Mobile app, web, SMS (OneBusAway); repeated cross-sectional survey, 2009 vs. 2012 users (n = n.r.)	Satisfaction and perceived safety (direct); data-accuracy/reliability indicator (indirect); ridership frequency (behavioural)	Higher satisfaction, perceived safety and ridership frequency; data errors partly offset gains

Source: Made by authors, based on the reviewed studies

Table 2. Vote-count summary of reported RTPI effects (SWiM): ✓ = positive effect; ✓[a] = positive, based on an indirect indicator; ✗ = negative or mixed effect; – = not investigated

Study	Waiting time (perceived / self-reported)	Satisfaction	Reliability perception & trust-related outcomes	Behavioural outcomes
Brakewood, Macfarlane & Watkins (2015)	–	–	–	✓
Henriquez-Jara, Arriagada & Tirachini (2025)	–	✓	–	–
Macedo et al. (2021)	–	–	✓[a]	–
Cullen & Ahuja (2017)*	✓	–	–	✓
Lu et al. (2018)	✓	–	–	–
Brakewood, Barbeau & Watkins (2014)	✓	✓	–	–
Deng & Chen (2021)	–	–	✓	✓
Gooze, Watkins & Borning (2013)	–	✓	✓[a]	✓
Total positive / investigated	**3 / 3**	**3 / 3**	**3 / 3**	**4 / 4**
Actual/system-level waiting time (not vote-counted)				
Cats & Loutos (2015) [18]	-	-	-	-
Liu & Miller (2020) [19]	-	-	-	-

Source: Made by authors, based on the reviewed studies

route choice (**Table 2**). Because the two studies that assessed actual or system-level waiting time did not meet the passenger-level outcome criterion above, that outcome is not vote-counted; the relevant evidence is instead discussed narratively in Sections 4 and 5. A positive effect is marked ✓; a positive effect based on an indirect indicator (a system-level metric or an inferred construct, such as a valued-information rating standing in for a direct trust measure) is marked ✓[a]; a negative or mixed effect is marked ✗; and a dash (–) indicates that the outcome was not investigated in that study. This vote-counting approach does not weight studies by sample size, statistical precision or study design, and no formal risk-of-bias or certainty-of-evidence tool (e.g., MMAT, JBI checklists, GRADE) was applied; the design and, where available, the sample size of each study are reported in **Table 1** so that readers can weigh the findings accordingly, and the certainty of the evidence is not formally graded (see Section 5).

4 RESULTS

Table 1 summarises the location, RTPI channel, design and measured outcomes of the eight included studies. **Table 2** presents the vote-counted direction of effect for each outcome, distinguishing directly measured from indirect indicators. The detailed findings are described narratively below.

4.1 Perceived and self-reported waiting time

All three studies that measured perceived, self-reported or stated waiting time reported a reduction. In a mixed-methods study combining a stated-preference survey (n = 850) with revealed-preference data from three bus corridors in a mid-sized North American city, passengers with access to real-time information perceived their waiting time as 23–28% shorter than the measured waiting time, even though actual waiting times were identical to those of non-users [23]. A stated-preference discrete-choice experiment among London bus users (n = 1,690 completed interviews) found that expected waiting time fell from 6.3 to 4.5 minutes (a 29% reduction) once real-time information became available, and the implicit "value of waiting time" multiplier fell from 2.2 to 1.7 for mobile-application

users, to 1.0 for web users, and to 0.8 for users combining both channels; as a hypothetical valuation from a choice experiment, this measure is not directly comparable with observed or recalled waiting times [24]. In a randomised field experiment in Tampa, Florida (n = 217: 107 in the control group, 110 in the treatment group), participants with access to a mobile/web application self-reported a reduction in their usual waiting time of almost two minutes greater than the control group [25].

None of the eight included studies directly measured actual or system-level waiting time as a passenger-level outcome (Section 3.2); related context is discussed in Section 5.

4.2 Passenger satisfaction

All three studies that investigated passenger satisfaction as an outcome reported a positive association. In the largest survey identified, covering 3,681 users of a nationwide real-time information application across 13 Chilean cities, sentiment analysis showed that 70% of satisfied users specifically valued the waiting-time information provided by the application and the resulting ability to organise their own time; the authors linked this finding to an objective, GPS-based measure of service reliability and concluded that the association between RTPI and satisfaction depends on the actual quality of the underlying public transport service [21]. The Tampa field experiment described above also reported significantly reduced frustration and anxiety among users of the real-time information application relative to the control group [25]. A repeated cross-sectional survey of OneBusAway users in Seattle, comparing 2009 and 2012 user cohorts, similarly found significant positive shifts in satisfaction with transit alongside increased perceptions of personal safety [11]. A related survey of 655 respondents from Portugal and Sweden did not measure satisfaction directly, but examined which RTI type and information platform users valued most; it is discussed in Section 4.3.

4.3 Reliability perception and trust-related outcomes

Three studies examined reliability perception or trust-related outcomes, and all three reported a positive association, although only one directly measured trust and two relied on indirect indicators. A survey of 660 bus users in Xi'an, China directly examined trust in real-time information and found that it depended strongly on the information's accuracy and timeliness, particularly for daily commuters [26]. The Portugal–Sweden survey found that arrival/departure-time information was the RTI type and platform respondents valued most, preferred by 82% of respondents ahead of general trip-planning information (73%); this is consistent with passengers valuing RTPI for the predictability it gives their journey, but because it reflects a usefulness or preference rating rather than a direct trust measure, it is marked as an indirect indicator in **Table 2** [22]. The Seattle OneBusAway survey found that inaccuracies in real-time data negatively affected rider experience, indicating that the benefits of RTPI depend on data accuracy; because this is a data-accuracy/reliability-related indicator rather than a direct measure of trust, it is likewise marked as indirect in **Table 2** [11].

4.4 Behavioural outcomes

Four studies reported behavioural outcomes. A New York City evaluation found ridership increases of up to 2.3% on the busiest routes (about 340 additional trips per route per weekday) after real-time information was introduced through mobile applications and the web [20]. In the mixed-methods study described above, the reduction in perceived waiting time was associated with a statistically significant increase in bus mode share among commuters with access to real-time information ($p < 0.01$) [23]. In Xi'an, greater accuracy of real-time information was associated with more frequent route-switching decisions [26], and the Seattle survey reported higher ridership frequency among OneBusAway users [11]. Because these are behavioural rather than perceptual outcomes, they are consistent with, but not counted as direct evidence of, greater trust.

5 DISCUSSION

The findings indicate that RTPI systems are broadly and positively associated with the perceived quality of bus transport services, although this association is conditional. Outcomes that rely on passengers' own perceptions or reports were consistently positive across the studies that examined them: perceived or self-reported waiting time (three of three studies), satisfaction (three of three), reliability perception and trust-related outcomes (three of three, of which one was directly measured and two relied on indirect indicators), and behavioural outcomes (four of four). This pattern suggests that RTPI acts mainly by reducing uncertainty and reshaping the experience of waiting rather than necessarily shortening the wait itself, consistent with earlier evidence that information provision is a core determinant of satisfaction [3] and that real-time information brings perceived waiting time closer to measured time [1], [4]. Because each outcome rests on only three or four purposively identified studies, counted without weighting, this pattern should be regarded as indicative rather than conclusive.

The magnitude of the reported waiting-time effects depended on how waiting time was measured and on the RTPI channel. The reported reductions – about two minutes in self-reported usual waiting time [25], 23–28% in perceived waiting time [23], and a fall in the value-of-waiting multiplier from 2.2 to 0.8 [24] – are based on self-reported, perceived and hypothetical measures respectively and are not directly comparable. The only study that compared channels directly found the lowest value of waiting among users combining a mobile application with web access (0.8), compared with 1.0 for web alone and 1.7 for the mobile application alone [24]; no included study compared displays with other channels, so no conclusion about the relative effectiveness of displays can be drawn.

None of the eight primary studies directly measured actual or system-level waiting time as a passenger-level outcome; two related studies excluded from the primary synthesis (Section 3.2) provide relevant context. An evaluation of an electronic bus-arrival display system found that its predictions were considerably closer to the actual arrival time than the printed timetable, but still systematically underestimated the remaining waiting time by 6.2% on average [18]. A simulation study using one year of empirical GPS/GTFS data from Columbus, Ohio similarly found that RTPI-based trip-planning strategies did not generally reduce waiting time relative to simply following the timetable, and that a "greedy" strategy resembling those used by popular transit apps performed worse, due to the risk of missing the bus [19]. Together, these two studies suggest that RTPI's effect on actual waiting time is considerably less certain than its effect on perceived or self-reported waiting time, and that the way passengers use the information – not only its availability – likely determines any realised benefit.

Reliability perception and trust-related outcomes form the category with the fewest studies and the most important caveats: only three studies examined it, of which only one directly measured trust and two relied on indirect indicators. Two studies indicate that accuracy is a necessary condition for any benefit in this category: trust in real-time information depended strongly on its accuracy and timeliness [26], and data inaccuracies partly offset the benefits found in the Seattle survey [11]. RTPI is therefore best understood as a complement to, not a substitute for, reliable operations, whose benefits are amplified – or eroded – by the quality of service delivery and of the underlying data.

These findings have practical implications for transport authorities and operators. Investment in RTPI infrastructure (displays, applications, data feeds) is likely to generate measurable improvements in passenger satisfaction, but the evidence reviewed here suggests that this benefit varies with, rather than being independent of, the underlying quality of the service: the largest study identified found that the association between RTPI and satisfaction depended on an objective, GPS-based measure of service reliability [21]. The association with trust-related outcomes and with the perceived reduction of waiting time is similarly contingent on prediction accuracy and on adequate service reliability. This suggests that RTPI should be implemented jointly with, rather than as a substitute for, investments in automatic vehicle location accuracy, headway regularity and data governance.

Two of the eight primary studies were conducted in Europe (London [24] and a survey in Portugal and Sweden [22]); a further European study used here as context evaluated prediction accuracy in Stockholm [18]. Most of the primary evidence comes from North America, with further studies from Chile and China. The European evidence concerns a capital-city bus network and a two-country survey, so evidence specific to mid-sized European cities is limited, and the findings should be transferred to such cities with caution. Since the reported benefits appear to depend on data accuracy and service reliability, authorities of such cities should verify the quality of their vehicle-location data and the regularity of their services before expecting the satisfaction, predictability and trust-related gains reported here.

Several limitations of this review should be acknowledged. First, this is a narrative review: although the eight included studies were selected by applying explicit eligibility criteria (Section 3.2), the underlying search was not an exhaustive, reproducible systematic search, and no PRISMA-style protocol or flow diagram is reported, because search dates, strings and record counts were not systematically recorded and the authors no longer have institutional access to some of the databases searched. Additional eligible studies may therefore exist beyond the eight identified here, and the findings should be read as indicative rather than exhaustive. Second, no formal risk-of-bias or certainty-of-evidence appraisal (e.g., MMAT, JBI checklists, GRADE) was applied; studies of different designs and precision – a randomised field experiment, stated-preference experiments, cross-sectional surveys, and a natural experiment – were vote-counted without weighting, so the reported proportions do not indicate comparable certainty across studies; **Table 1** reports the design and, where available, the sample size of each study so that readers can weigh the findings accordingly. Third, one finding relies on an indirect indicator (marked ✓[a] in **Table 2**), and one included study [23] is a non-peer-reviewed working paper reporting preliminary results. This single preprint contributes evidence to two of the four outcome categories and supplies the 23–28% estimate reported in the results, so those findings should be interpreted cautiously. Fourth, the eight included studies vary considerably in geographical context, sample size and methodology, which further constrains the comparability of reported effect sizes even within the same outcome category. Fifth, as a literature review rather than a primary study, this paper is subject to the availability and quality of the underlying published evidence and cannot rule out a publication bias toward studies reporting positive RTPI effects. Finally, the review was limited to bus-specific RTPI studies and to four predefined outcome categories; extending the synthesis to other modes, to actual/system-level waiting time, or to additional outcomes may reveal additional or diverging patterns. Future work with full database access should conduct a genuinely systematic search and apply a formal quality-appraisal tool to the identified studies.

6 CONCLUSION

This narrative literature review synthesised evidence from eight empirical studies on the effects of Real-Time Passenger Information systems on the perceived quality of bus transport services, using a Synthesis Without Meta-analysis approach appropriate to the observed heterogeneity of study designs and outcome metrics. The evidence indicates generally positive associations with perceived or self-reported waiting time and passenger satisfaction, and RTPI use is associated with higher ridership and other behavioural indicators, while evidence on reliability perception and trust-related outcomes is positive but rests on only three studies, of which only one directly measured trust; none of the eight primary studies directly measured actual or system-level waiting time. These results support RTPI as a valuable, comparatively low-cost measure for improving perceived bus service quality, provided that it is deployed together with adequate investment in the accuracy and reliability of the underlying operational data, and interpreted in light of the methodological limitations noted above. For transport planners, the practical implication is that RTPI should not be regarded as a stand-alone quality-improvement measure, but as one component of a broader strategy aimed at increasing the predictability and trustworthiness of bus transport services.

Use of AI tools: AI-assisted tools were used to support the literature search and language refinement of this manuscript. All scientific content, analysis, interpretation, and conclusions were developed and verified by the author(s), who remain fully responsible for the content.

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V. Smart Mobility, Rail and Evidence-Based Transport Planning

Integrated Transport and Mobility Analysis to Improve Marina Planning: The Case of Sestri Levante (Italy)

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ABSTRACT

Marinas must accommodate recreational-boating demand while ensuring the compatible integration of transport infrastructure, coastal space and local communities. This paper assesses two redevelopment scenarios for the harbour and Baia delle Favole in Sestri Levante (eastern Liguria, north-western Italy), originally proposed in a 2025 technical study. Scenario A involves rationalising and reorganising the existing harbour–bay system, whereas Scenario B entails developing a structured tourist marina. The study first characterises the two scenarios. Baseline conditions are then diagnosed through three analytical dimensions: land-side accessibility and effective boating catchment, potential berth-supply pressure, and recreational-boating activity and spatial concentration. The analysis finally compares how the scenarios respond to the identified constraints. Results show that Sestri Levante is strategically located relative to major Northern Italian boating-origin markets. Scenario A increases formal recreational berths from approximately 150 to 300 and adds 23 dedicated fishing moorings and a separate regulated 40-mooring buoy field; its reported annual economic effect exceeds €5.4 million. Scenario B provides 334 formal recreational berths, accommodates vessels up to 32 m and has a reported annual economic effect exceeding €7.3 million. The two scenarios respond differently to the identified constraints: Scenario A places greater emphasis on functional reorganisation and anchorage management, whereas Scenario B provides greater formal recreational-berth capacity, accommodates larger vessels and is associated with higher reported economic effects. Overall, the analysis shows that the two alternatives respond differently to the constraints identified in the baseline diagnosis and represent different planning priorities.

Keywords: sustainable marina planning; transport accessibility; port infrastructure; spatial analysis

University North

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1 INTRODUCTION

Recreational marinas are transport infrastructures, tourism-service facilities and interfaces between coastal waters, urban areas and local economies. In addition to berthing, they may provide technical assistance, surveillance, launching and hauling facilities, fuel and waste services and connections with local tourism and commercial activities. According to their infrastructure and service configuration, they may operate as home ports, transit ports or destination marinas [1]. Marina planning cannot therefore be reduced to the total number of available berths as infrastructure suitability also depends on berth dimensions, vessel characteristics, service provision, land-side accessibility, spatial patterns of boating activity and compatibility with fishing, bathing and other coastal uses. Marina development may support local economic activity, but its territorial effects depend on its integration with the surrounding destination and its environmental and social compatibility [2, 3]. These issues are evident in Sestri Levante, a tourism destination in eastern Liguria, Italy (**Figure 1a**). The town has a small mixed-use harbour with approximately 150 recreational berths, mainly for smaller craft, together with spaces used by fishing and other professional maritime activities. The harbour accommodates vessels up to approximately 20 m and provides fewer specialised services than several neighbouring marinas. Its spatial organisation does not fully optimise the coexistence of fishing and recreational boating. In addition, Baia delle Favole, the broad bay directly adjoining the harbour and the urban waterfront (**Figure 1a**), functions as a sheltered seasonal anchorage area for recreational vessels but currently lacks a structured mooring system [4].

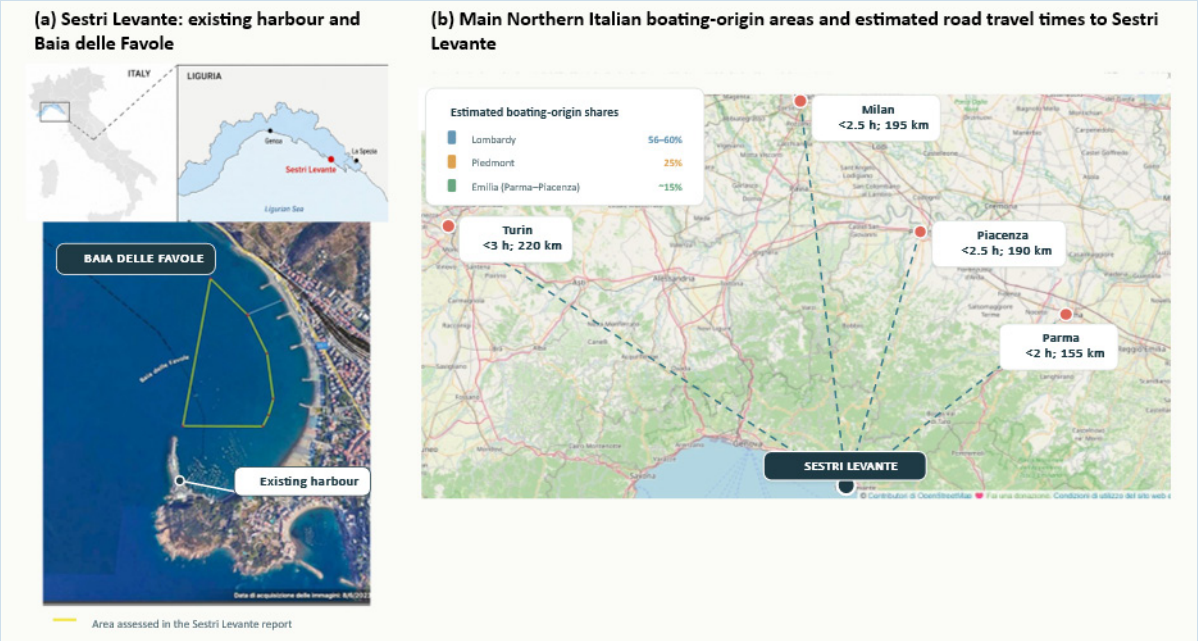


Figure 1. Location and territorial context of Sestri Levante: (b) main recreational-boating origin areas in Northern Italy and estimated road travel times to Sestri Levante; (a) the existing harbour and Baia delle Favole.
Source: Authors' elaboration based on [4], with regional boundaries adapted from OpenStreetMap.

Sestri Levante therefore presents a mismatch between its favourable territorial position and the capacity, service configuration and spatial organisation of its port system. It is accessible from important boating-origin markets in Lombardy, Piedmont and Emilia-Romagna. However, its ability to serve this wider potential market is constrained by berth availability, vessel-size provision and competition from more specialised facilities. A 2025 technical study developed within the Italian National Nautical Observatory, in collaboration with the Municipality of Sestri Levante and Confindustria Nautica, proposed

two redevelopment alternatives: an incremental rationalisation of the existing harbour and Baia delle Favole and a more intensive transformation towards a structured tourist marina. The aim of this paper is to diagnose the baseline conditions of the Sestri Levante harbour–bay system through three analytical dimensions, land-side accessibility and effective boating catchment, potential berth-supply pressure, and observed recreational-boating activity and spatial concentration, and to compare how the two redevelopment scenarios proposed in the 2025 technical study [4] respond to the identified constraints.

2 BACKGROUND

In 2024, Italy recorded approximately 162,700 recreational berths and 79,724 registered craft. Liguria accounted for 25,093 berths, equivalent to 15.4% of national supply, and 16,731 registered craft, corresponding to 21.0% of the national registered fleet. The region also recorded 64.5 berths per kilometre of coastline, compared with a national average of 21.2, reflecting its high concentration of recreational-boating infrastructure and activity [5]. Aggregate figures may nevertheless conceal differences between berth provision and fleet composition. The same statistics [5] indicate comparatively greater pressure in the 10–24 m vessel segment, showing that berth availability should be assessed in relation to the vessel sizes that infrastructure can accommodate. Demand is also not confined to the resident population of coastal regions. Recreational-boating facilities may attract users from inland territories and neighbouring regions, particularly where destinations can be reached within a few hours by road. Nautical-tourism planning should therefore consider registered craft, seasonal flows, territorial influence areas and transport accessibility rather than relying exclusively on administrative population [6,7]. Sestri Levante lies between the established tourist-port network of the Tigullio area and the larger boating infrastructure of the Gulf of La Spezia (**Figure 1b**). Its location gives it potential relevance for local, regional and transit demand, but also places it in competition with larger and more specialised recreational-boating facilities in nearby Ligurian coastal towns. The current harbour remains a predominantly local mixed-use facility. Its limited capacity and services are combined with an inefficient allocation of space among recreational boating, fishing and other maritime activities. The technical study identifies 21 registered fishing vessels, together with small-scale fishing, charter activities and recreational craft using the same constrained port basin. Baia delle Favole is located immediately beside the harbour and urban waterfront (**Figure 1a**). Its sheltered position makes it attractive for recreational boating during the summer, but vessels currently use the bay mainly through free or informal anchoring. The harbour and bay must therefore be treated as a single planning system characterised by limited formal capacity, weak separation among port functions, and seasonal recreational-boating activity and spatial concentration outside the harbour. In this study, sustainability is understood as the efficient and compatible use of harbour and coastal space, considering recreational capacity, fishing, anchorage management, public use and potential socio-economic effects. The analysis does not constitute an Environmental Impact Assessment, Strategic Environmental Assessment or engineering-feasibility study.

3 METHODOLOGY

This applied case study integrates official Italian recreational-boating statistics for 2024 with evidence from the 2025 technical study [4]. The latter provides accessibility estimates, data on boater origins, satellite-derived observations, scenario specifications and socio-economic estimates. The methodological sequence comprises three steps. First, the two redevelopment scenarios originally defined in the 2025 technical study are characterised. Second, the baseline conditions of the existing harbour and Baia delle Favole are diagnosed through three analytical dimensions: (i) land-side accessibility and effective boating catchment; (ii) potential berth-supply pressure; and (iii) observed recreational-

boating activity and spatial concentration. Third, the scenarios are compared according to their capacity to address the constraints identified in the baseline diagnosis. The analytical dimensions are used primarily to characterise the baseline, while the scenario comparison examines how each alternative responds to the identified constraints.

3.1 Scenario definition

The two redevelopment alternatives were originally defined in the 2025 technical study [4]. Scenario A represents an incremental rationalisation of the existing harbour–bay system, providing approximately 300 formal recreational berths, plus 23 dedicated fishing moorings and a separate regulated 40-mooring buoy field in Baia delle Favole. Scenario B represents a more intensive transition towards a structured tourist marina, providing 334 formal recreational berths and accommodating vessels up to 32 m. The technical study does not clearly specify whether the separate buoy field would also be implemented under Scenario B.

3.2 Analytical dimensions for baseline diagnosis

3.2.1 Land-side accessibility and effective boating catchment

Land-side accessibility was assessed from Milan, Turin, Parma and Piacenza, which represent the principal Northern Italian boating-origin markets identified in the technical study. The indicators shown in **Figure 1b** are road distance and estimated travel time to Sestri Levante. Potential accessibility was combined with the reported geographical origin of recreational boaters to define an effective boating catchment. The catchment estimate used in this paper was taken directly from the 2025 technical study [4], which combines reported boating-flow shares with regional population data. The underlying microdata and complete weighting procedure are not reproduced here. The figure is therefore treated as an estimate of the potential territorial market rather than as a direct measurement of demand. Physical proximity alone does not generate demand, which also depends on berth availability, services, destination characteristics and competition from alternative marinas [8, 9, 10].

3.2.2 Potential berth-supply pressure

The second dimension examines recreational-berth availability in relation to the effective boating catchment. Rather than using only the resident population of Liguria, the indicator includes the wider territorial market from which recreational boaters are reported to originate.

The potential berth-supply pressure indicator is calculated as:

$$BP_r = \frac{EC_r}{B_r} \tag{1}$$

where BP_r is the potential berth-supply pressure for coastal system r, EC_r is the estimated population within the effective boating catchment, and B_r is the number of recreational berths. Berth totals are taken from official 2024 statistics. Higher values indicate lower relative berth availability. The indicator is comparative and does not represent actual occupancy, waiting lists or individual-marina demand. For Liguria, EC_r corresponds to the estimated population of the effective boating catchment reported in the technical study. The national resident-population-to-berth ratio is used only as a contextual benchmark and is not strictly equivalent, as it is based on total resident population rather than on an effective boating catchment.

3.2.3 Observed recreational-boating activity and spatial concentration

Recreational-boating activity and spatial concentration in Baia delle Favole were assessed using aggregated satellite-derived observations reported for June–September 2025. The measures include the number of detected vessels, approximate size classes, monthly and weekday–weekend variation, and occupied water surface area. The paper does not independently process or validate the satellite imagery. The results are therefore interpreted as evidence of vessel presence and spatial concentration rather than as a reconstruction of movements or trajectories. Satellite-derived evidence complements formal berth and registration statistics because small recreational craft may be incompletely represented in Automatic Identification System (AIS) data [11, 12].

3.3 Scenario comparison criteria

The scenarios are compared according to their capacity to address the constraints identified in the baseline diagnosis. The comparison considers formal recreational-berth provision, maximum vessel size accommodated, fishing organisation, anchorage management, service configuration and reported socio-economic outcomes. The economic values are taken directly from the technical study and are not independently reconstructed through a cost-benefit or economic-impact model. The reported economic effects are derived within the same technical assessment and are therefore used for indicative comparison; however, they are not strictly like-for-like because the two scenarios incorporate different scenario-specific assumptions, including tariff adjustments and operating conditions. The comparison is therefore response-based rather than a complete quantitative projection of the three baseline dimensions under each scenario.

4 RESULTS

4.1 Baseline diagnosis

4.1.1 Land-side accessibility and effective boating catchment

Sestri Levante can be reached within approximately two to three hours from the principal boating-origin markets. Estimated travel times are below 2.5 hours from Milan, below 3 hours from Turin, below 2 hours from Parma and below 2.5 hours from Piacenza. According to the technical study, 56–60% of boaters originate from Lombardy, 25% from Piedmont and around 15% from Emilia-Romagna, particularly the Parma–Piacenza area. The technical study reports an effective boating catchment of approximately 11.0 million inhabitants.

4.1.2 Potential berth-supply pressure

In 2024, Liguria provided 25,093 recreational berths. Using the catchment estimate reported in the technical study, this corresponds to approximately 437 inhabitants within the estimated effective catchment per recreational berth. For contextual comparison, the national resident-population-to-berth ratio is approximately 362. Because the two ratios use different population bases, this comparison should be interpreted as indicative rather than strictly equivalent.

4.1.3 Observed recreational-boating activity and spatial concentration

Satellite-derived observations for June–September 2025 show that vessels below 18 m accounted for approximately 86% of the units detected in Baia delle Favole. Peak observations in August reached approximately 140 vessels and an occupied water surface area of approximately 200,000 m^2. These

observations indicate substantial seasonal recreational-boating activity and spatial concentration outside the formal harbour.

4.2 Scenario comparison

Table 1 summarises the baseline conditions and compares the main specifications and reported outcomes of the two redevelopment scenarios.

Table 1. Baseline conditions, scenario specifications and reported outcomes

Indicator	Baseline, 2025	Scenario A	Scenario B
Development model	Mixed-use harbour	Incremental harbour–bay rationalisation	Structured tourist marina
Formal recreational berths	≈150	≈300	334
Change in formal recreational berths from baseline	—	≈+150	≈+184
Maximum vessel size in formal berthing facilities	Up to ≈20 m	Not separately specified	Up to 32 m
Separate regulated buoy field	None	40 moorings for vessels of 10–25 m, with nearshore provision for smaller craft	Not clearly specified
Fishing organisation	Spatially unbalanced	23 dedicated fishing moorings, additional to the recreational berths	Unchanged and separately allocated
Service configuration	Limited	Improved organisation	More specialised services
Reported annual economic effect	Not estimated	>€5.4 million	>€7.3 million
Reported port-management revenues	Not estimated	Not separately reported	€1,832,204
Reported employment effect	Not estimated	Not separately reported	≈21.5 FTEs

Source: Authors' comparison based on [4]. Changes from the baseline are authors' calculations. The fishing moorings and buoy-field moorings in Scenario A are additional to the approximately 300 formal recreational berths. FTE: full-time equivalent. The reported economic effects should be interpreted as indicative rather than strictly like-for-like comparisons.

Scenario A approximately doubles formal recreational berths while reorganising harbour uses, providing dedicated fishing moorings and introducing a regulated buoy field. Scenario B provides 34 more formal recreational berths, accommodates larger vessels and is associated with higher reported annual economic and employment effects.

5 DISCUSSION

The findings show that the Sestri Levante planning problem cannot be interpreted solely as a numerical shortage of berths. Taken together, the three analytical dimensions reveal three main planning constraints. The first concerns infrastructure, including berth capacity, vessel dimensions

and service provision. The second concerns the coexistence of fishing and recreational boating within the harbour. The third concerns the spatial management of seasonal recreational activity outside regulated port facilities. Accessibility evidence and data on boater origins indicate a broad potential market extending beyond Liguria. However, land-side accessibility and the effective boating catchment represent contextual conditions that are common to both redevelopment scenarios rather than scenario-specific outcomes. Favourable road connections are an enabling but not sufficient condition for marina development, as their effects depend on berth availability, the range of vessel sizes accommodated, services, destination characteristics and competition from neighbouring facilities [8, 10]. The use of an effective boating catchment therefore provides a broader interpretation of potential berth-supply pressure than one based exclusively on the resident population, although it should not be interpreted as a direct forecast of demand, occupancy or future boating flows. Consistent with recent Earth-observation studies [11, 12], satellite-derived observations provide complementary evidence on the spatial expression of current recreational-boating activity. The concentration recorded in Baia delle Favole indicates that formal berth and registration statistics do not fully represent seasonal use of the harbour–bay system. The three baseline dimensions are therefore not equally scenario-dependent: accessibility and the effective boating catchment remain common to both alternatives, whereas formal berth provision, anchorage management and the functional organisation of harbour and bay activities vary between scenarios. Scenario A responds directly to the infrastructure, functional and spatial-management constraints identified in the baseline diagnosis. It approximately doubles the number of formal recreational berths, provides 23 dedicated fishing moorings in addition to the recreational berths, and introduces a separate regulated 40-mooring buoy field in Baia delle Favole. The scenario therefore combines increased formal recreational-berth provision with the reorganisation of harbour functions and a direct response to the seasonal concentration of recreational vessels outside the harbour. Its incremental character may enable more efficient use of the existing harbour–bay system and improve the separation between fishing and recreational activities. Nevertheless, implementation would require appropriate buoy-field design, seabed and habitat assessment, monitoring arrangements and clearly defined management responsibilities. Scenario B provides 34 more formal recreational berths than Scenario A, accommodates larger vessels and offers more specialised marina services. However, the total recreational capacity of the harbour–bay system cannot be directly compared because the 40-mooring buoy field in Baia delle Favole is separate from the marina development and its treatment under Scenario B is not clearly specified in the technical study. Scenario B may strengthen Sestri Levante's role as a transit and destination marina and is associated with a higher reported annual economic effect. However, this more intensive transformation would require more comprehensive engineering, environmental, financial and administrative assessments. It would also require effective integration between the marina, local businesses and public waterfront spaces. The two alternatives therefore represent different planning models. Scenario A combines increased formal recreational-berth provision with adaptive reuse, functional separation and anchorage management, whereas Scenario B prioritises a more intensive marina configuration, accommodation for larger vessels, specialised services and economic expansion. The comparison is intended to clarify these trade-offs rather than identify an automatically preferred scenario.

The study has five main limitations: some demand, boater-origin and economic data are unavailable at microdata level; satellite observations cover only June–September 2025 and were not independently validated; economic values come from the technical study rather than an independent cost–benefit analysis; engineering, environmental and financial feasibility are not assessed; and future demand, occupancy and spatial-use patterns are not modelled, while the treatment of the buoy field under Scenario B remains unclear. The findings should therefore be interpreted as preliminary decision support. Future research should combine multi-year satellite, field, AIS and administrative data with scenario-specific feasibility assessments and stakeholder consultation.

6 CONCLUSION

The Sestri Levante case shows that marina redevelopment cannot be assessed through berth numbers alone. Accessibility evidence and the estimated effective boating catchment indicate a broad potential market extending beyond Liguria, while satellite-derived observations reveal substantial seasonal recreational-boating activity and spatial concentration outside the formal harbour. Scenario A responds to infrastructure, functional and spatial-management constraints by increasing formal recreational-berth provision, allocating dedicated fishing moorings and introducing a separate regulated buoy field. Scenario B provides 34 more formal recreational berths, accommodates larger vessels and is associated with a higher reported annual economic effect. However, the total recreational capacity of the harbour–bay system cannot be directly compared because the treatment of the buoy field under Scenario B is not clearly specified. The two alternatives therefore respond differently to the constraints identified in the baseline diagnosis and represent different planning priorities. The analytical approach provides a structured basis for preliminary decision support, but detailed environmental, engineering and financial assessments, together with stakeholder consultation, are required before implementation.

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VI. Urban Mobility, Road Safety and Transport Behaviour

Analysis of Cycling Infrastructure and Road Accidents Involving Cyclists in the European Union

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ABSTRACT

Cyclists remain among the most vulnerable road users. Unlike occupants of cars, vans and lorries, cyclists have little physical protection. As a result, collisions involving cyclists are more likely to lead to serious injury or death. In the EU, cyclists represent 10% of all road user deaths. In 2024, 1,926 cyclists were killed on EU roads, and a further 22,153 cyclists were killed between 2014 and 2024. The increasing use of electric bicycles is influencing casualty trends. In countries that distinguish between bicycle types, deaths among electric bicycle users have increased while deaths among conventional bicycle users have generally decreased. The growing popularity of electric bicycles, particularly among older riders, may partly explain this trend. Although there is no official source that provides information about the cycling infrastructure, European Union research has identified more than 900,000 km of cycle paths and lanes at EU level. Of that, a little over 300,000 km belongs to the dedicated cycle network (cycle tracks + cycle lanes), and the rest is cycle-friendly mixed traffic roads. The results highlight strong national differences in coverage, quality, classification systems, definitions, and completeness. Using cycling infrastructure tracker ECF quantifies the different types of cycling infrastructure across the European countries and compare the lengths of relevant public road networks to estimate the level of completeness of the cycle network. Using the data, this paper will compare the development of cycling infrastructure with the number of traffic accidents, especially in countries with a pronounced separate cycling infrastructure.

Keywords: cycling safety; cycling infrastructure; cyclist accidents

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1 INTRODUCTION

Sustainable development of the transport system is increasingly based on encouraging alternative forms of transport that can reduce dependence on motor vehicles, traffic congestion, harmful gas emissions and the negative effects of traffic on the quality of urban life. In this context, the bicycle represents one of the most important forms of sustainable urban mobility, especially for short and medium-distance journeys. Increasing the share of bicycle traffic is therefore becoming an important goal of the transport and urban policy of many European and world cities. However, the increase in the number of cyclists at the same time raises the question of their safety, especially in conditions of intensive interaction with motor vehicles and other road users.

Cycling infrastructure is one of the key elements of the transport system that can simultaneously affect the attractiveness of cycling and the level of cyclist safety. The construction of cycle paths, lanes, separate cycle corridors, safe intersections and other infrastructure elements can increase the accessibility and continuity of the cycle network and encourage citizens to use bicycles more often. At the same time, a well-designed and interconnected infrastructure can reduce the number of conflict situations between cyclists and motor vehicles. However, the relationship between the development of cycling infrastructure, the intensity of cycling traffic and traffic safety is not unambiguous and depends on several traffic, spatial and social factors.

Previous research has mainly developed in several interconnected directions. The first refers to the influence of cycling infrastructure on the risk of traffic accidents and injuries, the second to the connection between the number of cyclists and their safety, while the third focuses on the problem of properly defining risk exposure, that is, the relationship between the number of accidents and the actual intensity of cycling traffic.

This paper will compare the development of cycling infrastructure with the number of traffic accidents, especially in countries with a pronounced separate cycling infrastructure.

2 BACKGROUND

In one of the earlier significant systematic reviews 23 papers that addressed the impact of traffic infrastructure on cyclist injuries and accidents was analysed. The authors distinguished between infrastructure at intersections and infrastructure on sections between intersections and concluded that the type of infrastructure significantly affects the risk of accidents and injuries. The importance of purpose-designed bicycle infrastructure was particularly emphasised, with bicycle paths and lanes generally associated with lower risk compared to cyclists riding in mixed traffic. At the same time, the authors warned about an important methodological problem – difficulties in controlling for risk exposure, namely the fact that the number of accidents should be observed in relation to the number of cyclists and the routes or distances travelled [1, 2].

Another important area of research is the relationship between the number of cyclists and road safety. This area has popularised the concept of Safety in Numbers, which analyses the relationship between the number of pedestrians and cyclists and the frequency of their collisions with motor vehicles. The analysed data showed a nonlinear relationship according to which an increase in the number of cyclists is not accompanied by a proportional increase in the number of collisions. In other words, an increase in the number of cyclists can reduce the estimated risk for an individual cyclist [3].

That said, that the relationship between cycling infrastructure and safety cannot be observed independently of the intensity of cycling traffic. The introduction of new cycling infrastructure can increase the number of cyclists, while a larger number of cyclists can simultaneously affect the level of safety. This creates a kind of interrelationship between the three observed elements: infrastructure can affect

the number of cyclists, the number of cyclists affects their exposure to traffic, and infrastructure and traffic intensity together can affect the number of traffic accidents.

3 METHODOLOGY

Despite significant progress in bicycle safety research, there is still a need for integrated analyses that simultaneously link the level of development of bicycle infrastructure, the intensity of bicycle traffic and the number of road accidents.

Therefore, there is a need for empirical research that will examine these relationships in an integrated manner. In this context, the aim of this research is to analyse the correlation between the development of cycling infrastructure, the number of cyclists and traffic accidents involving cyclists in the observed area. Special attention is paid to determining the direction and intensity of the connection between the above variables and to examining whether the number of traffic accidents changes proportionally with the increase in the number of cyclists and the development of cycling infrastructure.

Based on previous research, it is assumed that an increase in the development of cycling infrastructure may be associated with an increase in the number of cyclists, but at the same time with a change in the level of traffic safety. However, it is expected that the relationship between the absolute number of cyclists and the number of accidents will not necessarily be linear and that accident indicators normalised by the number of cyclists will provide a more relevant assessment of the actual risk. Such an approach allows distinguishing the effect of increased exposure from the actual change in safety conditions and represents the basis for a better evaluation of transport policy and planning development of cycling infrastructure.

The research aims to contribute to the understanding of the complex relationship between investment in cycling infrastructure, increased bicycle use and road safety. The results obtained may be relevant for transport planners, local and national governments and other stakeholders involved in sustainable urban mobility planning, especially when making decisions on priorities for the development of the cycling network and measures aimed at reducing risks for cyclists.

It must be noted that bicycle crashes, and single bicycle crashes in particular, are severely underreported, which leads to a substantial underestimation of the crash risk for cyclists. If, for example, a cyclist hits a fixed object or falls, the event is rarely reported to the police and therefore also not included in the official crash statistics. Research and comparison of police databases and medical databases confirms this thesis, and it is possible to conclude that the average reporting rate of injured cyclists in police collision databases in Europe is around 10% [4].

Data sought in various literature for this research are: cyclist fatalities per million inhabitants, cyclist fatalities per 100 million km cycled and dedicated cycle network per 1000 km2 land area per country (km) and dedicated cycle network per million inhabitants (km), were collected from various literature and relate to the EU 27 countries.

In the reports used to configure **Figures 1** and **2**, it was concluded that that most cyclist fatalities occurred on urban roads (57% for cyclists compared with 40% for all road fatalities). Compared with total road fatalities, the proportion of cyclist fatalities was lower on road stretches (67% versus 80%), and considerably higher at junctions (16% versus 9%). Also the number of fatalities in cyclist crashes remain constant, in contrast to the number of fatalities in crashes with other modes of transport which have mostly decreased in last ten years [6, 7]. At the EU- 27 level, there are significant differences in coverage, quality, classification systems, definitions, and completeness of cycling infrastructure, so OpenStreetMap (OSM) was used to create a comparable EU overview of the network accessible to cyclists and form the baseline for future monitoring. It is divided into dedicated cycle network and cycle-friendly mixed traffic roads as shown in **Table 2** [9].

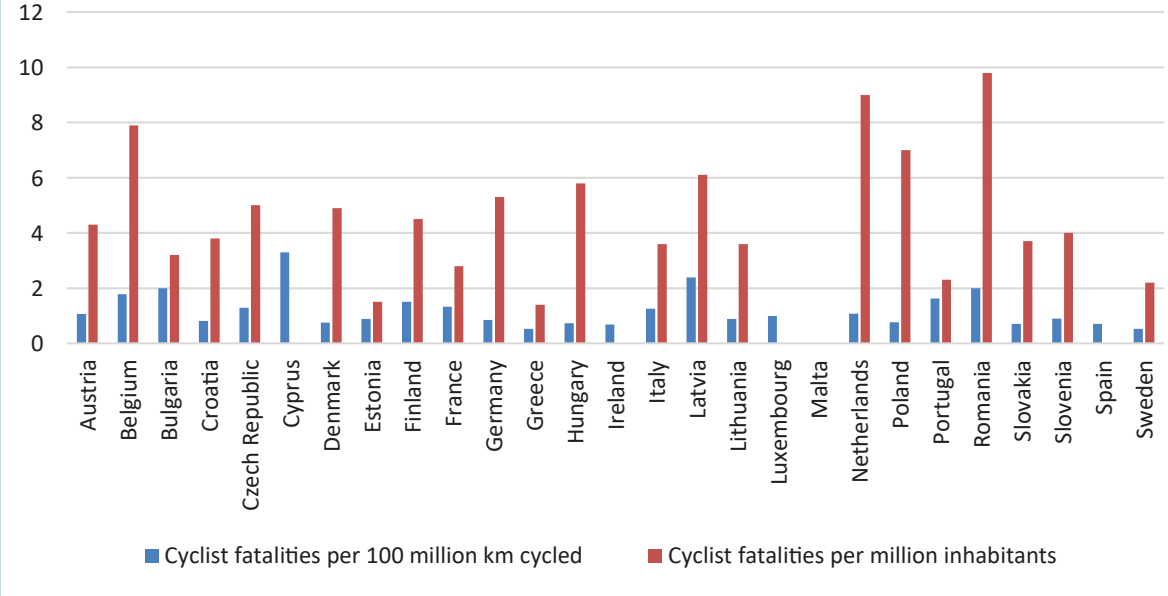


Figure 1. Cyclist fatalities per million inhabitants and per 100 million km cycled per country [5, 6]

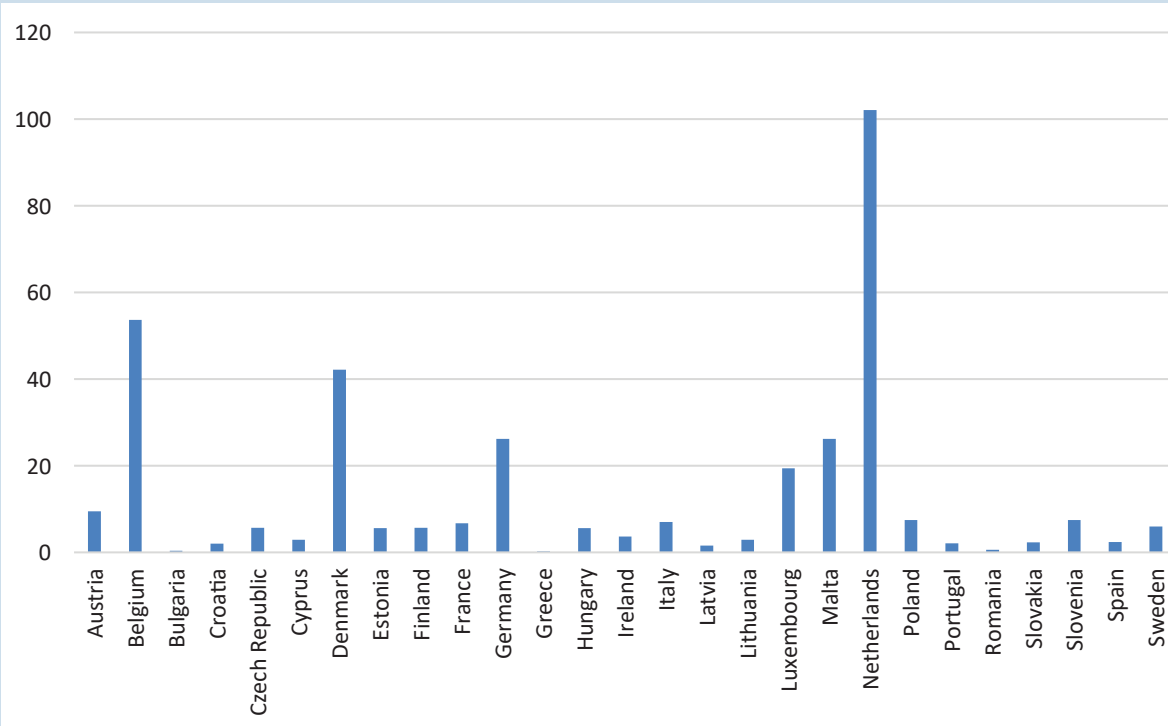


Figure 2. Dedicated cycle network per 100 km2 (km) per country [7]

Table 1. Categories of cycling infrastructure and their variations

Categories	Variations		
Cycle track	Cycle and pedestrian track	Dedicated cycle network	Extended cycle network
	Greenway		
Cycle lane	Bus-and-cycle lane		
	Advisory cycle lane		
Cycle friendly mixed traffic road	Cycle street		
	Residential area		
	Specific service road		
	30 km/h road		
	Low Traffic Road		

Source: [9]

Table 2. EU cycle network

Category	Length (km)
Cycle tracks	312,115
Cycle lanes	30,816
Dedicated cycle network	342,931
Cycle-friendly mixed traffic roads	631,389
Total extended cycle network	974,320

Source: [9]

4 RESULTS

The most complete and comparable data for all EU 27 countries were available for cyclist fatalities per 100 million km cycled and dedicated cycle network per 1000 km² land area per country (km). Based on this data, a two-dimensional assessment of cycling safety was created.

All 27 countries are ranked according to:

1. cyclist fatalities / 100 million cycle km travelled – lower value = higher safety;
2. dedicated cycle network / 1,000 km² – higher value = higher infrastructure development.

Analysing each parameter separately, the safest countries would be: Malta, Sweden, Greece and Ireland while Bulgaria, Romania, Latvia and Cyprus would be the most unsafe. On the other hand, the most developed countries in terms of bicycle network density are the Netherlands, Belgium and Denmark, which is expected, and the least developed are Bulgaria and Romania. By combining those two indicators and using a simple 50:50 index, the results are shown in **Figure 3**, and the Netherlands, Denmark and Belgium stand out as the safest countries.

Table 3. Data required for analysis based on EU 27 countries

Country	Cyclist fatalities per 100 million km cycled [6]	Dedicated cycle network per 100 km² (km) [7][1]
Austria	1.06	9.5
Belgium	1.78	53.7
Bulgaria	1.96	0.4
Croatia	0.81	2.0
Czech Republic	1.29	5.7
Cyprus	3.30	2.9
Denmark	0.66	42.2
Estonia	0.88	5.6
Finland	0.90	5.7
France	1.33	6.7
Germany	0.85	26.2
Greece	0.53	0.2
Hungary	0.73	5.6
Ireland	0.68	3.7
Italy	1.25	7.0
Latvia	2.39	1.6
Lithuania	0.88	2.9
Luxembourg	0.99	19.4
Malta	**0.00**	**26.2**
Netherlands	**1.13**	**102.1**
Poland	0.76	7.5
Portugal	1.62	2.1
Romania	1.99	0.6
Slovakia	0.71	2.3
Slovenia	0.90	7.5
Spain	0.71	2.4
Sweden	0.52	6.0

Source: Made by authors

[1] For each EU country, a separate publication was published from which this information was taken, and all publications were placed under a common number [7].

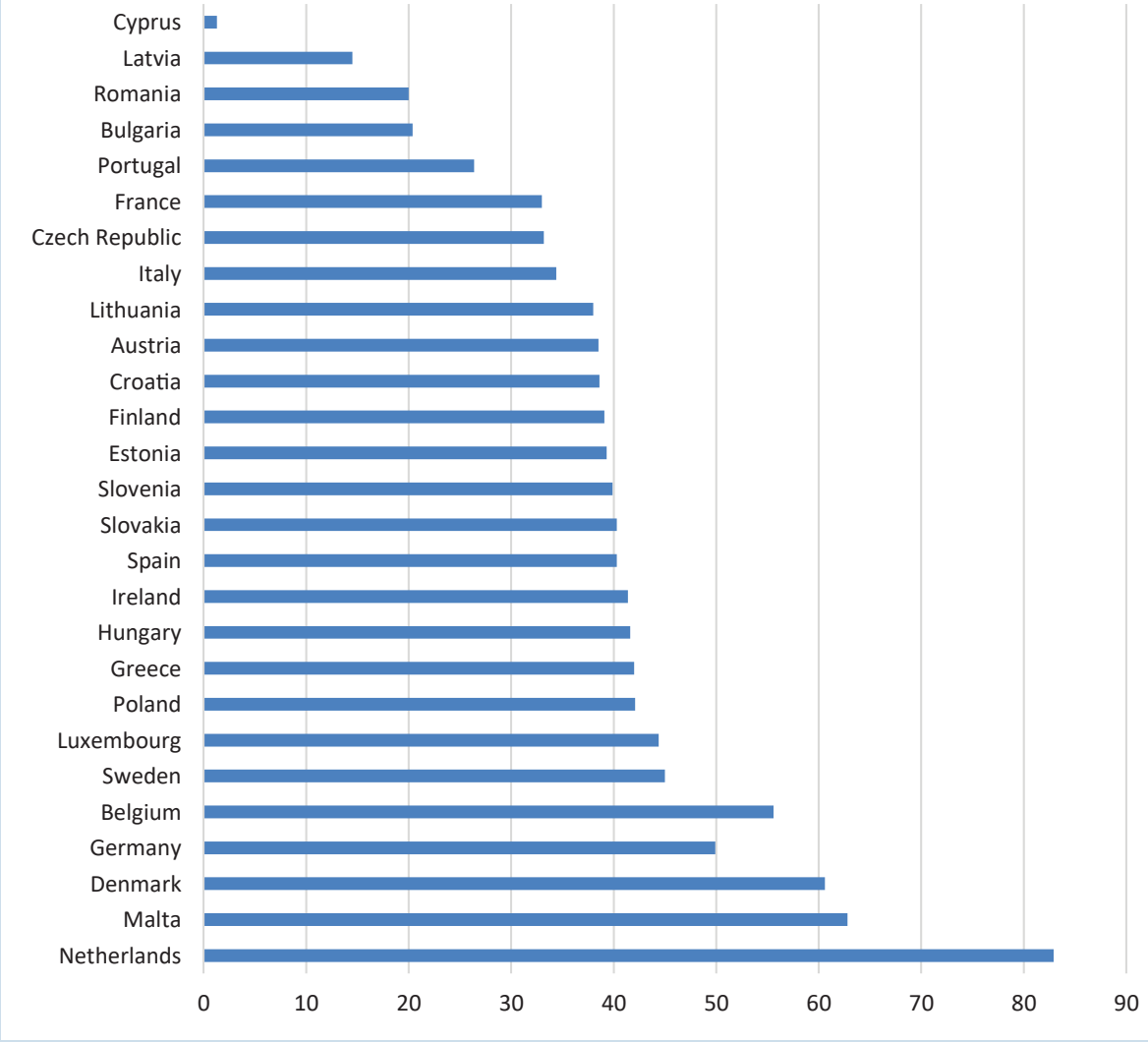


Figure 3. Simple 50:50 index

5 CONCLUSION

Although a more comprehensive and relevant analysis could have been conducted using cyclist fatalities per million inhabitants and the length of dedicated cycling networks per million inhabitants, comparable data for these indicators were not available for all EU-27 countries. Therefore, a simple index was constructed by assigning equal weights (50:50) to two alternative indicators: cyclist fatalities per 100 million kilometres cycled and the length of dedicated cycling networks per 100 km² of land area. Therefore the results should be described as **"countries with the most favourable combination of cyclist fatality rate and cycling-network density"**, rather than simply calling them "the safest countries".

Countries with more developed cycling infrastructure do not necessarily have the lowest rate of cyclist fatalities per kilometre travelled, but the combination of relatively low risk and high density of dedicated infrastructure gives an advantage to countries like the Netherlands and Denmark [10, 11].

The Dutch case shows that the number of cyclist fatalities per capita is not sufficient to assess the safety of cycling. Despite a very high level of cycling infrastructure, the Netherlands has a relatively

high number of cyclist fatalities per million inhabitants, while the risk expressed per cycle kilometre travelled is significantly more favourable. This highlights the importance of including actual exposure to cycling in the safety assessment.

At the same time, it is not possible to conclude that higher infrastructure density directly causes higher safety. This does not mean that cycling infrastructure does not increase safety. It means that its effect cannot be proven only by correlating these two aggregated variables at the country level. The quality of infrastructure, segregation from motor traffic, vehicle speeds, intersections, the share of cyclists in traffic, urban structure and modal share are probably very important additional factors. However, this is still relevant enough to make it possible to draw conclusions about the impact of infrastructure on cycling safety.

On the other hand, on a global scale, and despite having lower infrastructure density and traffic calming metrics than the Global Top 30, Asian cities maintain a better safety rate, proving that sheer volume and cultural integration can create “safety in numbers” [12].

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VI. Urban Mobility, Road Safety and Transport Behaviour

Mobile Eye Tracking as a Tool for Behaviour Analysis of Vulnerable Road Users

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ABSTRACT

Mobile eye-tracking glasses enable researchers to analyse where road users look and how they respond to different traffic situations. This technology is especially useful for studying vulnerable road users, such as pedestrians, cyclists, and users of e-scooters, because their behaviour is strongly influenced by the surrounding traffic environment. This paper presents a structured literature review of mobile eye-tracking applications among vulnerable road users. The focus is on pedestrian crossing behaviour, cyclist visual attention, interaction with transport infrastructure, and the emerging use of eye tracking in micromobility research. The review shows that mobile eye tracking can provide valuable insights into visual attention, hazard perception, and decision-making in urban traffic environments. However, existing research is still unevenly distributed. Pedestrians and cyclists have been studied more frequently, while e-scooter and other micromobility users remain less explored. The paper identifies key research gaps, including the need for more real-world studies, more consistent use of eye-tracking metrics, and more comparative research across different vulnerable road user groups. The findings suggest that mobile eye tracking can support safer infrastructure design, better road safety measures, and the development of more sustainable urban mobility systems.

Keywords: eye-tracking glasses; vulnerable road users; visual attention; sustainable urban mobility

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1 INTRODUCTION

Vulnerable road users, including pedestrians, cyclists and micromobility users, are an important group in contemporary transport safety and sustainable urban mobility research. Unlike occupants of motor vehicles, they are directly exposed to traffic environments and have limited physical protection. At the same time, walking, cycling and micromobility contribute to more sustainable urban transport by reducing congestion, environmental impacts and dependence on motorised transport. However, the increasing use of personal mobility devices, particularly e-scooters, has introduced new safety challenges related to speed, infrastructure sharing and interaction with other road users [3, 15, 16].

Understanding the behaviour of vulnerable road users requires insight into how they perceive and interpret traffic situations. Visual attention plays a central role in this process, as road users rely on visual information to detect hazards, assess traffic conditions and make movement decisions. Eye-tracking technology enables researchers to analyse gaze behaviour and provides objective indicators of visual attention, information processing and decision-making [2, 7]. In transport research, such methods have been used to study how road users observe traffic infrastructure, identify potential hazards and allocate attention in complex environments [8].

Mobile eye-tracking glasses are particularly suitable for studying vulnerable road users because they allow gaze data to be collected in real-world and semi-controlled environments. Unlike stationary systems, wearable devices enable participants to move naturally while walking, cycling or using micromobility devices. Previous studies have applied eye-tracking methods to pedestrian crossing behaviour, signalised intersections, cyclist visual behaviour, infrastructure interaction and emerging micromobility contexts [4, 5, 9–18]. Research has also started to examine interactions between pedestrians and automated vehicles, where eye tracking can help analyse how vulnerable road users perceive external communication cues [6].

Although mobile eye tracking has strong potential for analysing vulnerable road user behaviour, the existing literature remains unevenly distributed. Pedestrians and cyclists have been studied more frequently, while e-scooter and other micromobility users are still less represented. In addition, previous studies differ in research environments, eye-tracking metrics and methodological approaches, which makes comparison between findings more difficult.

The aim of this paper is to provide a structured literature review of mobile eye-tracking applications in the analysis of visual attention and behaviour of vulnerable road users. The review focuses on pedestrians, cyclists and micromobility users, with particular attention to road-crossing behaviour, infrastructure interaction, hazard perception and emerging research on e-scooter use. By identifying current trends, methodological characteristics and research gaps, the paper contributes to a better understanding of how mobile eye tracking can support road safety research and sustainable urban mobility planning.

2 LITERATURE REVIEW

2.1 Mobile eye tracking in traffic behaviour research

Eye-tracking technology is used to investigate visual attention, perception and information processing by analysing where individuals look, how long they focus on specific objects and how their gaze shifts between elements of the environment [2, 7]. In traffic research, such information is valuable because road users continuously rely on visual cues to detect hazards, interpret traffic situations and make movement-related decisions. Commonly used indicators include fixation duration, fixation count, gaze direction, scan paths and heat maps, which can provide insight into attention allocation, situational awareness and hazard perception [2, 7].

Mobile eye-tracking glasses have expanded the possibilities of traffic behaviour research because they enable gaze data collection outside laboratory settings. Wearable systems allow participants to move naturally while walking, cycling or using micromobility devices, which is particularly important for studying behaviour in dynamic urban environments. Software tools developed for mobile eye-tracking systems also support gaze data processing in relation to the surrounding visual scene [1]. Previous traffic-related research has shown the value of eye-tracking indicators for analysing attention, distraction and safety-related behaviour [8], while studies on vulnerable road users require specific consideration due to their direct exposure to traffic risks.

2.2 Eye tracking and pedestrian behaviour

Pedestrian eye-tracking research has mainly focused on road-crossing behaviour, visual search strategies, signalised intersections and interaction with traffic infrastructure. Since pedestrians are physically unprotected, understanding their gaze behaviour is important for improving crossing safety and designing more understandable infrastructure. Lévêque et al. [12] provide a state-of-the-art review of pedestrian road-crossing studies and show that pedestrians distribute visual attention across vehicles, road space, signals and other environmental cues when deciding whether and when to cross.

Several empirical studies further demonstrate the relevance of eye tracking for pedestrian safety research. Gruden et al. [4] analysed young pedestrian behaviour at signalised intersections, while Gruden et al. [5] examined how different signalised intersection typologies influence pedestrian performance. Age-related differences were investigated by Zito et al. [18], who compared street-crossing behaviour among younger and older pedestrians using eye- and head-tracking methods. These studies show that pedestrian gaze behaviour is influenced by crossing context, infrastructure design and user characteristics.

2.3 Eye tracking and cyclist behaviour

Cyclist eye-tracking research has developed in parallel with the increasing importance of cycling in sustainable urban mobility. Cyclists operate in complex traffic environments and must continuously monitor vehicles, pedestrians, road surfaces, intersections, traffic signs and cycling infrastructure. For this reason, gaze behaviour is an important indicator of cyclist perception, attention allocation and safety-related decision-making.

Previous studies have analysed cyclist visual behaviour in different traffic contexts. Kovácsová et al. [11] examined cyclists' eye movements and crossing judgements at uncontrolled intersections, while Kircher and Ahlström [10] investigated attentional requirements on cyclists and drivers in urban intersections. Mantuano et al. [14] studied cyclist gaze behaviour in urban space, and Vansteenkiste et al. [17] showed that bicycle path quality can influence how cyclists distribute visual attention. Recent review studies by Ma et al. [13] and Kchour et al. [9] confirm the growing use of eye-tracking technology in cyclist research, but also point to differences in metrics, experimental environments and reporting practices.

2.4 Eye tracking and micromobility users

Micromobility users, especially e-scooter riders, represent an emerging group of vulnerable road users. The European Commission [3] identifies personal mobility devices as an important road safety issue because their integration into existing infrastructure and regulation remains challenging. Compared with pedestrian and cyclist research, eye-tracking studies involving e-scooter users are still limited.

Pashkevich et al. [15] conducted a field eye-tracking experiment comparing pedestrians, cyclists and electric scooter riders on shared road infrastructure. Their study is particularly relevant because it compares different vulnerable road user groups in the same traffic context. Trefzger et al. [16] also compared gaze behaviour of e-scooter riders and cyclists in a real test environment, focusing on road

surface quality. These studies indicate that micromobility users may have specific visual attention patterns that should be considered in infrastructure design and traffic safety measures.

In addition to traditional traffic environments, eye tracking has also been applied to interactions between vulnerable road users and automated vehicles. Guo et al. [6] investigated pedestrian interaction with automated vehicles using video-based eye tracking and showed that this method can help assess how pedestrians perceive external vehicle communication cues. The literature confirms the potential of mobile eye tracking for analysing vulnerable road users, but also shows that research remains unevenly distributed across pedestrians, cyclists and micromobility users.

3 METHODOLOGY

This paper applies a structured narrative literature review approach to examine the use of mobile eye-tracking glasses in the analysis of vulnerable road user behaviour. The review was designed to identify the main application areas, methodological approaches, eye-tracking indicators and research gaps in studies focusing on pedestrians, cyclists and micromobility users.

The literature search was based on scientific databases and academic search platforms, including Scopus, Web of Science, ScienceDirect and Google Scholar. The search focused on publications related to mobile eye tracking, vulnerable road users and urban traffic behaviour. The following keywords and keyword combinations were used: “mobile eye tracking”, “eye-tracking glasses”, “vulnerable road users”, “pedestrians”, “cyclists”, “e-scooter”, “micromobility”, “visual attention”, “gaze behaviour”, “hazard perception” and “traffic safety”.

Studies were included if they examined the use of eye-tracking technology in a traffic or urban mobility context and focused on at least one category of vulnerable road users. The review included journal articles, conference papers, book chapters and relevant institutional reports published mainly between 2014 and 2025. Studies were excluded if they focused exclusively on motor vehicle drivers, medical diagnostics, marketing, general human-computer interaction or applications outside the transport and mobility context.

The selected studies were analysed according to predefined categories: road user group, research environment, research focus, eye-tracking metrics and main contribution. This categorisation enabled a structured comparison of previous studies and supported the identification of key limitations and future research directions.

Table 1 presents the categories used for the analysis of the selected literature.

Table 1. Categories used for literature analysis

Category	Description
Road user group	Pedestrians, cyclists, e-scooter users and other micromobility users
Research environment	Real-world field study, simulator, video-based experiment or laboratory setting
Research focus	Road crossing, infrastructure interaction, hazard perception, visual attention, micromobility or automated vehicle interaction
Eye-tracking metrics	Fixation duration, fixation count, gaze direction, scan paths, heat maps and related indicators
Main contribution	Safety implications, methodological contribution, infrastructure recommendations or identified research gaps

Source: Made by authors.

An initial search identified a broader set of potentially relevant publications, which were screened according to the defined inclusion and exclusion criteria. The final analysis included 18 publications directly related to mobile eye tracking, vulnerable road users and urban traffic behaviour.

4 RESULTS

The structured review shows that mobile eye-tracking applications among vulnerable road users can be grouped into three main research areas: pedestrian behaviour, cyclist behaviour and micromobility. A smaller but relevant research direction concerns the interaction between pedestrians and automated vehicles. The reviewed studies differ in terms of road user group, research environment, eye-tracking metrics and research focus, but they collectively demonstrate the value of eye tracking for analysing visual attention and behaviour in traffic environments.

4.1 Main application areas

Pedestrian studies mainly focus on road-crossing behaviour, signalised intersections, visual search strategies and age-related differences [4, 5, 12, 18]. These studies show that eye-tracking methods can provide useful information on how pedestrians observe vehicles, signals, road space and other traffic elements before and during crossing.

Cyclist studies represent another well-developed area of eye-tracking research. Existing studies examine visual behaviour at intersections, attentional requirements in urban traffic, cycling infrastructure, bicycle path quality and cyclist perception in urban environments [9–11, 13, 14, 17]. These studies indicate that cyclists continuously allocate attention between vehicles, road surfaces, traffic signs, pedestrians and potential conflict points.

Compared with pedestrians and cyclists, micromobility users have received less attention in eye-tracking research. Available studies mainly focus on e-scooter riders and their comparison with cyclists or pedestrians [15, 16]. This indicates that micromobility is an emerging but still underdeveloped research area, although personal mobility devices represent an increasingly relevant road safety issue [3].

Eye tracking has also been used to examine pedestrian interaction with automated vehicles. Guo et al. [6] investigated how external human-machine interface modalities and locations influence pedestrian interaction with automated vehicles. This shows that eye tracking can support the evaluation of how vulnerable road users perceive and interpret communication cues in future traffic environments.

4.2 Eye-tracking metrics and research approaches

Across the reviewed studies, the most common eye-tracking indicators include fixation duration, fixation count, gaze direction, scan paths and heat maps. These measures are commonly interpreted as indicators of visual attention, information processing and situational awareness [2, 7]. In vulnerable road user research, they are used to analyse how users observe traffic infrastructure, detect hazards and interact with other road users.

The reviewed studies also differ in their research environments. Some are based on real-world field experiments, which provide higher ecological validity and allow researchers to observe behaviour in natural traffic conditions [15–17]. Others use controlled or semi-controlled environments, including video-based experiments and structured test scenarios [6, 11]. Field studies better reflect actual traffic complexity, while controlled studies make it easier to compare behaviour under similar conditions.

4.3 Overview of selected studies

Table 2 provides a compact overview of the most relevant application-oriented studies included in the review.

Table 2. Overview of selected studies on eye-tracking applications among vulnerable road users

Reference	Road user group	Main focus	Key contribution
Lévêque et al. [12]	Pedestrians	Road crossing	Overview of pedestrian gaze behaviour during crossing
Gruden et al. [4]	Pedestrians	Signalised intersections	Analysis of young pedestrian behaviour and safety
Zito et al. [18]	Pedestrians	Age-related differences	Comparison of younger and older pedestrians
Ma et al. [13]	Cyclists	Behaviour and perception	Review of eye-tracking measures in cyclist research
Kovácsová et al. [11]	Cyclists	Uncontrolled intersections	Analysis of cyclist eye movements and crossing judgements
Vansteenkiste et al. [17]	Cyclists	Bicycle path quality	Influence of infrastructure quality on gaze behaviour
Pashkevich et al. [15]	Pedestrians, cyclists and e-scooter riders	Shared infrastructure	Comparison of visual attention and speeds among VRU groups
Trefzger et al. [16]	E-scooter riders and cyclists	Road surface quality	Comparison of gaze behaviour in a real test environment
Guo et al. [6]	Pedestrians	Automated vehicle interaction	Evaluation of pedestrian perception of eHMI communication cues

Source: Made by authors.

When the reviewed studies are considered together, several common patterns can be identified. Pedestrian studies show that gaze behaviour is closely related to crossing decisions, attention to vehicles, traffic signals and road space. Cyclist studies indicate that visual attention is strongly influenced by intersection complexity, infrastructure quality and the need to monitor several potential conflict points at the same time. In contrast, micromobility studies suggest that e-scooter users may have different gaze and speed-related behaviour, but the available evidence is still limited. This indicates that mobile eye tracking is useful not only for describing individual user groups, but also for comparing how different vulnerable road users perceive and respond to similar traffic environments.

5 DISCUSSION AND CONCLUSION

The results of the structured literature review show that mobile eye tracking is a useful method for analysing visual attention and behaviour among vulnerable road users. Eye-tracking glasses can provide objective information on how pedestrians, cyclists and micromobility users observe traffic environments, detect relevant stimuli and respond to potential hazards.

However, the reviewed literature also shows that research unevenly covers different road user groups. Pedestrian and cyclist studies are more represented than studies focusing on micromobility users.

Pedestrian research has mainly investigated road-crossing behaviour, signalised intersections and age-related differences in visual scanning [4, 5, 12, 18]. Cyclist research is also relatively well developed, particularly in relation to intersections, infrastructure quality, urban cycling environments and attentional requirements [9–11, 13, 14, 17]. In contrast, the number of studies focusing on e-scooter riders and other micromobility users remains limited, although these users represent a growing group within sustainable urban transport systems [3, 15, 16].

Another important issue is the diversity of research environments and methodological approaches. Some studies are conducted in real-world conditions, while others use video-based experiments, controlled test environments or semi-controlled research settings [6, 11, 15–17]. Field studies provide higher ecological validity because they capture behaviour in actual traffic environments, but they are more difficult to control and compare. Controlled studies offer better experimental consistency, but may not fully reflect natural traffic behaviour.

The reviewed literature also shows that eye-tracking metrics are not always reported consistently. Studies use different indicators, including fixation duration, fixation count, gaze direction, scan paths and heat maps [2, 7]. Although these metrics are useful for analysing attention and perception, differences in definitions, data processing and reporting make comparison between studies more difficult. This limits the possibility of drawing broader conclusions about vulnerable road user behaviour.

Overall, the review confirms that mobile eye tracking has strong potential for supporting road safety research and sustainable urban mobility planning. Across the reviewed studies, a common finding is that gaze behaviour reflects how vulnerable road users identify relevant traffic elements, detect potential hazards and adapt their behaviour to infrastructure and traffic conditions. Pedestrian and cyclist studies already provide useful evidence on attention allocation in crossing situations, intersections and infrastructure-related contexts, while micromobility research is still too limited to allow broader conclusions. This imbalance shows that future research should move beyond separate case studies and include more comparative analyses across different vulnerable road user groups, more real-world experiments and more consistent reporting of eye-tracking indicators. Such research can support the development of safer infrastructure, more effective road safety measures and more sustainable urban mobility systems.

Use of AI tools: AI-assisted tools were used to support the structural organisation and language refinement of the manuscript. All scientific content, interpretation and conclusions were reviewed and verified by the authors, who remain fully responsible for the content.

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VI. Urban Mobility, Road Safety and Transport Behaviour

Pedestrian Crossing Behaviour in Relation to Traffic Infrastructure Near the University North Campus: A Case Study of Vinka Međerala Street in Varaždin

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ABSTRACT

This paper examines how the location of the existing marked pedestrian crossings on Vinka Međerala Street near the University North campus in Varaždin corresponds to observed pedestrian crossing behaviour. The study combined field observation, 36 hours of manual counts in 12 sessions and an online survey of 210 students and staff. In the average nine-hour profile (07:30–16:30), 77.8% of 1,397 pedestrian movements occurred outside the two marked crossings; across individual sessions, this share ranged from 68.0% to 93.5%. Overall, 57.1% of respondents reported using the marked crossings rarely or never, and 75.6% of those who did not always use them stated that crossing elsewhere was faster. A dominant informal crossing path, identified by qualitative observation, lies 89.2 m from the northern and 46.6 m from the southern crossing. As a concept, the paper proposes an additional marked crossing on this path with kerb extensions and local carriageway narrowing, while retaining the existing crossings. Its exact location and expected safety effects remain hypotheses that require path-specific counts, speed and sight-distance measurements and a traffic engineering study.

Keywords: pedestrian desire line; university campus; pedestrian safety; sustainable urban mobility

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Pedestrian safety and accessibility are key components of sustainable urban mobility. They are influenced by road characteristics, vehicle speeds, visibility, the location of pedestrian crossings and the organisation of the surrounding space. Well-designed crossings, traffic-calming measures and shorter crossing distances can improve pedestrian safety [1]. However, the effectiveness of pedestrian infrastructure also depends on how closely it corresponds to actual user behaviour [2]. Pedestrians often seek direct routes that minimise walking distance and travel time. If a marked crossing requires a substantial detour, some users choose to cross elsewhere. This decision is influenced by perceived time savings, traffic volume and willingness to walk an additional distance to a crossing [3]. Long-term observations also show that the frequency and temporal distribution of crossings at unmarked locations depend on local traffic and spatial conditions [4]. Repeated use of the same routes creates pedestrian desire lines, which may reveal a mismatch between planned infrastructure and users' actual needs.

This mismatch is particularly relevant in university settings, where the arrangement of buildings, car parks and surrounding facilities generates concentrated pedestrian flows. Studies conducted on university campuses indicate that combining field observations with survey data allows actual behaviour to be considered alongside users' reported habits and perceptions [5], [6]. Frequent crossing away from marked locations has also been documented at Mae Fah Luang University, highlighting the importance of locating crossings in relation to students' everyday destinations [7]. Moreover, design guidance does not always reflect the difficulties experienced by users of unsignalised crossings. Technical design should therefore be considered together with user experience and observed movement patterns [8]. A mismatch between the existing infrastructure and pedestrian desire lines was identified on Vinka Međerala Street adjacent to the University North campus in Varaždin.

Although the study section includes two marked pedestrian crossings, their locations do not fully correspond to the dominant movement pattern between the campus and the facilities on the eastern side of the street. This study therefore aims to determine the proportion of observed pedestrian movements occurring at and outside the marked crossings, identify the reported reasons for not always using them and examine users' views on potential improvements. The study combines field observation, manual traffic counts and a survey of University North students and staff. Based on the findings, a preliminary traffic-engineering concept adapted to the dominant pedestrian desire line is outlined and the evidence still required for its verification is identified.

2 STUDY AREA AND METHODOLOGY

The empirical research was conducted by second-year students enrolled in the undergraduate Logistics and Mobility programme as part of the *Urban Traffic Infrastructure* course during the summer semester of the 2025/2026 academic year.

2.1 Study area

The study area covers the section of Vinka Međerala Street between Jurja Križanića Street to the north and 104th Brigade Street to the south. Two existing marked pedestrian crossings are located on this section: PP1 in the northern part and PP2 in the southern part. Their locations, the spatial extent of the study and the observed pedestrian desire lines are shown in **Figure 1**.

The road carries two-way traffic, with one traffic lane in each direction, and has an estimated carriageway width of 6-7 m based on field observation. Footways are provided on both sides of the carriageway, but no dedicated cycling infrastructure is present. Parking spaces and access points to adjacent properties are located along the carriageway. The University North campus in Varaždin is located on the

western side of the street. Hospitality, retail and service facilities are located on the eastern side and are collectively referred to as pedestrian trip generators. PP1 is located near Jurja Križanića Street and PP2 near 104th Brigade Street.

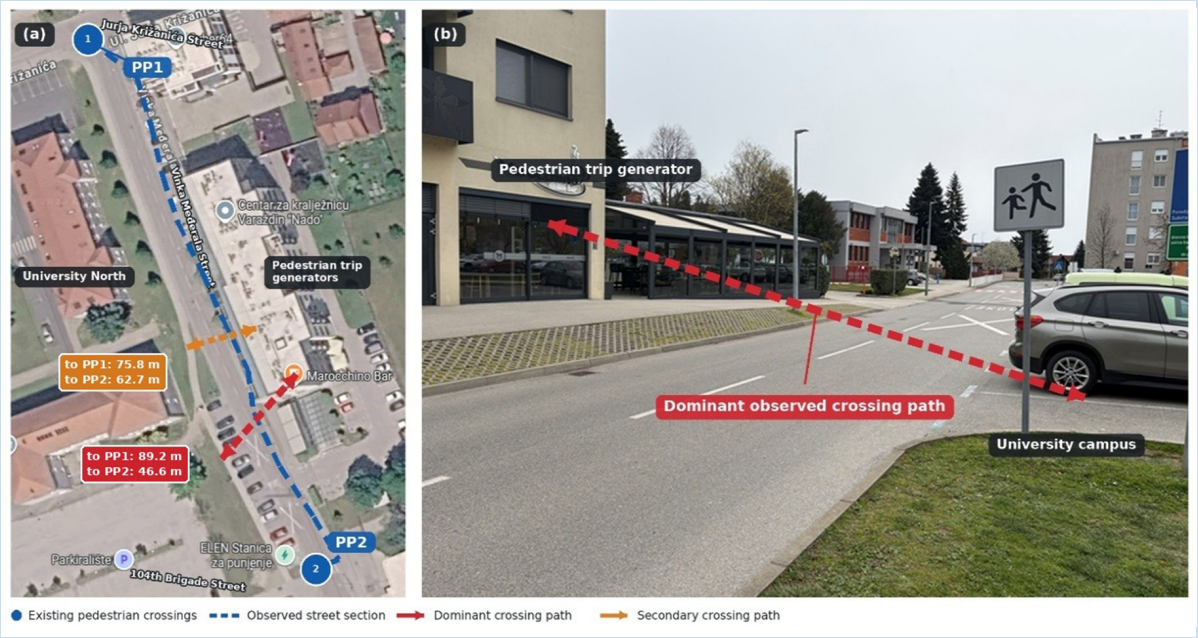


Figure 1. Study area: (a) locations of crossings PP1 and PP2, the observed dominant and secondary crossing paths and their distances from the existing crossings, measured along the street; (b) site view of the dominant crossing path between the campus and the pedestrian trip generators.

Source: Google Maps base map; field photograph, distance measurements and graphic processing by the authors, 2026.

Two informal crossing paths were observed between PP1 and PP2 (**Figure 1a**). The dominant path connects the campus with the facilities on the eastern side of the street and lies 89.2 m from PP1 and 46.6 m from PP2, measured along the street. The secondary path, located further north, lies 75.8 m from PP1 and 62.7 m from PP2. Assuming that a pedestrian starts and ends at the ends of the dominant path, using PP2 instead would add approximately 93 m of walking (2 × 46.6 m) and using PP1 approximately 178 m; for the secondary path, the corresponding detours are approximately 125 m and 152 m. At typical walking speeds, even the shortest of these detours adds roughly one minute to the trip.

2.2 Field observation and traffic counting

Manual counts of road traffic and pedestrian movements were conducted by six student groups on 10, 13, 14, 17, 20 and 21 April 2026, on weekdays with regular teaching. The schedule comprised 12 three-hour sessions (36 hours) in three time blocks: 07:30–10:30 (five sessions), 10:30–13:30 (four sessions) and 13:30–16:30 (three sessions). All counts were made from the same fixed observation point, selected to provide an unobstructed view along the whole study section in both directions. Data were recorded on pre-prepared forms in 15-minute intervals. Vehicles passing the observation point in both directions were recorded as passenger cars, delivery vehicles, buses or other modes (motorcycles, mopeds and bicycles). Each crossing of the carriageway by a pedestrian within the study section was recorded as one pedestrian movement, classified as made at a marked crossing or elsewhere and by observed destination (University Centre, hospitality facilities, shop, copy shop or other). The locations of crossings outside the marked crossings were noted qualitatively; recurring patterns were used to identify the dominant and secondary paths (**Figure 1a**), but no separate counts were kept for them. For each

session, the 15-minute counts were summed into hourly counts. For each hourly interval, the mean across all sessions covering that interval was calculated (n = 5, 4 or 3), and the average nine-hour profile was obtained by summing the nine hourly means. The profile thus represents a typical teaching day (07:30–16:30), not the total recorded in 36 hours. Shares were calculated from unrounded means, and counts are rounded to whole numbers only for presentation.

2.3 Survey

The questionnaire was created in Google Forms and administered online in April and May 2026 to students of several departments and to University North staff. Participation was voluntary and anonymous, respondents were informed about the purpose of the study and the use of the data, and no personally identifiable information was collected.

A total of 210 respondents participated, comprising 171 students (81.4%) and 39 staff members (18.6%). As this was a convenience sample of users of the University North campus in Varaždin, the findings are interpreted descriptively and are not generalised to the wider campus population. The questionnaire contained 13 questions covering travel mode and parking location, crossing behaviour on Vinka Međerala Street, use of the existing marked crossings, perceived safety, experience of dangerous situations and potential improvement measures. Closed-ended responses were analysed using absolute and relative frequencies, and open-ended responses were grouped thematically.

The question on crossing frequency referred to arrival at or departure from the University, while the question on the use of marked pedestrian crossings referred to behaviour at the study location and was analysed for the full sample (N = 210). Reasons for not always using a marked crossing were analysed for the 180 respondents who used the marked crossings sometimes, rarely or never; as multiple responses were permitted, the percentages may sum to more than 100%.

3 RESULTS

3.1 Field counting results

The average nine-hour profile comprised 2,069 road traffic movements. Passenger cars accounted for 1,757 (84.9%), other modes for 228 (11.0%), delivery vehicles for 53 (2.6%) and buses for 32 (1.5%). The highest mean hourly passenger-car volume, 243 vehicles, was recorded between 07:30 and 08:30. Session means ranged from 173 to 279 vehicles per hour.

The same profile comprised 1,397 pedestrian movements, of which 1,086 (77.8%) occurred outside the marked crossings and 311 (22.2%) at the marked crossings. Movements towards the University Centre accounted for 37.3% and movements towards the hospitality, retail and service facilities on the eastern side of the street for 40.2%; together, 77.4% of movements linked the campus with the facilities opposite (**Table 1**).

These figures aggregate all crossings outside the marked crossings along the study section; they do not quantify the dominant and secondary paths separately and therefore do not measure demand at the proposed crossing location.

Crossing outside the marked crossings prevailed in every hourly interval (**Figure 2**). Mean hourly pedestrian volumes ranged from 113 (07:30–08:30) to 175 (13:30–14:30), but volumes varied considerably between sessions, from 57 to 278 movements per hour. The share of crossings outside the marked crossings was more stable: it ranged from 68.0% to 93.5% across the 12 sessions (mean 80.8%) and exceeded 60% in each of the 36 observed session-hours. The pattern was thus not confined to particular days or peak periods, although absolute volumes rest on only three to five sessions per interval.

Table 1. Observed pedestrian movements in the average nine-hour profile.

Variable	Category	Movements per average nine-hour profile (n)	Share (%)
Crossing behaviour	Outside marked crossings	1,086	77.8
	Using marked crossings	311	22.2
Observed direction of movement	University Centre	520	37.3
	Hospitality facilities	317	22.7
	Shop	195	14.0
	Copy shop	49	3.5
	Other destinations	315	22.6

Note: Values are sums of the nine hourly means (each the mean of three to five sessions), rounded to whole numbers. Crossing-behaviour shares are based on 1,397 movements and direction shares on the 1,396 movements with a recorded direction.

Source: Authors' calculations based on the field traffic counts.

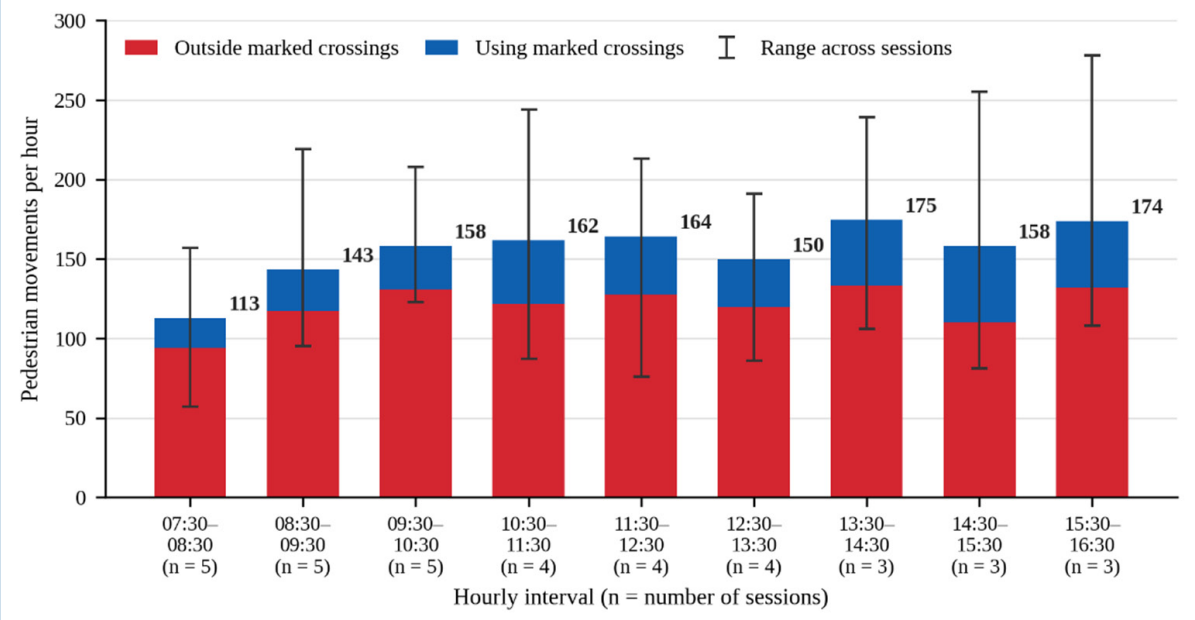


Figure 2. Mean hourly pedestrian movements at marked crossings and at unmarked locations, with the range of hourly totals across sessions.

Note: Bars show the means of the sessions covering each interval (n = 5, 4 or 3); whiskers show the minimum and maximum hourly totals. Values are rounded for presentation.

Source: Authors' calculations based on the field traffic counts.

3.2 Survey results

The car was the most commonly reported primary mode of transport to the University Centre (135 respondents; 64.3%), followed by walking (50; 23.8%), cycling (12; 5.7%), public transport (8; 3.8%) and other modes (5; 2.4%). Eighty-five respondents (40.5%) usually parked in nearby streets. When arriving

at or leaving the University, 76 respondents (36.2%) crossed Vinka Međerala Street regularly, 70 (33.3%) sometimes, 43 (20.5%) rarely and 21 (10.0%) never.

In a separate question, 30 respondents (14.3%) reported always using a marked pedestrian crossing at the study location, 60 (28.6%) sometimes, 55 (26.2%) rarely and 65 (31.0%) never (**Figure 3a**). Among the 180 respondents who did not always use a marked crossing, the most frequently reported reasons were that crossing elsewhere was faster (136; 75.6%) and that the existing crossing was too far away (100; 55.6%), followed by good visibility of approaching traffic (60; 33.3%), low traffic volume (57; 31.7%), poor visibility of the crossing (11; 6.1%) and other reasons (8; 4.4%) (**Figure 3b**).

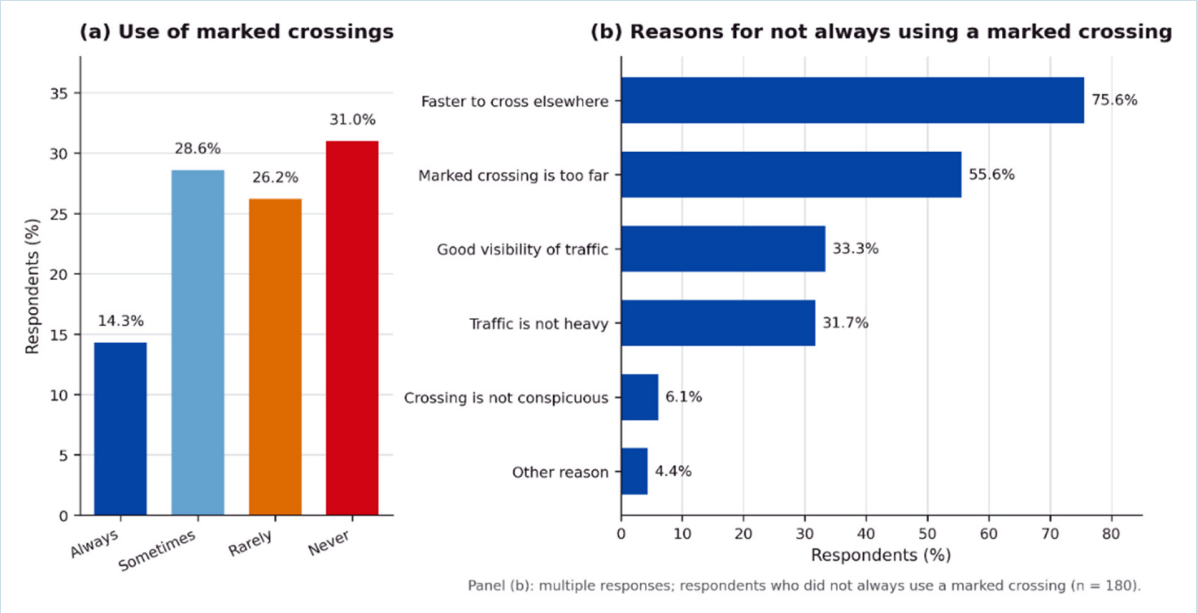


Figure 3. Survey results: (a) frequency of use of marked pedestrian crossings (N = 210); (b) reasons for not always using a marked crossing (n = 180; multiple responses permitted).

Source: Authors' calculations based on the survey data.

Crossing was rated as very safe by 49 respondents (23.3%), mostly safe by 80 (38.1%), neither safe nor unsafe by 59 (28.1%), mostly unsafe by 15 (7.1%) and very unsafe by 7 (3.3%); 32 respondents (15.2%) had experienced a dangerous situation while crossing. Additional measures were considered likely to improve safety by 135 respondents (64.3%), while 18 (8.6%) disagreed and 57 (27.1%) were unsure. Asked to select the single most useful measure, 101 respondents (48.1%) chose a new marked pedestrian crossing, 40 (19.0%) vehicle speed reduction, 22 (10.5%) better traffic signage, 21 (10.0%) pedestrian traffic signals and 4 (1.9%) better lighting, while 22 (10.5%) selected another measure.

3.3 Comparison of observed and self-reported behaviour

Field observations and survey responses point in the same direction but are not directly comparable. The counts record pedestrian movements, so a frequent crosser contributes many observations and non-university pedestrians are also included, whereas the survey records the self-reported habits of individual students and staff from a convenience sample. The 77.8% of observed movements outside the marked crossings and the 57.1% of respondents who rarely or never use them therefore describe different quantities and cannot be converted into one another. Both nevertheless indicate limited use of the existing crossings, and the main reported reasons (75.6% faster elsewhere; 55.6% crossing too far) are consistent with the detours estimated in subsection 2.1. Neither data source, however, quantifies demand at the proposed crossing location itself.

4 DISCUSSION AND PROPOSED TRAFFIC SOLUTION

The findings can be separated into three levels of evidence. First, observed behaviour shows that most crossings on the study section take place outside the marked crossings, consistently across sessions, and that a recurring dominant path links the campus with the facilities opposite at a point 89.2 m from PP1 and 46.6 m from PP2. Second, user preferences indicate that route directness and crossing distance are the main reasons for not using the marked crossings and that a new marked crossing is the most frequently preferred measure. Third, the engineering feasibility and safety effect of such a crossing have not yet been assessed, as no speeds, sight distances or conflicts were measured. The main problem is therefore a spatial mismatch between the existing crossings and the dominant path rather than an absence of crossings, and favourable safety perceptions alone do not show that the layout is adequate. This is consistent with evidence that crossing-location choice depends on route directness, time savings, local conditions and users' experience of infrastructure [3, 4, 8]. On this basis, a preliminary concept is proposed: an additional marked crossing on the dominant path, with kerb extensions on both sides and local carriageway narrowing, while PP1 and PP2 are retained because they serve other movements, including those towards the Medical School (**Figure 4**). Because the location rests on qualitative observation, it should be confirmed by path-specific counts, for example from video recordings, before design.

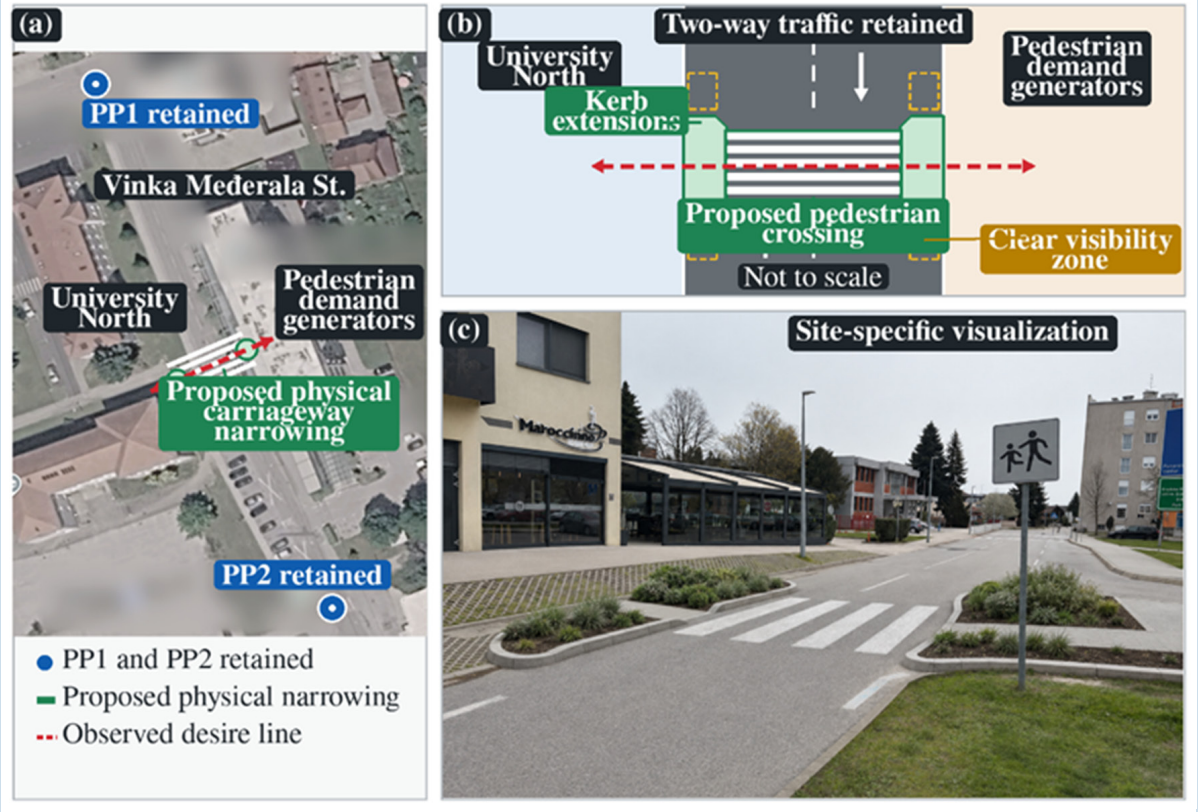


Figure 4. Proposed concept: (a) new crossing location; (b) local carriageway narrowing; (c) visualisation of the proposed layout.

Source: Google Maps base map; field photograph, conceptual design and graphic processing by the authors, 2026. The illustration is schematic and not drawn to scale; distances are given in Figure 1a.

The new pedestrian crossing, road markings and associated signage must comply with the applicable Ordinance on Traffic Signs, Signalling and Equipment on Roads [9]. At the proposed location, on-street parking should be removed or rearranged and short-term stopping restricted. Stopping and parking are prohibited on a marked crossing and within 5 m of it [10], while a traffic engineering study should determine whether adequate sight distance requires parking removal over a greater distance. Dropped kerbs and tactile paving should be provided to ensure accessibility for persons with disabilities and reduced mobility [11]. The final crossing location, kerb-extension geometry, remaining lane widths, sight distance, drainage and design-vehicle swept paths must be verified through a traffic engineering study and design documentation. Any safety benefit of the concept should therefore be treated as a hypothesis. Kerb extensions and narrowing are expected to shorten the crossing distance and improve intervisibility, but these effects, as well as the need for a raised crossing, depend on measured vehicle speeds, available sight distances and swept-path checks for the design vehicle. Alternative layouts and demand scenarios could also be tested in a microsimulation model of the study area before implementation.

5 CONCLUSION

The study identified a spatial mismatch between the existing marked crossings and pedestrian movement patterns on Vinka Međerala Street. In the average nine-hour profile, 77.8% of pedestrian movements occurred outside the marked crossings, a share that remained between 68.0% and 93.5% across observation sessions, and 57.1% of survey respondents reported using the marked crossings rarely or never. Route directness and crossing distance were the most frequently reported reasons, and a new marked crossing was the most frequently preferred measure. The proposed concept adds a marked crossing on the dominant path, 46.6 m from the nearest existing crossing, while retaining PP1 and PP2.

Its exact location and expected safety benefits remain to be verified: the dominant path was identified qualitatively, the survey was based on a convenience sample, and no speed, sight-distance, conflict or crash data were collected.

Future research should include path-specific video counts, speed, sight-distance and conflict observations, survey cross-tabulations by travel mode and parking location, microsimulation of alternative layouts and, if implemented, a before-and-after evaluation.

Use of AI tools: AI-assisted tools supported statistical coding and verification, structural organisation and language editing; the authors reviewed all analyses, results, interpretations and conclusions and remain fully responsible for the content.

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VI. Urban Mobility, Road Safety and Transport Behaviour

Pedestrian Desire Lines and Crossing Location at a University Campus: A Case Study of Peteranska Road, Koprivnica

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ABSTRACT

Pedestrians do not always use designated crossing facilities when these deviate from their preferred walking routes, choosing instead more direct paths known as desire lines. This study examines whether the location of the marked pedestrian crossing on Peteranska Road (DC41), next to the University North campus in Koprivnica, Croatia, corresponds to observed pedestrian movements, and which factors are associated with crossing elsewhere. Five-day field counts of pedestrians and motor vehicles (39 observation hours) were combined with a questionnaire survey of 131 campus users. Of 1,328 recorded pedestrian crossings, 73.8% (95% CI: 71.4–76.1%) occurred outside the marked crossing. Informal crossings predominated on all five days, although their share varied significantly between days, and field observation indicated that they followed a more direct connection between the campus entrance and facilities on the opposite side of the road, 51.55 m from the marked crossing. Among respondents who cross the road and do not always use the marked crossing (n = 87), the most frequent reasons were that it was faster to cross elsewhere (41.4%) and that the crossing was too far away (29.9%). The findings indicate a spatial mismatch between the marked crossing and dominant pedestrian movements and provide a basis for a further traffic-safety assessment rather than a direct recommendation for a specific intervention.

Keywords: pedestrian desire lines; pedestrian safety; traffic infrastructure; sustainable mobility

University North

FACULTY OF TRANSPORT AND TRAFFIC SCIENCES

1 INTRODUCTION

Walking is a fundamental mode of everyday mobility and an important component of sustainable transport systems. However, pedestrian infrastructure does not always follow the most direct routes between origins and destinations. Additional distance and detours may reduce route convenience, making directness an important factor in pedestrian accessibility [1]. Research on road-crossing behaviour further indicates that the spatial distribution of origins and destinations, together with characteristics of the immediate road environment, influences the choice of crossing location and route [2]. This behaviour is reflected in *pedestrian desire lines*, i.e., direct paths chosen by pedestrians instead of formally designated routes. When a designated route is longer or requires a deviation from the desired direction of travel, pedestrians may choose a shorter informal path, including crossing outside a marked pedestrian crossing [3, 4].

Such choices are influenced not only by the availability of formal pedestrian infrastructure but also by route convenience, the traffic environment, and individual characteristics [3, 5]. The presence of a marked crossing, therefore, does not necessarily ensure its consistent use [6]. This issue is particularly relevant where major pedestrian trip generators are located on both sides of a road.

University campuses are particularly relevant settings for studying desire lines. They generate large and regular pedestrian flows of mostly young, time-constrained users, often concentrated in short intervals between lectures, and campus users make repeated trips to nearby services during the day. Where a campus borders a road with a through-traffic function, such trips necessarily involve crossing the road, and the location of crossing facilities becomes decisive for both convenience and safety.

Pedestrian route choice is multidimensional and is influenced by the built environment, subjective preferences and dynamic factors related to traffic [7]. Combining observed movement patterns with user-reported reasons for crossing behaviour can therefore provide a more comprehensive assessment of how well pedestrian infrastructure matches actual user needs.

This study investigates Peteranska Road (DC41) in the University North campus area in Koprivnica, Croatia, where the campus and commercial and hospitality facilities on the opposite side of the road generate frequent crossing movements. Although a marked pedestrian crossing is provided, field observations identified informal crossing locations offering a more direct connection. The study combines five-day field counts with a questionnaire survey of campus users to address three research questions: (RQ1) To what extent do pedestrians use the marked crossing compared with informal crossing locations? (RQ2) What reasons do users report for crossing outside the marked crossing? (RQ3) Do observed movement patterns and reported user preferences indicate a spatial mismatch between the existing pedestrian infrastructure and dominant *pedestrian desire lines*?

2 MATERIALS AND METHODS

2.1 Study area and existing pedestrian infrastructure

The study was conducted on Peteranska Road (DC41), a state road next to the University North campus in Koprivnica, with pedestrian trip generators on both sides (**Figure 1**). On the observed section, the road has one traffic lane in each direction and a carriageway width of approximately 7.0 m. No speed limit is posted; the general limit of 50 km/h for built-up areas therefore applies [8]. Accesses to the University parking area and to the parking area of the commercial facilities join the road on the section. The main campus entrance lies directly opposite the southern end of the informal crossing path, beyond the marked crossing over the mouth of Dr. Žarka Dolinara Street. The informal path lies 51.55 m from the marked pedestrian crossing (measured on the national geoportal), so that using the marked crossing implies a detour of approximately 100 m between the campus entrance and the facilities opposite.

The facilities on the opposite side of the road include hospitality venues, a supermarket, a bakery and a petrol station, which are used by students and staff during the day. As the campus is poorly served by public transport, many users arrive by car, so crossing movements are likely to be related largely to trips between the campus and these facilities during the day rather than to arrivals and departures.

In **Figure 1**, the marked pedestrian crossing is shown in red and the observed informal crossing path in green.

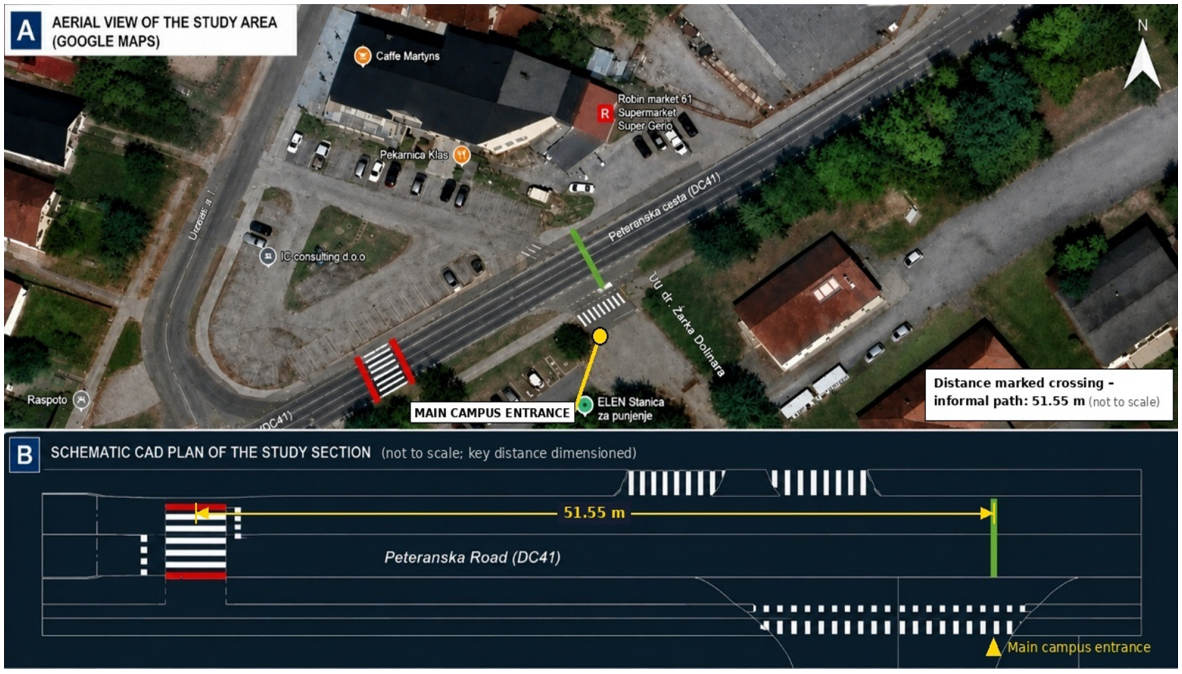


Figure 1. Spatial location of the study area and existing pedestrian infrastructure on Peteranska Road (DC41): (A) aerial view of the study area (not to scale); (B) schematic CAD view of the observed section (not to scale), with the distance between the marked crossing and the informal crossing path. The main campus entrance is marked in both views.

Source: (A) adapted from Google Maps; (B) Authors' elaboration.

2.2 Field observation and traffic and pedestrian counts

Field data were collected on five working days in April 2026 (16, 17, 20, 21 and 23 April). Motor vehicles and pedestrians were counted manually in 15-minute intervals in three-hour sessions between 07:30 and 16:30 at a single observation location: three sessions on 16, 17 and 23 April and two sessions on 20 April (07:30–13:30) and 21 April (07:30–10:30 and 13:30–16:30), i.e. 39 observation hours in total, each covered by one or two observers. Motor vehicles were recorded by direction as passenger cars, delivery vans, heavy goods vehicles, buses and other vehicles (mopeds, motorcycles and tractors); pedestrian crossings were recorded by direction (towards and away from the campus). Observer positions, counting rules for groups and repeated crossings, and weather conditions were not systematically recorded.

Each pedestrian crossing was classified as crossing at the marked crossing or outside it. Crossings outside the marked crossing were not subdivided by location, so the spatial distribution of informal crossings cannot be quantified; this would require video- or trajectory-based methods [9].

The informal path shown in **Figure 1** was identified through field observation as the location where such crossings were concentrated; its repeated use along a more direct connection provided the basis for considering it a *pedestrian desire line*.

2.3 Questionnaire survey

The questionnaire survey was conducted between 3 and 18 May 2026 among users of the University North campus in Koprivnica, mainly students and University employees (n = 131). It was administered in person: students involved in the study approached campus users and invited them to complete an anonymous, voluntary online questionnaire with closed- and open-ended questions. As the number of persons approached was not recorded, a response rate could not be calculated. The questionnaire is available from the authors upon request.

This study uses the questions on the frequency of crossing Peteranska Road, use of the marked crossing, reasons for not using it, perceived safety, and experience of dangerous situations.

2.4 Data analysis

Data were analysed using descriptive statistics. For the field data, the 95% confidence interval (CI) for the share of crossings outside the marked crossing was calculated using the Wilson score method, and differences between days were tested using the chi-square test of homogeneity. Motor-vehicle volumes were summarised as total and mean hourly two-way flows per day.

Questionnaire data were analysed as frequencies and percentages. Because the question on reasons for not using the marked crossing was presented to all respondents, reasons were analysed both for the whole sample and for relevant respondents, i.e. those who cross Peteranska Road and do not always use the marked crossing (n = 87).

The two data sources were interpreted jointly to address RQ3, without assuming a direct link between individually observed pedestrians and individual respondents.

3 RESULTS

3.1 Observed pedestrian crossing patterns

During the five days, 1,328 pedestrian crossings were recorded: 348 (26.2%) at the marked crossing and 980 (73.8%; 95% CI: 71.4–76.1%) outside it, i.e. almost 2.8 times more. Of all crossings, 696 (52.4%) were directed towards the campus and 632 (47.6%) away from it. The distribution by day is shown in **Figure 2**. The share of crossings outside the marked crossing was almost identical in both directions (74.0% towards and 73.6% away from the campus), indicating that the informal path is used for both outbound and return trips.

Crossings outside the marked crossing predominated on all five days, ranging from 57.0% (20 April) to 85.6% (21 April), but their share differed significantly between days ($\chi^2(4) = 60.6$, $p < 0.001$). The observation windows also differed: no afternoon session was held on 20 April and no midday session on 21 April. These differences, together with unrecorded factors such as lecture timetables and weather, may contribute to the daily variation, which cannot be attributed to a specific cause on the basis of five days.

Total two-way motor-vehicle volumes ranged from 2,484 vehicles on 20 April (6 h) to 9,468 vehicles on 23 April (9 h), i.e. approximately 410 to 1,050 veh/h (about 700 veh/h over all 39 hours); the low volume on 20 April partly reflects the missing afternoon session. Passenger cars accounted for 84.3% and heavy goods vehicles for 2.8% of vehicles. Vehicle volumes peaked between 13:00 and 16:00, while pedestrian volumes increased after 10:00, when the student canteen opens. Pedestrian volumes ranged from 19.0 crossings per hour on 17 April to 48.5 on 21 April (34.1 crossings per hour on average).

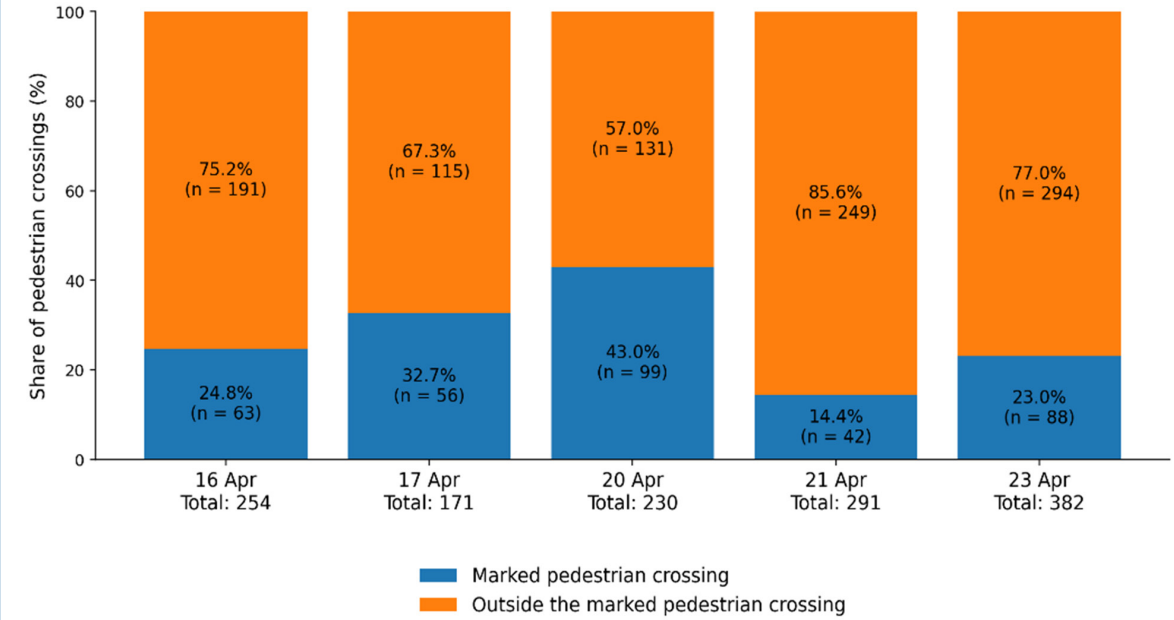


Figure 2. Distribution of pedestrian crossings at and outside the marked pedestrian crossing by observation day (absolute numbers of crossings in brackets).

Source: Authors' elaboration based on field observation data.

Although individual crossing positions were not recorded, field observation indicated that informal crossings were concentrated along the more direct connection between the campus entrance and the facilities opposite (**Figure 1**) on all five days.

3.2 Questionnaire survey results

Of the 131 respondents, 82.4% were students and the rest University employees or both. Overall, 45.0% reported crossing Peteranska Road on every arrival or departure, 29.0% occasionally, 9.9% rarely and 13.7% never (three combined responses were not assigned to a category). Results on the use of the marked crossing are presented in **Table 1**. Most respondents travel to the campus by car (73.3%), while 12.2% walk. In addition, 34.4% come to the campus every working day, 42.0% several times a week and 22.9% occasionally.

The marked crossing was always used by 21.4% of respondents, while 48.1% used it rarely or never. In the whole sample, the most frequent reasons for not using it were that it was faster to cross elsewhere (36.6%) and that the crossing was too far away (23.7%). Among relevant respondents (n = 87), these directness-related reasons were even more prominent (41.4% and 29.9%; together 71.3%). "Other reason" was selected by 11.5% of relevant respondents; as the questionnaire had no open-ended follow-up to this option, these responses could not be analysed further.

Perceptions of safety varied: 9.2% of respondents rated the crossing as very safe, 33.6% as mostly safe, 30.5% as neutral, 18.3% as mostly unsafe and 6.9% as very unsafe. In addition, 42.7% had experienced a dangerous situation at least once at this location, and a new pedestrian crossing was the most frequently selected safety measure (53.4%; multiple answers allowed). Respondents who never use the marked crossing rated crossing as mostly unsafe or very unsafe (41.7%) more often than those who always use it (14.3%), while the share of respondents reporting a dangerous situation was similar in both groups (50.0% and 53.6%). As the safety question did not distinguish between crossing at and outside the marked crossing, these differences should be interpreted with caution.

Table 1. Key questionnaire survey results related to the use of the existing marked pedestrian crossing.

Indicator	Response	n	%
Use of the existing marked pedestrian crossing	Always	28	21.4
	Sometimes	39	29.8
	Rarely	27	20.6
	Never	36	27.5
Reason for not using the marked pedestrian crossing	It is faster to cross elsewhere	48	36.6
	The crossing is too far away	31	23.7
	Other reason	24	18.3
	Good visibility of traffic	12	9.2
	Traffic is not heavy	12	9.2
	The crossing is not sufficiently visible	4	3.1

Note: For the question on the frequency of using the existing marked pedestrian crossing, one respondent selected a combined response ("sometimes/rarely"); therefore, the four individual response categories sum to 130.

Source: Authors' elaboration based on the questionnaire survey results.

Besides a new crossing, the measures most often selected were pedestrian traffic lights (35.9%), better traffic signs (26.7%) and a lower speed limit (25.2%). Of the 34 respondents who made a specific suggestion in the open-ended question, 19 proposed a new or relocated crossing, most of them closer to the campus exit, and 13 proposed speed-reducing measures such as speed cameras, speed bumps or a lower speed limit. One respondent explained that the crossing should be moved closer to the campus exit so that students could quickly buy food at the shop and return to lectures.

3.3 Relationship between observed patterns and user-reported behaviour

Considered jointly, the two data sources point in the same direction: informal crossings predominated on all observation days, and the most frequently reported reasons for not using the marked crossing were related to directness and distance. This correspondence exists at the aggregate level only, as individual observed pedestrians were not linked to individual respondents, but it indicates a spatial mismatch between the location of the marked crossing and dominant pedestrian movements. The open-ended suggestions point in the same direction, as most proposals concerning the crossing called for it to be moved closer to the campus exit.

4 DISCUSSION

The results indicate that the formal availability of a marked crossing does not ensure its functional alignment with actual pedestrian movements; route directness and convenience appear to be decisive.

With regard to the research questions, the results show that the marked crossing was used for only about one quarter of observed crossings (RQ1), that users mainly attribute crossing elsewhere to directness and distance (RQ2), and that both data sources consistently indicate a spatial mismatch between the marked crossing and the dominant movement between the campus entrance and the facilities opposite (RQ3).

This is consistent with Zhang et al. [2], who found that origin and destination points of interest and the immediate road environment are associated with the choice of crossing location. On Peteranska Road, using the marked crossing requires a deviation from the direct connection between the main trip generators, so the identified *pedestrian desire line* illustrates a mismatch between provided infrastructure and everyday movement.

Loo et al. [1] similarly show that detours reduce walking convenience. The present study complements such findings by combining observed crossing patterns with user-reported reasons, although this correspondence does not reveal the motivations of individual observed pedestrians.

The share of informal crossings observed on Peteranska Road is high in comparison with other studies. In the iMOVE study of two public transport interchanges in Melbourne, about one third of pedestrians used desire lines instead of the designated route, and their use was more frequent in the afternoon and in bad weather [4]. The considerably higher share found here may reflect the short distance between the campus entrance and the facilities opposite, regular and repeated nature of trips made by students and staff, and a regulatory setting in which crossing outside the marked crossing is not prohibited at this distance. It also suggests that, where a detour is perceived as unnecessary, a marked crossing located about 50 m from the main desire line is used by only a minority of pedestrians.

Crossing location choice is, however, multidimensional [7]. Crossing decisions combine route-level choices and local decisions influenced by traffic conditions [10], and the varying safety perceptions found here add a further contextual dimension. As safety perceptions were not linked to individual crossings, their effect on crossing location choice cannot be determined.

The small shares of relevant respondents citing good visibility of traffic (6.9%) or low traffic (6.9%) suggest that crossing outside the marked crossing is primarily a matter of convenience rather than a deliberate judgement that the location is safe. This is consistent with the finding that respondents who never use the marked crossing rated crossing as unsafe more often than those who always use it: many pedestrians appear to accept a perceived risk in exchange for a shorter route, which makes the location relevant for further safety assessment.

From a planning perspective, the desire line indicates a location where a more detailed evaluation is warranted, but the findings alone are insufficient to recommend relocating the crossing or adding a new one. Such a decision requires a separate traffic-safety assessment considering traffic volume, vehicle speeds, visibility and technical requirements.

A subsequent assessment could compare several options, such as an additional marked crossing on the desire line with appropriate visibility and lighting, relocation of the existing crossing, measures guiding pedestrians towards the existing crossing, or measures reducing vehicle speeds on the section. The survey indicates that users would primarily welcome a new crossing (53.4%), but user preferences need to be weighed against traffic volume, the proximity of junctions and accesses, and the technical requirements for pedestrian crossings on state roads.

The informal path is also relevant from a safety perspective. It ends at the mouth of the side street leading to the campus entrance and lies close to the parking access of the commercial facilities, where pedestrians may interact with turning vehicles as well as through traffic.

Field observation also indicated that visibility of the marked crossing is limited for drivers approaching from the direction of Koprivnica because of a slight horizontal curve, and that the crossing is announced by only one advance warning sign, which may reduce the perceived safety advantage of using it. Sudden braking caused by pedestrians crossing outside the marked crossing was observed during the counts, 42.7% of respondents reported a dangerous situation, and pedestrians must find gaps in continuous two-way traffic of about 700 veh/h on average. Under the Croatian Road Traffic Safety Act, pedestrians must use a marked crossing if it is not more than 50 m away in a built-up area and must not step onto the carriageway if this would obstruct vehicles [8]. With the informal path

51.55 m from the marked crossing, crossings along it fall just outside this distance and are not prohibited as such. That the dominant informal crossing lies almost exactly at the regulatory threshold shows that the legal framework alone does not ensure safe crossing conditions. Guidance on uncontrolled crossings likewise stresses that crossing facilities should reflect where pedestrians want to cross, with their design matched to traffic volume, speed and road configuration [11].

The study has several limitations. Observations covered five working days in one period of the academic year, with observation windows differing between days, and were conducted manually without recording individual crossing positions, observer positions, counting rules for groups or weather. The survey used a convenience sample and self-reported data, and the reasons question was presented to all respondents; results were therefore also reported for relevant respondents. Future research should include longer observation periods, video-based trajectory tracking and vehicle speed measurements. In addition, the counts covered only daytime hours on working days, so crossing behaviour in the evening, at weekends and in darkness, when visibility conditions differ, was not captured.

5 CONCLUSION

The study showed that pedestrian movements on Peteranska Road near the University North campus in Koprivnica differ from the pattern implied by the existing infrastructure: 73.8% of crossings occurred outside the marked crossing, predominantly along a more direct path towards the campus entrance, and users most often cited directness and distance as their reasons.

Two further findings stand out. The main informal crossing is located only 1.55 m beyond the distance within which pedestrians are legally obliged to use a marked crossing, so the current regulations neither prevent nor address the dominant crossing movement at this site. At the same time, pedestrians who avoid the marked crossing judge the road to be less safe to cross than regular users of the crossing do, which suggests that the shorter route is chosen despite, rather than because of, the conditions on the road. This *desire line* is therefore best understood as a signal that the site needs a closer safety and infrastructure review. A new crossing, although it is the measure users ask for most often, is only one of the possibilities that such a review would have to weigh.

Methodologically, the study shows that combining simple manual counts with a short user survey can provide a low-cost first indication of a mismatch between crossing facilities and pedestrian desire lines, which can then guide more detailed video-based and safety analyses.

Use of AI tools: AI-assisted tools were used to support statistical coding and verification, structural organisation, language refinement, and preparation of Figure 1. All analytical decisions, reported results, interpretations, and conclusions were reviewed by the authors, who remain fully responsible for the content.

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VI. Urban Mobility, Road Safety and Transport Behaviour

Evidence-Based Urban Mobility Planning Using Multi-Source Transport Data: A Case Study of Opatija, Croatia

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ABSTRACT

Public transport planning in tourist cities requires reliable and complementary evidence. Travel behaviour surveys describe mobility patterns and user preferences, traffic counts describe observed demand, and infrastructure assessments identify physical constraints; each captures a different dimension of urban mobility. This paper examines how these sources, together with public transport user perceptions, can be integrated to support public transport planning in the City of Opatija, Croatia. The analysis draws on a transport study comprising a travel behaviour survey, automatic and manual traffic counts and an infrastructure assessment, and focuses on the complementary contribution of these sources rather than on the evaluation of a proposed network. The findings show that car-oriented travel behaviour coexists with stated willingness to use public transport under improved service conditions, while high summer traffic demand and spatial constraints shape the planning context. The proposed multi-source evidence approach, operationalised as a four-step procedure leading from source-specific indicators to explicit planning requirements, does not require statistical fusion of heterogeneous datasets and may be applicable to other tourist-oriented and spatially constrained urban areas.

Keywords: public transport planning; sustainable mobility; travel behaviour survey; traffic counts; evidence-based planning

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1 INTRODUCTION

Sustainable urban mobility planning has become contingent on reliable and complementary transport data. Travel surveys provide information on mobility patterns, trip characteristics and user preferences, traffic counts provide direct observations of traffic volumes and their temporal distribution, and infrastructure assessments identify physical constraints affecting accessibility and the organisation of transport services. Since each source captures a different dimension of urban mobility, recent research increasingly emphasises the value of combining complementary evidence rather than relying on a single dataset [1-3].

Survey data help explain travel choices and user needs, whereas observed traffic data describe actual demand but provide limited information on the reasons behind individual travel decisions [1]. Previous studies have therefore combined survey-based information with other mobility data to improve the interpretation of travel patterns [2, 3], and data-driven approaches in public transport planning highlight the importance of incorporating different forms of evidence when identifying mobility needs [4].

This is particularly relevant in tourist-oriented coastal cities, where seasonal demand, constrained urban morphology and limited road capacity concentrate transport flows along a few corridors. Opatija, a coastal tourist city in Croatia, represents such a setting: its transport network is strongly shaped by the relationship between the coastal urban area and the surrounding terrain. Previous research has identified traffic-management challenges on its main urban corridors [5].

Against this background, the aim of this paper is to examine how travel behaviour data, observed traffic demand, infrastructure conditions and public transport user perceptions can be integrated into a common evidence base for public transport planning, drawing on a transport study completed for the City of Opatija in May 2025 [6]. Rather than evaluating a proposed public transport network, the paper focuses on the complementary contribution of these sources and their joint interpretation.

Accordingly, the study addresses the following research question: How can the integration of travel behaviour, observed traffic demand, infrastructure conditions and public transport user perceptions support evidence-based urban public transport planning?

2 MATERIALS AND METHODS

The research was conducted as a case study of the City of Opatija, a coastal tourist destination with a spatially constrained urban structure and a road network concentrated along a few major corridors. All data were compiled within a transport study completed for the City in May 2025 [6].

The travel behaviour data come from the survey *Travel Habits and Mobility of the Citizens of Opatija*, conducted by the City of Opatija and the Promocija Plus agency using computer-assisted telephone interviewing (CATI) between 24 and 30 January 2025 [7]. A random sample of 500 residents aged over 15 was drawn from a database of private fixed and mobile telephone numbers, so residents without a telephone line could not be included; the survey report does not state a response rate or weighting. The realised sample comprised 31% men and 69% women; respondents aged over 64 formed the largest age group, 55% were employed and 58% lived in the settlement of Opatija [7]. The survey results were therefore used as unweighted descriptive evidence on travel patterns, mode use, public transport perceptions and stated preferences, rather than as population estimates.

Automatic traffic count data comprised average summer daily traffic (ASDT, June–August) for 2017–2024 at three counting sites on the principal corridors serving Opatija: the A8 motorway at Vranja-east, the DC8 state road at Pavlovac and the DC66 state road at Opatija-south. The data originate from the continuous counting programme of Hrvatske ceste d.o.o. and are published annually [8]; they were used to identify long-term trends and seasonal demand [6].

Manual counts were carried out in spring 2025 at seven intersections selected in the transport study as characteristic locations of the urban road network: four on the principal urban corridors, Nova cesta and Ulica Maršala Tita, and three elsewhere in the network (**Table 2**). Traffic was recorded from 06:00 to 09:00 and from 13:00 to 16:00 by direction in 15-minute intervals, classified into passenger cars, light and heavy goods vehicles, buses and motorcycles, and expressed in passenger car units (PCU). Hourly totals were used to identify peak hours and the most heavily loaded approaches [6].

The infrastructure assessment was a qualitative expert assessment based on field observation with photographic documentation, the official road classification and the City's WebGIS data [6]. Road infrastructure was described by road category, carriageway configuration and the availability of alternative routes; pedestrian infrastructure by the continuity of pavements and the equipment of pedestrian crossings and of vertical connections between the upper and lower parts of the city (steep streets and stairways, handrails, lighting, surfaces for persons with reduced mobility); and cycling infrastructure by the presence of cycle paths or lanes, marked routes, bicycle parking and bicycle sharing. The role of each source is summarised in **Table 1**.

Table 1. Multi-source evidence framework used in the study.

Data source	Information provided	Planning dimension	Role in integrated analysis
Travel behaviour survey results	Travel patterns, mode use, preferences and perceptions (CATI survey, January 2025; n = 500 residents aged over 15)	Mobility needs and behaviour	Explains user-related factors underlying mobility patterns
Automatic traffic counts	ASDT, 2017–2024, at three counting sites (A8, DC8, DC66)	Long-term and seasonal traffic demand	Identifies traffic trends and seasonal variation
Manual traffic counts	Directional and vehicle-specific flows at seven intersections, 06:00–09:00 and 13:00–16:00	Local and peak-period demand	Identifies spatial distribution and critical traffic periods
Infrastructure assessment	Road, pedestrian and cycling network conditions (field observation)	Accessibility and network constraints	Identifies conditions relevant to public transport organisation

Note: ASDT – Average Summer Daily Traffic.

Source: Authors' elaboration based on the City of Opatija Transport Study [6].

The sources were thus treated not as interchangeable measures of mobility but as complementary evidence addressing different planning dimensions, and were integrated at the level of analytical interpretation in four steps (**Figure 1**). First, each source was assigned to the planning dimension it can inform (**Table 1**). Second, a limited set of indicators was extracted from each source: modal split, work-trip destinations, perceived deficiencies and conditional stated use from the survey; ASDT levels and trends from the automatic counts; peak hours, peak-hour volumes and dominant approaches from the manual counts; and the presence or absence of the assessed elements.

Third, indicators from different sources relating to the same planning question were read together, recording whether they confirm, complement or qualify one another. Fourth, each joint interpretation was formulated as a planning requirement rather than as a prediction of behavioural change (**Table 3**).

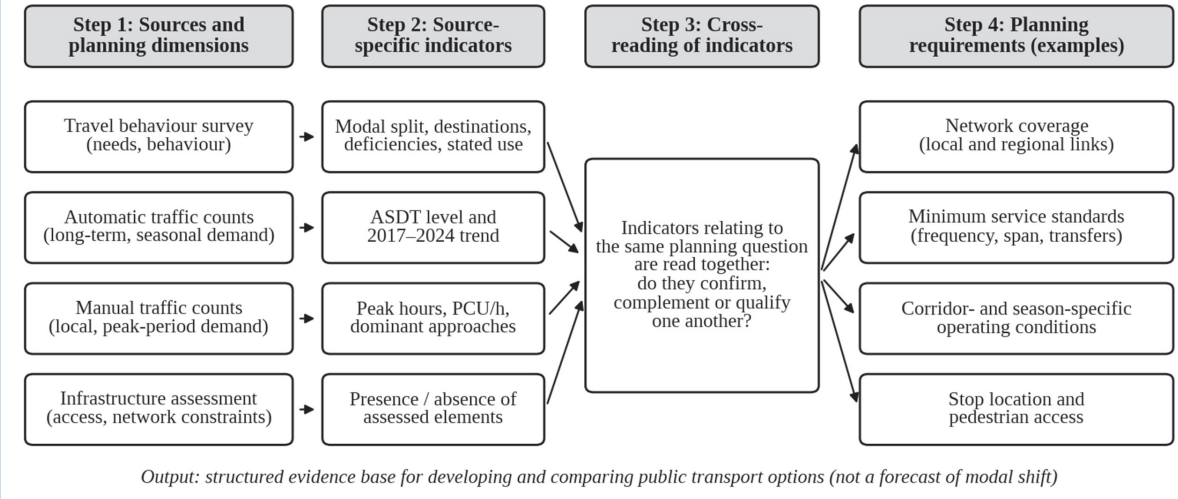


Figure 1. Workflow of the multi-source evidence framework.
Source: Authors' elaboration.

3 RESULTS

3.1 Travel behaviour and public transport needs

The survey results indicate a strong dependence on private cars. Among respondents travelling to work, school or university, 75.1% travelled primarily as car drivers, 10.2% by bus, 7.5% as car passengers and 4.8% on foot, while cycling and other modes accounted for marginal shares [6].

Among respondents reporting a work destination, 53.6% travelled to Opatija and 18.4% to Rijeka, followed by Veprinac (6.5%) and Lovran (4.8%) [6].

Public transport planning should therefore consider connections with surrounding settlements and the regional system, not only movements within Opatija. Despite the dominance of private cars, the survey reveals both dissatisfaction with the existing service and substantial stated willingness to use improved public transport. About one third of current users reported being dissatisfied with the existing system, and almost 29% of respondents did not use it at all. The most frequently identified shortcomings concerned uncoordinated timetables, which cause waiting times when transferring, an insufficient number of lines and departures, and poor connectivity of bus lines [6].

Respondents were then presented with two hypothetical scenarios. In the first, an urban bus service would be affordable and operate at least once per hour from early morning until midnight; under these conditions, 64.3% of respondents stated that they would use public transport as much as or more than the car, or exclusively, and 23% would use public transport only. In the second, an integrated public transport system covering the city, the county and neighbouring counties would offer a single ticket for train, bus and ferry services, harmonised timetables with easy transfers, affordable fares and at least hourly departures from early morning until midnight; here the corresponding share rose to 71.3%, with almost 29% stating that they would exclusively use public transport [6]. The difference between the scenarios suggests that integration with the regional system adds to the perceived attractiveness of public transport, although both figures express stated rather than revealed preferences.

The survey therefore adds a user-oriented dimension that cannot be derived from traffic counts, particularly regarding perceived service deficiencies and the conditions under which public transport use might increase.

3.2 Traffic Demand and Infrastructure Constraints

Between 2017 and 2024, ASDT on the A8 at Vranja-east increased from 13,240 to 15,988 vehicles/day (+20.7%), whereas on the DC8 at Pavlovac it decreased from 9,369 to 8,575 vehicles/day (−8.5%). The highest summer volumes were consistently recorded on the DC66 at Opatija-south (18,786 vehicles/day in 2017 and 18,552 in 2024), which remained the most heavily loaded of the three sections [6]. As **Figure 2** shows, all three sections recorded a marked decrease in 2020, followed by a recovery on the A8 and DC66, while summer traffic on the DC8 has remained below its 2019 level. The DC66 corridor through Opatija thus carries summer volumes above 17,700 vehicles/day in every year except 2020, on a two-lane road passing through the urban area.

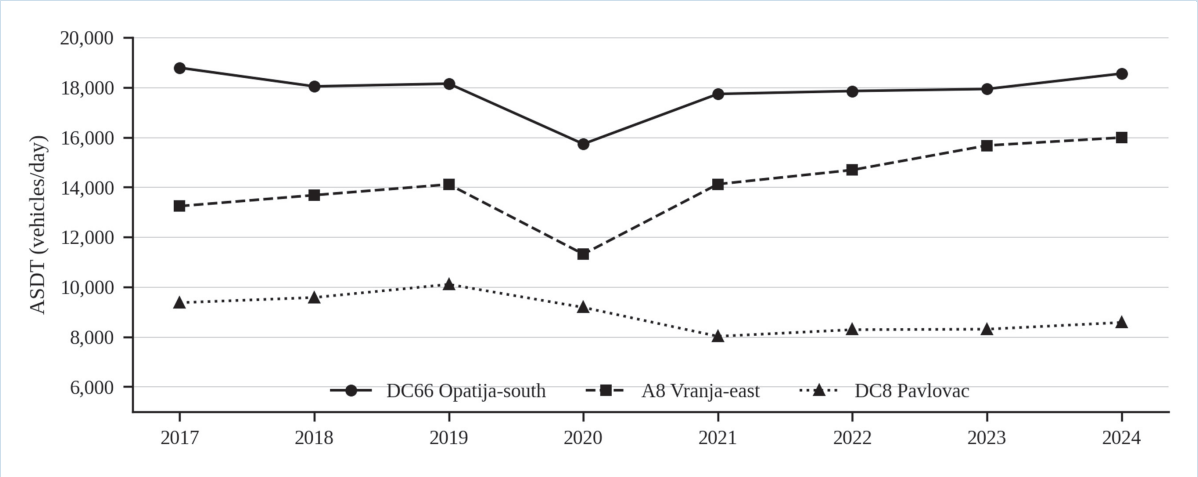


Figure 2. Average summer daily traffic (ASDT) at the three automatic counting sites, 2017–2024.
Source: Authors' elaboration based on [6, 8].

The manual counts show that peak-period demand is unevenly distributed across the urban network (**Table 2**). The highest peak-hour volumes were recorded at the three intersections on Nova cesta, with 1,326–1,620 PCU in the morning and 1,266–1,582 PCU in the afternoon peak hour. The intersection of Ulica Borisa Zdrinšćaka, Primorska ulica and Ulica Viktora Cara Emina also exceeded 1,000 PCU in both peak hours, whereas the remaining three intersections carried between 363 and 712 PCU in the peak hour. The morning peak hour occurred between 07:00 and 08:00 at five of the seven intersections, and the afternoon peak hour between 15:00 and 16:00 at six. At most intersections, flows were concentrated on two dominant approaches, and passenger cars formed the large majority of recorded vehicles [6].

The infrastructure assessment identifies additional constraints. Pedestrian infrastructure is relatively well developed along the main roads and the coast, but the steep topography creates discontinuities between the upper and lower parts of the city; some connecting streets and stairways lack adequate pedestrian facilities and accessibility elements, and narrow roads limit pedestrian space at certain locations. No separated cycle paths or lanes exist on the main roads, and cyclists share narrow carriageways with high seasonal traffic [6].

Table 2. Peak-hour traffic volumes at the seven manually counted intersections.

No.	Intersection	Morning peak hour, PCU (time)	Afternoon peak hour, PCU (time)
1	Trg Vladimira Gortana – Ulica Maršala Tita	712 (08:00–09:00)	659 (15:00–16:00)
2	Varljenska cesta – Nova cesta – Ulica Matka Laginje	1,620 (07:00–08:00)	1,565 (15:00–16:00)
3	Nova cesta – Ulica Dr. Ivana Pošćića – Matuljska cesta	1,468 (07:00–08:00)	1,582 (15:00–16:00)
4	Nova cesta – Ulica Maršala Tita	1,326 (07:00–08:00)	1,266 (15:00–16:00)
5	Pobarska cesta – Put za Matulji	505 (08:00–09:00)	590 (15:00–16:00)
6	Ulica Ivana Matetića Ronjgova – Ulica Črnikovice	363 (07:00–08:00)	415 (14:00–15:00)
7	Ulica Borisa Zdrinšćaka – Primorska ulica – Ulica Viktora Cara Emina	1,095 (07:00–08:00)	1,078 (15:00–16:00)

Note: PCU – passenger car units. Counting periods 06:00–09:00 and 13:00–16:00; peak hour = hour with the highest PCU value within each period.

Source: Authors' elaboration based on the City of Opatija Transport Study [6].

3.3 Integrated evidence for public transport planning

Table 3 reports the outputs of the third and fourth steps of the procedure: the evidence read together, its joint interpretation and the resulting planning implication.

Table 3. Integrated evidence and implications for public transport planning.

Integrated evidence	Joint interpretation	Planning implication
High car dependence (75.1% of commuters travel as car drivers) + stated willingness to use improved public transport (64.3–71.3%)	Current car use does not necessarily indicate a lack of potential demand for public transport	Service quality, frequency and connectivity should be considered alongside the current modal split
High summer corridor demand (ASDT above 18,500 vehicles/day on DC66) + peak-hour concentration on Nova cesta (up to 1,620 PCU/h)	Road-network pressure occurs at both corridor and local levels	Public transport planning should account for seasonal and spatial variations in demand
Public transport needs + steep topography and poorly equipped vertical pedestrian links	Potential public transport use depends on both service provision and access conditions	Public transport accessibility should be considered together with pedestrian connections and topography
Seasonal traffic pressure + constrained road space + no separated cycling infrastructure	The physical context constrains the implementation of space-intensive mobility measures	Public transport should be considered as part of an integrated sustainable mobility approach

Source: Authors' elaboration based on the City of Opatija Transport Study [6].

The principal output is therefore not a specific public transport solution but a set of planning requirements, each traceable to specific evidence, against which network and service options can be developed and assessed.

4 DISCUSSION

The data sources differ in analytical purpose, spatial and temporal coverage and type of information, and their joint interpretation offers a broader basis for planning than any source alone, consistent with research on the complementary use of mobility datasets [1-4].

In Opatija, the predominance of car use does not by itself show whether current behaviour reflects preferences, limitations of the available services or characteristics of the urban environment. Read together with perceived service deficiencies and stated willingness to use improved public transport, the modal structure acquires a broader planning meaning. The higher stated willingness under the integrated regional scenario is consistent with the share of work trips directed to Rijeka and indicates that local and regional services should be planned together. Stated willingness should not, however, be interpreted as a forecast of modal shift; it indicates the conditions under which public transport could become more attractive.

Similarly, seasonal and spatial variations in road demand and topographical and road-space constraints define the conditions within which services would operate and be accessed, which is particularly relevant in tourist destinations with strongly seasonal demand [9, 10].

The contribution of the study lies between two established practices. In conventional transport studies, such as the study on which this paper draws [6], surveys, counts and infrastructure assessments are reported side by side, and their combination is left to implicit expert judgement. Data-fusion approaches technically combine heterogeneous datasets, for example travel surveys with mobile device or mobile phone data [2-4], but require data with sufficient spatial, temporal and statistical overlap, which is rarely available in small and medium-sized cities. The proposed framework retains the distinct role of each source but makes the integration explicit and repeatable (**Figure 1**, **Table 3**). Its novelty therefore lies not in a new statistical technique, but in a transparent procedure that allows heterogeneous, non-aligned and pre-existing data to be used jointly and makes planning implications traceable to specific evidence.

In practice, the framework can inform specific planning decisions. The share of work trips to Rijeka (18.4%) indicates that network design should cover regional connections, not only intra-urban lines.

The service attributes associated with stated willingness (at least hourly departures, operation from early morning until midnight, affordable fares and, at the regional level, integrated ticketing and harmonised timetables) can serve as minimum service standards for comparing network and timetable options. Summer corridor demand combined with peak-hour concentration on Nova cesta identifies where buses would share the most heavily loaded road space, and thus where seasonal timetables and bus priority should be examined. Finally, steep topography and poorly equipped vertical pedestrian links indicate that stop locations and pedestrian access should be planned together.

The evidence base was subsequently used by the authors' team in a follow-up study for the City of Opatija [11], which developed line-network variants organised around an integrated clock-face timetable, with the Opatija Slatina bus station as the central node for coordinated transfers, including to the regional line serving Rijeka and Lovran. Evaluating these variants is beyond the scope of this paper.

The study has several limitations. The datasets differ in spatial and temporal coverage and were not collected within a single research design. The survey provides self-reported information and stated preferences, and its unweighted sample over-represents women and older residents, so survey shares should be read as indicative. Traffic counts represent observed vehicle flows but do not identify travellers' motivations or characteristics, nor distinguish residents from tourists. The manual counts cover short periods in spring 2025, for which the exact dates are not documented, and therefore

describe off-season conditions. These differences limit direct correspondence between the sources, a recognised challenge in multi-source mobility analysis [1-4].

Accordingly, the integrated evidence identifies planning requirements but does not demonstrate that a particular network or service intervention would change travel behaviour or traffic demand; this would require evaluation of implemented measures using temporally aligned before-and-after data. The approach is therefore a planning-support framework rather than a predictive or causal model.

The framework may be transferable to other tourist-oriented and spatially constrained urban areas [9, 10]. Its minimum requirements are modest: a travel behaviour survey that includes questions on perceived service deficiencies and conditional use, long-term corridor counts that distinguish annual from summer traffic, short-term intersection counts at the principal corridors, and a structured assessment of pedestrian and cycling access. The procedure does not require these sources to be temporally aligned, but it does require that each indicator is reported with its source, period and coverage, so that the planning requirements derived from it can be traced and later revisited. The relevance of individual sources will nevertheless depend on local mobility patterns and on the data available.

5 CONCLUSION

This study examined how complementary transport evidence can be integrated to support public transport planning in a tourist-oriented, spatially constrained city. In Opatija, reading travel behaviour and user perceptions together with observed traffic demand and infrastructure conditions showed that high car dependence coexists with conditional willingness to use improved public transport, and that potential public transport use depends on access conditions shaped by topography.

The main contribution is a multi-source evidence framework, operationalised as a four-step procedure, in which heterogeneous data retain their distinct roles and are integrated at the level of planning interpretation. Without statistical fusion and without predicting the effects of interventions, it translates available evidence into explicit planning requirements, such as regional network coverage, minimum service standards, corridor- and season-specific operating conditions and stop access.

Although developed in the specific context of Opatija, the framework may be applied to other tourist-oriented and spatially constrained urban areas where public transport planning must reconcile user needs, seasonal traffic demand and infrastructure limitations. Future research should include testing in other cities and extension through temporally aligned data collection and the evaluation of implemented public transport measures, enabling stated preferences, observed travel behaviour and changes in traffic demand to be compared over time.

Use of AI tools: AI-assisted tools were used to support structural organisation, language refinement, and consistency checking. All analytical decisions, reported results, interpretations, and conclusions were reviewed by the authors, who remain fully responsible for the content.

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VI. Urban Mobility, Road Safety and Transport Behaviour

Video-Based Assessment of Spatial Driver Behaviour in a Speed Enforcement Zone: A Case Study from Northern Croatia

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ABSTRACT

This study examines spatial variations in vehicle speed and total acceleration magnitude near a fixed speed-enforcement camera on the rural D2 state road in Zamlaka, northern Croatia. UAV recordings were processed using DataFromSky to obtain matched observations for 153 passenger-vehicle passages travelling through the entry, camera-adjacent, and exit zones in one direction. Mean speeds were 58.90, 66.25, and 59.34 km/h, and mean total acceleration magnitude was highest in the camera-adjacent zone; both outcomes differed significantly across zones (Friedman $\chi^2(2) = 34.92$ and 65.41, respectively, $p < 0.001$), with pairwise comparisons showing the camera-adjacent zone significantly elevated relative to both neighbouring zones. After excluding passages with mean speeds below 40 km/h in any zone ($n = 124$), the camera-adjacent speed peak remained, and the acceleration-magnitude pattern proved more robust to filtering than the pairwise speed pattern. Based on zone-mean speeds, 22.2%, 32.7%, and 92.2% of matched passages exceeded the applicable posted limits in the entry, camera-adjacent, and exit zones, respectively, reflecting the downstream reduction from 70 to 50 km/h. The findings reveal a non-uniform spatial speed profile characterised by higher speeds near the camera followed by a downstream reduction, rather than progressive slowing when approaching the enforcement site. The study demonstrates the value of UAV-derived matched observations while highlighting the importance of speed-limit transitions and site geometry when interpreting local kinematic patterns.

Keywords: unmanned aerial vehicles; vehicle trajectories; speed adaptation; speed enforcement

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1 INTRODUCTION

Excessive speed remains an important road-safety problem because it increases both crash risk and injury severity. Fixed speed cameras are therefore widely used to support speed-limit compliance and reduce speed-related crashes. A recent systematic review reported generally favourable effects that depend on road type, geometry, posted speed limit, camera visibility, measurement distance, and evaluation design [1], and site-specific studies have likewise reported favourable outcomes [2-4]. However, aggregate crash indicators and measurements collected at isolated points do not reveal how vehicle-motion patterns vary over short distances near an enforcement location.

This spatial dimension matters because responses to a fixed camera may be localised rather than sustained along the road. De Pauw et al. [5] identified abrupt speed changes near fixed cameras, Fu and Liu [6] showed that upstream and downstream halo effects may differ in spatial extent, and a comparison of upstream, camera-adjacent, and downstream observations identified distinct speed and manoeuvring patterns [7]. These findings indicate that single-point measurements may conceal short-range changes before, adjacent to, and after a camera. Video-based traffic monitoring allows such variation to be examined using spatially distributed vehicle-trajectory data.

Computer-vision methods can detect and track individual vehicles [8], classify microscopic driving behaviour [9], and combine speed and acceleration variables in behavioural assessment [10].

UAV monitoring also enables extended road sections to be observed without installing multiple roadside detectors [11], and appropriately processed drone recordings can provide trajectory data suitable for traffic-flow and road-safety analyses [12].

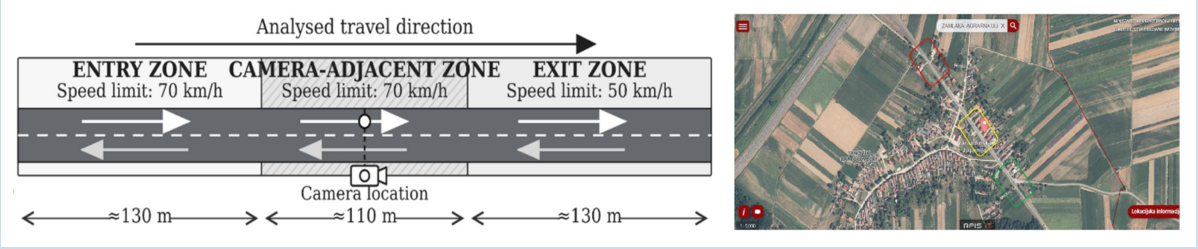
Nevertheless, limited attention has been given to matched, passage-level comparisons of consecutive observation zones around a fixed speed camera, particularly on rural roads and with an explicit assessment of sensitivity to sample definition. This study addresses that gap through a case study on the D2 state road in Zamlaka, northern Croatia, analysing 153 matched passenger-vehicle passages across three consecutive zones (entry, camera-adjacent, exit). RQ1 asks how vehicle-level mean speed differs across the zones; RQ2 asks how mean total acceleration magnitude differs; RQ3 assesses whether these spatial patterns remain consistent between the complete sample and a filtered sample excluding passages with a mean speed below 40 km/h in any zone. Based on evidence that kinematic patterns near fixed cameras may vary spatially, H1 states that mean speed differs among the three zones and H2 that mean total acceleration magnitude differs among them. The study contributes a matched, repeated-measures assessment combining speed, acceleration magnitude, effect sizes, and sensitivity analysis to characterise short-range spatial variation; its purpose is to identify spatial associations, not an independent causal camera effect, which cannot be inferred given the exit-zone speed-limit change and the absence of a control location.

2 MATERIALS AND METHODS

2.1 Study area and observation zones

The study was conducted on Agrarna Street, a section of the D2 state road in the settlement of Zamlaka in northern Croatia. The approximately 650 m long street passes through a predominantly rural area and consists of an approximately 6 m-wide two-way carriageway. Three consecutive analysis zones were defined within the observed road section: an entry zone of approximately 130 m, a camera-adjacent zone of approximately 110 m near the roadside speed-enforcement camera located at house number 22, and an exit zone of approximately 130 m. The posted speed limit was 70 km/h in the entry and camera-adjacent zones and 50 km/h in the exit zone. The speed-enforcement camera is mounted on a roadside utility pole and was operational during the recording period; no advance warning

signage was present in either direction of approach, and the 50 km/h sign is located just downstream of the camera, at the start of the exit zone. The approach to the entry zone passes through an unpopulated, predominantly agricultural stretch of road with no intersections or driveways, which may contribute to the comparatively high variability in entry-zone speeds. The camera enforces both directions of travel on this section, confirming that the analysed direction is subject to active enforcement. Only vehicles travelling from the entry zone through the camera-adjacent zone towards the exit zone were analysed. **Figure 1** shows the zones, camera location, and analysed direction schematically and in an aerial view.



(a) (b)

Figure 1. (a) Schematic representation of the observation zones, segment lengths, camera location, and posted speed limits (not to scale). (b) Corresponding aerial view of the study site, with the entry zone (green), camera-adjacent zone (yellow), and exit zone (red) delineated.

Source: (a) Authors' own elaboration based on the study data. (b) Adapted by the authors from the Spatial Planning Information System (ISPU), Croatian Ministry of Physical Planning, Construction and State Assets.

2.2 Video Data Acquisition and Trajectory Extraction

Traffic movements were recorded from an aerial perspective in June 2025, starting at 15:00. Three UAVs (DJI Mavic 2 Pro, DJI Air 2S, and DJI Mavic 3 Pro) were deployed simultaneously, with each UAV covering one of the three consecutive observation zones. The recording session lasted one hour and captured vehicles passing successively through the entry, camera-adjacent, and exit zones. Because each zone was recorded with a different UAV model and flight altitude, camera settings, and calibration data were not retained for any of the three recordings, systematic differences in image scale, resolution, or tracking quality between devices cannot be ruled out as a contributing factor to the observed zone differences; this limitation is discussed further in Section 4.

Each recording was processed separately using DataFromSky software, which applies computer-vision and artificial-intelligence procedures to detect and track traffic participants and generate trajectory-related and kinematic data [13]. Each zone produced a separate data table with independently assigned Track IDs. Passages were matched across the three concurrent recordings by tracing their successive movement through the zones, and a common study ID (1-153) was assigned to each matched passage and used to merge the three tables. Only passenger-vehicle passages that were successfully matched and had a complete set of measurements in all three zones were retained in the analytical sample; the total number of vehicles recorded before matching, the matching success rate, and the exact recording date and weekday were not retained in the available records.

For each matched passage and zone, the exported data contained minimum, mean, and maximum speed and total acceleration, travelled distance, and observation time; the analytical database contained only trajectory identifiers and kinematic variables, with no information enabling driver identification.

2.3 Data preparation and outcome measures

The merged dataset was organised in a repeated-measures format, with one row corresponding to one matched passenger-vehicle passage and separate columns containing the measurements obtained in the three observation zones. The complete analytical sample comprised 153 matched passages with complete data for all variables included in the analysis. Because complete measurements across all three zones constituted an inclusion criterion, no missing-value imputation was performed. The principal outcome variables were zone-level mean speed, expressed in km/h, and the zone-level mean of the DataFromSky variable labelled total acceleration, expressed in m/s^2. Mean values were selected because they summarised the observed motion throughout each spatial zone rather than at a single location or time point. The variable corresponds to the "Total acceleration" field exported directly by DataFromSky, which represents the magnitude of the acceleration vector combining longitudinal and lateral components rather than a purely longitudinal measure; DataFromSky did not export a decomposed longitudinal-only acceleration field for this recording, so a direct comparison between the two was not possible. Total acceleration was exported as a non-negative scalar, an unsigned indicator of kinematic-change magnitude: higher values indicate more pronounced motion changes but do not distinguish acceleration from deceleration or braking, nor changes in heading (e.g., turning). Accordingly, no directional interpretation concerning acceleration, deceleration, or braking was derived from this measure, and given that lateral components may contribute to the observed magnitude, the acceleration-based findings (H2) are interpreted as exploratory rather than confirmatory. The complete sample was retained for the primary analysis to preserve the full range of vehicle passages observed during the recording period. As a sensitivity analysis, a secondary filtered sample was constructed by excluding passages for which the mean speed was below 40 km/h in at least one observation zone.

This operational threshold, below the lowest posted limit at the site, was used only to test whether unusually slow passages influenced the findings, not as a legal or behavioural cut-off.

A cause-based, headway-derived free-flow exclusion was not implemented because DataFromSky did not export inter-vehicle spacing data, so this speed-based threshold was used as a pragmatic substitute. Application of this criterion removed 29 passages and resulted in a filtered sample of 124 matched passages. The filtered sample was used only to assess the robustness of the findings obtained from the complete sample.

For descriptive comparisons, a passage was classified as having a mean speed above the posted limit when its zone-level mean speed exceeded 70 km/h (entry/camera-adjacent) or 50 km/h (exit); these classifications were not interpreted as formally established speeding offences.

2.4 Statistical analysis

Descriptive statistics (mean, SD, median, IQR, min, max) were calculated separately for zone-level mean speed and mean total acceleration magnitude in each zone, along with the proportion of passages exceeding the posted limit; no inferential comparison of these proportions was performed. The normality of each zone-specific outcome distribution was assessed using the Shapiro-Wilk test. Because the distributions departed from normality and the observations were matched across the three zones, spatial differences were examined using nonparametric procedures for related samples. The Friedman test was applied separately to vehicle-level mean speed and mean total acceleration magnitude to test for overall differences among the entry, camera-adjacent, and exit zones. Kendall's coefficient of concordance (W) was reported as the effect-size measure for each Friedman test. When a Friedman test was significant, two-sided Wilcoxon signed-rank tests compared the entry-camera, camera-exit, and entry-exit zone pairs, with Holm-adjusted p-values and matched-pairs rank-biserial correlation as the effect-size measure (defined as second-named zone minus first-named zone, so positive values indicate higher values in the second-named zone). The Friedman test for mean speed served as the primary test of H1, and the corresponding test for total acceleration magnitude as the

primary test of H2; pairwise comparisons identified which zones differed. To address RQ3, the same descriptive and inferential procedures were repeated for the filtered sample, and robustness was assessed by comparing zone ordering and the direction, magnitude, and significance of effects across the two (non-independent, nested) samples.

Statistical significance was evaluated at $\alpha = 0.05$. The analyses were conducted in Python 3.12 using pandas 2.2.3 and SciPy 1.17.0.

3 RESULTS

3.1 Descriptive statistics and mean speed relative to posted limits

Table 1 presents the descriptive statistics for mean speed and mean total acceleration magnitude across the three zones. Mean speed increased from 58.90 km/h (entry) to 66.25 km/h (camera-adjacent) before decreasing to 59.34 km/h (exit); medians followed the same pattern (62.90, 65.14, 58.40 km/h). The 85th-percentile speed (V85), commonly used in traffic engineering to characterise the upper tail of the speed distribution, followed the same spatial pattern: 72.84 km/h in the entry zone, 79.02 km/h in the camera-adjacent zone, and 65.94 km/h in the exit zone, indicating that even the faster-driving segment of the sample substantially exceeded the posted limit in the camera-adjacent zone. Speed variability was greatest in the entry zone, where the standard deviation reached 17.30 km/h. Mean total acceleration magnitude was also highest in the camera-adjacent zone, reaching 2.45 m/s². The corresponding values were 1.93 m/s² in the entry zone and 1.42 m/s² in the exit zone.

Table 1. Descriptive statistics for the complete sample (n = 153)

Outcome	Zone	Mean ± SD	Median [IQR]	Min-max	Mean speed above posted limit, n (%)
Mean speed (km/h)	Entry	58.90 ± 17.30	62.90 [53.36-69.80]	0.94-109.38	34 (22.2)
	Camera-adjacent	66.25 ± 10.03	65.14 [58.31-72.44]	42.12-91.16	50 (32.7)
	Exit	59.34 ± 9.04	58.40 [55.52-63.63]	19.23-99.98	141 (92.2)
Mean total acceleration magnitude (m/s²)	Entry	1.93 ± 1.06	1.74 [1.27-2.38]	0.55-7.26	—
	Camera-adjacent	2.45 ± 1.32	2.40 [1.31-3.21]	0.67-7.69	—
	Exit	1.42 ± 0.77	1.17 [0.94-1.77]	0.45-5.67	—

Note: Classification relative to the posted limit was based on the mean zone speed. The posted speed limits were 70 km/h in the entry and camera-adjacent zones and 50 km/h in the exit zone.

Source: Authors' calculations based on the analysed vehicle trajectory data.

Based on mean zone speed, 34 matched passages (22.2%) recorded a value above the posted limit in the entry zone, while 50 matched passages (32.7%) did so in the camera-adjacent zone. In the exit zone, where the posted limit was 50 km/h, 141 matched passages (92.2%) had a mean zone speed above the applicable limit.

3.2 Spatial differences in speed and total acceleration magnitude

The Shapiro–Wilk tests indicated statistically significant departures from normality for all zone-specific distributions of speed and total acceleration magnitude ($p < 0.05$).

Consequently, spatial differences were evaluated using non-parametric repeated-measures tests. The complete results of the Friedman tests and post hoc pairwise comparisons are presented in **Table 2**.

The Friedman test identified a statistically significant difference in mean speed among the three observation zones (**Table 2**). Pairwise comparisons showed that mean speed in the camera-adjacent zone was significantly higher than in both the entry and exit zones, with no significant difference detected between the entry and exit zones in the complete sample.

Table 2. Friedman tests and post hoc pairwise comparisons for the complete sample

Outcome	Friedman test	Kendall's W	Pairwise comparison	Wilcoxon T	Holm-adjusted p	r_{rb}
Mean speed	$\chi^2(2) = 34.92$, $p < 0.001$	0.114	Entry-Camera	3272.0	< 0.001	0.445
			Camera-Exit	2126.0	< 0.001	-0.639
			Entry-Exit	5616.0	0.617	-0.047
Mean total acceleration magnitude	$\chi^2(2) = 65.41$, $p < 0.001$	0.214	Entry-Camera	3199.5	< 0.001	0.457
			Camera-Exit	1774.0	< 0.001	-0.699
			Entry-Exit	2814.0	< 0.001	-0.522

Note: Pairwise comparisons were conducted using Wilcoxon signed-rank tests. The resulting p-values were adjusted using the Holm procedure. Rank-biserial correlations were calculated from paired differences defined as the second-named zone minus the first-named zone; positive values therefore indicate higher values in the second-named zone.

Source: Authors' calculations based on the analysed vehicle trajectory data.

A statistically significant spatial difference was also identified for mean total acceleration magnitude (**Table 2**), with all three pairwise comparisons significant; magnitude was highest in the camera-adjacent zone, followed by the entry zone, with the lowest values in the exit zone.

3.3 Sensitivity analysis and hypothesis assessment

The sensitivity analysis excluded 29 passages whose mean speed was below 40 km/h in at least one observation zone, resulting in a filtered sample of 124 matched passages.

Mean speeds in the filtered sample were 64.62 ± 10.30 km/h in the entry zone, 67.52 ± 9.73 km/h in the camera-adjacent zone, and 61.07 ± 7.76 km/h in the exit zone. The corresponding V85 speeds were 73.50, 79.37, and 66.70 km/h, respectively, consistent with the complete-sample values. The camera-adjacent zone therefore retained the highest mean speed, although the relative ordering of the entry and exit zones changed. The corresponding mean total acceleration magnitudes were 2.00 ± 1.06, 2.56 ± 1.35, and 1.49 ± 0.82 m/s², preserving the complete-sample ordering. Mean speed continued to differ significantly among the three zones, $\chi^2(2) = 32.63$, $p < 0.001$, Kendall's $W = 0.132$. Mean speed was significantly higher in the camera-adjacent zone than in the entry zone (Holm-adjusted $p = 0.040$, $r_{rb} = 0.213$) and the exit zone ($p < 0.001$, $r_{rb} = -0.658$). Unlike the complete-sample result, the filtered sample also showed a significant difference between the entry and exit zones ($p < 0.001$, $r_{rb} = -0.375$), with higher mean speed in the entry zone. The proportions of matched passages with mean zone speeds above the applicable limits were 25.8%, 36.3%, and 97.6%, respectively.

Mean total acceleration magnitude also continued to differ significantly among the zones, $\chi^2(2) = 51.73$, $p < 0.001$, Kendall's $W = 0.209$.

All pairwise differences remained significant after Holm correction ($p < 0.001$; rrb = 0.475 entry-camera, -0.682 camera-exit, -0.487 entry-exit). The omnibus results support H1 and H2 in both samples. Regarding RQ3, the camera-adjacent speed peak persisted, but the pairwise speed pattern was only partially consistent (the entry-exit conclusion changed after filtering), while the acceleration-magnitude pattern was more consistent across samples.

4 DISCUSSION

The significant omnibus tests showed that vehicle-level mean speed and mean total acceleration magnitude varied across the three zones, supporting H1 and H2, though Kendall's W values (0.114 for speed, 0.214 for acceleration magnitude) indicate only modest, non-uniform spatial effects: both outcomes were highest in the camera-adjacent zone, a localised concentration of kinematic variation rather than uniform slowing. H1 and H2 were deliberately formulated as non-directional because a directional hypothesis (e.g., lower speeds at the camera) would presuppose the simple monotonic slowing pattern that this non-uniform result does not support; future studies with a priori directional evidence could adopt one-sided tests to increase power.

Previous systematic reviews and site-based evaluations have generally reported favourable average effects of fixed speed cameras on speed, compliance, or crash occurrence [1-4], although outcomes vary with road characteristics and evaluation design. De Pauw et al. [5] identified abrupt slowing near fixed cameras followed by renewed acceleration, Fu and Liu [6] showed that upstream and downstream halo effects may differ in spatial extent, and Sheykhfard et al. [7] reported distinct behavioural patterns upstream, adjacent to, and downstream of camera locations. The camera-adjacent speed peak observed in the present study differs from the simple slowing pattern reported in some previous studies but supports the broader conclusion that speed profiles around fixed cameras may be localised, heterogeneous, and spatially asymmetric.

Although mean speed decreased in the exit zone relative to the camera-adjacent zone, 92.2% of matched passages still had a mean exit-zone speed above the applicable 50 km/h limit, so the downstream reduction did not bring most passages below the posted limit. However, this finding does not establish either the effectiveness or ineffectiveness of the camera because the observed pattern may reflect the combined influence of the enforcement location, speed-limit transition, road geometry, signage, and other characteristics of the road environment.

A follow-up site assessment should therefore examine the 50 km/h sign's visibility and placement, the distance available for speed adjustment, local access movements, and road geometry before any specific measure is proposed. Because the 40 km/h threshold used in the sensitivity analysis was an operational filtering criterion rather than an established behavioural cut-off, and the acceleration-magnitude pattern proved more robust to this filtering than the pairwise speed pattern, the complete sample remains the primary basis for interpretation.

The scientific contribution of this study lies in matching passenger-vehicle passages across three consecutive road segments and analysing their spatial kinematic patterns using repeated-measures statistics, effect sizes, and sensitivity analysis; recording the three zones simultaneously let each matched passage serve as its own reference, reducing between-passage differences that could obscure short-range spatial variation. Unlike isolated spot-speed measurements, this approach characterises kinematic variation across an extended enforcement corridor, illustrating the applicability of UAV-derived trajectory data to local road-safety assessment [11], [12]. However, zone-level summaries compress the underlying time series and cannot identify the exact position or moment at which a change in vehicle motion occurred. This limitation is particularly relevant for comparison with De Pauw et al. [5], who used continuous trajectory data to identify abrupt, spatially localised speed changes near fixed cameras; the zone-mean approach used here cannot distinguish

whether slowing and re-acceleration occur within, rather than across, the 110 m camera-adjacent zone. The findings are limited by the single rural location, one analysed travel direction, a single one-hour afternoon observation period in June 2025, and a sample of 153 matched passenger-vehicle passages. The very low zone-minimum speeds in **Table 1** (e.g., 0.94 km/h in the entry zone) likely reflect stopping, turning, or tracking artefacts rather than typical driving behaviour; this is why zone-level means, not minima, were used as the outcome variable, although the exact cause of these extreme values could not be verified from the exported data. As noted in Section 2.2, each zone was recorded with a different, uncalibrated UAV model, and weather conditions, video settings, flight altitude, and DataFromSky frame-rate and smoothing parameters were unavailable; device differences therefore cannot be excluded as a contributing factor, particularly for the acceleration-magnitude results. The transition from a 70 to a 50 km/h speed limit represents a structural confounding factor, while the absence of a control site and before-installation observations prevents the independent effect of the camera from being estimated. No crash data were analysed, and the trajectory-derived measurements were not independently validated against radar or lidar. The zone-level aggregates available for this study did not support finer-grained analysis such as speed-distance profiles in short spatial bins along the corridor, which would show more precisely where slowing or acceleration occurs; future research should construct such profiles from continuous trajectory data, include matched camera and non-camera sites across multiple dates, validate measurements against independent sensors, retain signed acceleration data, and apply predefined trajectory-quality and headway-based exclusion criteria to better isolate the influences of enforcement, speed-limit transition, road design, and traffic composition.

5 CONCLUSION

This study examined spatial variations in vehicle-level mean speed and mean total acceleration magnitude across the entry, camera-adjacent, and exit zones around a fixed speed camera on a rural D2 state road section in Zamlaka. Both outcomes differed significantly among the zones in both samples, supporting H1 and H2. The camera-adjacent zone recorded the highest mean speed and total acceleration magnitude, followed by a reduction in mean speed in the exit zone.

Nevertheless, 92.2% of matched passages had a mean exit-zone speed above the applicable 50 km/h limit, and the acceleration-magnitude pattern was more robust to sample definition than the pairwise speed pattern.

By matching 153 passenger-vehicle passages across three simultaneously recorded consecutive zones, the study illustrates the value of passage-level video analysis for identifying localised kinematic variation that may remain concealed in isolated spot-speed measurements.

The findings support assessing an enforcement location together with the downstream speed-limit transition and the wider road environment rather than treating the camera as an isolated point. However, the results describe spatial associations and do not establish an independent causal effect of the camera. The generalisability of these findings is constrained by the methodological limitations detailed in Section 4, most notably the single study site, the absence of a control location, and incomplete acquisition metadata; addressing these limitations, particularly through independent validation of trajectory measurements, is a priority for future research.

Use of AI tools: AI-assisted tools were used to support statistical coding and verification, structural organisation, and language refinement. All analytical decisions, reported results, interpretations, and conclusions were reviewed by the authors, who remain fully responsible for the content.

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VI. Urban Mobility, Road Safety and Transport Behaviour

Simulation-Based Generation of Traffic-State Datasets for Machine-Learning-Based Decision Support in Centralised Traffic Management

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ABSTRACT

Operational ITS and centralised traffic management increasingly require reliable data driven methods for understanding and managing dynamic traffic conditions in relation to predefined performance indicators. However, the development of data driven decision support models is often limited by the lack of representative datasets, especially for congested, imbalanced, or unusual traffic states, often unachievable in a real world environment. Therefore, this research proposes a simulation based approach for generating structured traffic state datasets for data driven decision support in centralised traffic management. The proposed methodology uses microscopic traffic simulation to generate different assignment scenarios, demand levels, saturation conditions, and route distributions. Simulation outputs are transformed into machine learning ready datasets using selected network state variables, including vehicle counts, average speed, delay, queue length, stopped time, and route impedance. The generated datasets are then used as a basis for regression based traffic state estimation, following the broader role of travel time and traffic state prediction in transport decision support systems. Several machine learning algorithms are subsequently trained using the generated datasets, and their evaluation, based on relevant performance metrics, demonstrates satisfactory predictive performance in estimating network performance and identifying traffic conditions relevant to management interventions. The results indicate that microsimulation provides a controllable and reproducible environment for generating representative traffic states that are difficult to systematically observe in real world conditions. These findings contribute to the integration of traffic simulation, machine learning, and decision support methods within operational ITS and centralised traffic management.

Keywords: decision-support system; traffic network performance; traffic microsimulation; machine learning; centralised traffic management

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1 INTRODUCTION

Digitalisation has substantially increased the volume and diversity of data available for urban traffic monitoring and management. Cities are increasingly deploying sensors, cameras, detectors, connected systems, data repositories, dashboards, and software platforms, to collect and integrate mobility data [1, 2]. However, the mere availability of data does not guarantee improved traffic management decisions. The operational value of data depends on its transformation into actionable information and subsequently into knowledge that supports the interpretation of traffic conditions and the formulation of appropriate responses [2]. In this context, operational intelligence involves extracting and interpreting relevant patterns and dependencies from traffic data to inform network level decision making. This distinction is especially significant when assessing traffic management interventions. Improvement in a predefined key performance indicator (KPI) at a single location does not necessarily translate to network level enhancement, as congestion, delays, or queue formation may shift to downstream or adjacent network elements [3]. Consequently, effective traffic management requires capabilities that extend beyond sensing, data storage, and visualisation, encompassing the identification of spatial and temporal relationships between traffic states and overall network performance [1]. Data fusion and repositories, such as data lakes, establish the foundation for this process, while analytical and decision support methods are essential for extracting operationally relevant knowledge. Machine learning (ML) methods are increasingly used for traffic state estimation, prediction, and anomaly detection because of their ability to identify complex relationships among traffic variables [4]. Their effectiveness, however, depends strongly on the quality and representativeness of the available data. Real world datasets may contain missing observations, uneven spatial and temporal coverage, and predominantly recurrent conditions, while congested, highly saturated, or unusual traffic states may be insufficiently represented [4, 5]. Microscopic traffic simulation provides a complementary environment for addressing this limitation by enabling controlled and reproducible generation of heterogeneous traffic conditions, including states that may be difficult to observe systematically in real-world data [5, 6]. Its value therefore lies not only in generating large numbers of observations, but in creating informative datasets for model development and evaluation. This research develops a simulation based methodology for generating structured traffic state datasets and evaluates their suitability for ML route performance estimation. The main contribution lies in the systematic integration of microscopic simulation and ML within a reproducible framework in which heterogeneous traffic state datasets are generated through controlled variation of demand levels, temporal demand profiles, route distributions, and stochastic conditions, and subsequently used for ML based route performance estimation.

2 BACKGROUND

Reliable information about traffic state is critical for monitoring network performance and supporting operational traffic management. Traffic conditions are commonly characterised by variables such as flow, speed, travel time, delay, and congestion indicators. Conventional sensing systems, however, provide observations only at instrumented locations, which restricts the reconstruction of traffic conditions across the whole network [7]. To resolve these limitations, researchers more frequently integrate heterogeneous data sources through fusion approaches to improve the estimation of traffic variables and network states [8, 9]. ML methods have secured prominence in traffic state analysis because they can identify complex nonlinear relationships among traffic variables. These methods have been applied to congestion prediction, traffic flow forecasting, travel time estimation, and broader traffic management purposes [5, 10, 11]. The effectiveness of ML models depends significantly on the availability and composition of training data. In practice, observed datasets may be partial or insufficiently representative of less frequent operating conditions, complicating model recognition or the estimation of states outside recurrent patterns [9]. Synthetic traffic data offer a complementary solution when suitable observations, like (un)usual traffic conditions are unavailable or difficult to obtain.

Microscopic simulation enables controlled reproduction of traffic conditions while maintaining detailed observability of system states. Empirical and simulated analyses have shown that microscopic models can replicate distinct congested traffic regimes, and recent studies have explicitly combined simulation generated data with ML [12]. For example, Sroczyński and Czyżewski [4] used microscopic simulation to generate data for ML based traffic prediction, while Kim et al. [13] combined pre generated simulation scenarios with ML to enhance real time traffic prediction under conditions insufficiently represented in historical data. Tišljarić et al. [14] used SUMO generated scenarios representing different congestion and bottleneck conditions to evaluate a data driven bottleneck probability estimation method, further showing the potential of microsimulation for systematically generating heterogeneous traffic conditions. These approaches facilitate exploration of operating states poorly represented in historical observations, although the utility and transferability of synthetic data depend on simulation validity and the representativeness of generated scenarios [15]. Taken together, these studies demonstrate the potential of integrating microscopic traffic simulation with data driven modelling. The present research extends this direction by focusing on the systematic construction of heterogeneous traffic state datasets for subsequent ML based route performance estimation.

3 METHODOLOGY

3.1 Framework

The proposed research framework combines microscopic traffic simulation and supervised ML to generate and analyse structured traffic state datasets. The simulation environment is used to systematically reproduce heterogeneous traffic conditions by varying demand levels and route distributions, after which selected traffic variables are extracted and transformed into ML ready datasets. The generated datasets are subsequently used to train and evaluate regression models for estimating route level traffic performance.

3.2 Microscopic simulation environment and reference network

The microscopic simulation environment was developed using Simulation of Urban Mobility (SUMO), version 1.18.0, an open source microscopic traffic simulator. Its functionality can also be extended through application programming interfaces (APIs), particularly the Traffic Control Interface (TraCI), which enables programmatic interaction with a running simulation and provides flexible access to simulation states, traffic variables, and model parameters [16]. Supply, represented by the network infrastructure, and traffic demand, defined by the number and temporal distribution of vehicles entering the network. A modified Braess network (**Figure 1**) was used as the reference network. Its relatively simple topology allows systematic control of traffic demand and route distribution while retaining sufficient interaction between alternative routes to reproduce heterogeneous traffic states and evaluate changes in network performance under controlled conditions [17, 18].

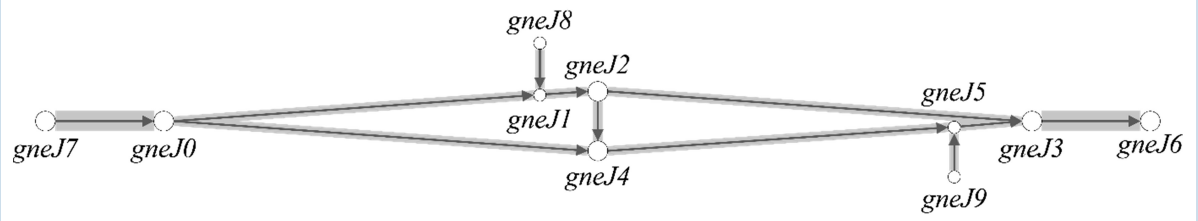


Figure 1. Reference network
Source: Made by authors.

The network consists of 10 nodes and 11 directed links and provides three alternative routes between a common origin and destination. Two internal nodes, *gneJ1* and *gneJ5*, are controlled by fixed time traffic signals, while the remaining internal nodes operate under priority rules.

The network provides three alternative routes with different geometric and operational characteristics. Routes R1 and R3 are comparable in length and free flow performance, whereas R2 provides a faster central alternative but interacts with traffic on both outer routes. The signalised nodes operate with a fixed cycle length of 70 s, consisting of two 29 s green intervals separated by 6 s intergreen intervals.

3.3 Traffic demand and traffic state scenario generation

Traffic demand generation was based on predefined degrees of saturation in order to systematically reproduce traffic conditions around the network capacity threshold. The degree of saturation x was defined as [19]:

$$X = \frac{V}{c} \tag{1}$$

where V is the traffic volume and c is the network capacity. A degree of saturation of X = 1.0 was taken as the reference capacity condition, after which traffic demand was varied in increments of ΔX=0.1. Network capacity was estimated at the critical signal controlled nodes *gneJ1* and *gneJ5*. Saturation flow was derived from vehicle saturation headways h measured using SUMO E1 detectors and verified according to the HCM methodology [19]. Approximately the first four vehicles discharged during each green interval were excluded to account for start up effects. The resulting saturation headway of h=2.509 s corresponded to a saturation flow S=1434.84 veh/h. Considering an effective green time of 26 s, the estimated capacity c was 533 veh/h/lane, corresponding to 1066 veh/h for the two lane entry link. Based on this reference capacity, five demand levels were defined to represent conditions ranging from moderate loading to oversaturation, with X varying from 0.8 to 1.2 (**Table 1**).

Table 1. Determined traffic demand values corresponding to the target degrees of saturation

X	0.8	0.9	1.0	1.1	1.2
Demand, *q* (veh/h)	852	960	1066	1172	1280

Source: Made by authors.

Traffic state variability was further increased by varying the temporal distribution of demand. The 3600 s simulation period was divided into four 900 s intervals. In addition to the uniform demand profile, five alternative temporal profiles were defined by varying the proportion of vehicles entering the network during individual intervals. Combining different demand magnitudes with different temporal profiles enabled the controlled generation of heterogeneous traffic states ranging from moderate loading to highly saturated network conditions.

3.4 Traffic state data extraction and dataset construction

For each traffic demand scenario, route assignment was determined through an iterative simulation based procedure using the SUMO *dualterate.py* script [16]. Route distributions were iteratively updated using the Gawron route choice model and MSA until the prescribed convergence criterion was satisfied. The simulation procedure was considered converged when the relative standard

deviation of the average travel time over the previous ten iterations was equal to or below 0.01; otherwise, the procedure was terminated after a maximum of 300 iterations. The resulting converged assignments were used as representative traffic states for subsequent data extraction. Each scenario was simulated using five random number generator seeds to account for stochastic variability. Randomisation affected vehicle entry times and stochastic vehicle behaviour parameters, while additional variability in successive vehicle arrivals was introduced through randomised flow generation. Combining the predefined demand levels, temporal demand profiles and stochastic realisations resulted in 150 simulation cases, providing a broad set of traffic conditions for dataset generation. Traffic state data were collected through the SUMO Traffic Control Interface (TraCI). The client–server architecture enabled continuous interaction with the running simulation and retrieval of traffic variables at a frequency of 1 Hz [16]. Seven traffic variables were selected to characterise route level traffic conditions and network performance as follows [10, 20, 21]: Number of vehicles on route, N^p (veh); Average route speed, $\bar{v}^p$ (m/s); Departure delay, Dd^p (s); Average route delay, $\bar{D}^p$ (s); Stopped queue length, QL^p (m); Average stopped time, $\bar{s}t^p$ (s); Route impedance, I^p (s). The first six variables provide complementary information on the prevailing traffic conditions, while route impedance provides an aggregated representation of route performance, and was calculated as follows:

$$I^p = \sum_{e \in R_p} I^{e,p} \tag{2}$$

$$I^e = \frac{l^e}{\bar{v}^e} \tag{3}$$

where (l^e) and ($\bar{v}^e$) denote the length and average traffic flow speed of link (e), respectively. Unlike completed vehicle travel time, which becomes available only after a trip has ended, route impedance can be updated during simulation and therefore provides a time dependent representation of changing route conditions. Traffic variables were measured using E2 lane area detectors configured along the links forming routes (R1), (R2), and (R3), with an aggregation interval of 1 s.

3.5 Machine learning modelling and evaluation

The generated route level traffic state datasets were used to formulate a supervised multivariable regression problem. Separate models were developed for routes R1, R2, and R3. For each route p, the input vector consisted of the six traffic state variables defined in Section 3.4, while route impedance I^p represented the continuous target variable. The dataset for each route was divided into three mutually exclusive subsets by random selection of observation indices: 60% for training (352249), 20% for validation (117416), and 20% for testing (117416). The resulting subsets were independently normalised using min–max transformation, with all variables scaled to the range [0,1]. Eight supervised regression algorithms were evaluated: Decision Tree, DT; Random Forest, RF; Extremely Randomised Trees, ET; Gradient Boosting, GB; Extreme Gradient Boosting, XGB; Light Gradient Boosting Machine, LGBM; Multilayer Perceptron, MLP; k Nearest Neighbours, KNN [22]. The models were implemented in Python using the scikit-learn, XGBoost, and LightGBM libraries. Hyperparameter optimisation was performed using randomised search. For each algorithm, 100 configurations were sampled from predefined hyperparameter spaces and evaluated using five-fold cross validation [23]. Following hyperparameter selection, the final model configurations were trained on the combined training and validation subsets, representing 80% of the observations, while the remaining 20% were retained as an independent test set for final performance evaluation. Predictive performance was assessed using standard metrics: mean squared error (MSE), mean absolute error (MAE), root mean squared error (RMSE), and the coefficient of determination (R^2).

4 RESULTS

4.1 Characteristics of the generated traffic state datasets

The simulation based procedure generated three route specific traffic state datasets, each containing 587082 observations. The generated data covered a broad range of operating conditions and exhibited different levels of variability across the three routes. Route R2 showed the highest overall variability, with a mean impedance of 224.39 s and a standard deviation of 144.65 s, compared with 190.15 s and 109.11 s for R1, and 169.49 s and 99.18 s for R3. The range of generated impedance values extended from 66.32 to 534.47 s for R1, from 42.38 to 751.25 s for R2, and from 64.69 to 715.17 s for R3. The particularly wide ranges observed for R2 reflect the stronger variation in its performance under different demand and route distribution conditions. No missing values were identified in the generated datasets. Extreme observations were retained because, within the controlled simulation environment, they represented valid traffic states rather than measurement errors. Consequently, no interpolation of missing observations or removal of extreme values was performed prior to model development. Route impedance was positively associated with vehicle accumulation, average delay, and queue length, while average speed showed a relatively strong negative relationship. No problematic multicollinearity among the explanatory variables was observed. Departure delay showed only a weak relationship with impedance but was retained because it captures delayed network entry under highly saturated conditions. Overall, the descriptive results confirm that the systematic variation of demand magnitude, temporal demand profiles, route distributions, and stochastic simulation conditions produced datasets containing a wide spectrum of route performance states suitable for subsequent regression modelling.

4.2 Machine learning model performance

The predictive performance of the tested ML models was first evaluated collectively on the test datasets for routes R1, R2, and R3. The mean values and standard deviations of the evaluation metrics across all tested algorithms indicate that the investigated models were able to learn and reproduce the relationships between the selected traffic state variables and route impedance, although the achieved accuracy differed among the three routes (**Table 2**).

Table 2. Overall tested ML models performance

	MAE	MSE	RMSE	R^2
R1 average	16.6418	1100.1415	32.5586	0.9078
R1 st. deviation	4.7590	507.7413	6.7646	0.0426
R2 average	40.4233	4163.1654	64.2431	0.8015
R2 st. deviation	6.1846	902.6980	6.5313	0.0424
R3 average	17.3805	1326.9934	35.7440	0.8653
R3 st. deviation	4.5594	603.1696	7.5162	0.0612

Source: Made by authors.

Based on overall performance across the considered metrics, RF was selected for R1 and R2, while XGB was selected for R3. For R1, RF achieved an MAE of 14.1452 s and R^2 of 0.9321; for R2, the corresponding values were 36.8821 s and R^2 of 0.8288, indicating comparatively lower predictive accuracy. For R3, XGB

achieved an MAE of 14.8830 s and R^2 of 0.9048. The selected models were therefore chosen based on their strongest overall predictive performance across the considered evaluation metrics, rather than on any single error indicator. The comparison between simulated and estimated impedance values on the test datasets shows that the selected models generally reproduced the variability and overall distribution of the target variable across all three routes. Estimation accuracy, however, was not uniform across the complete range of traffic states (**Figure 2**).

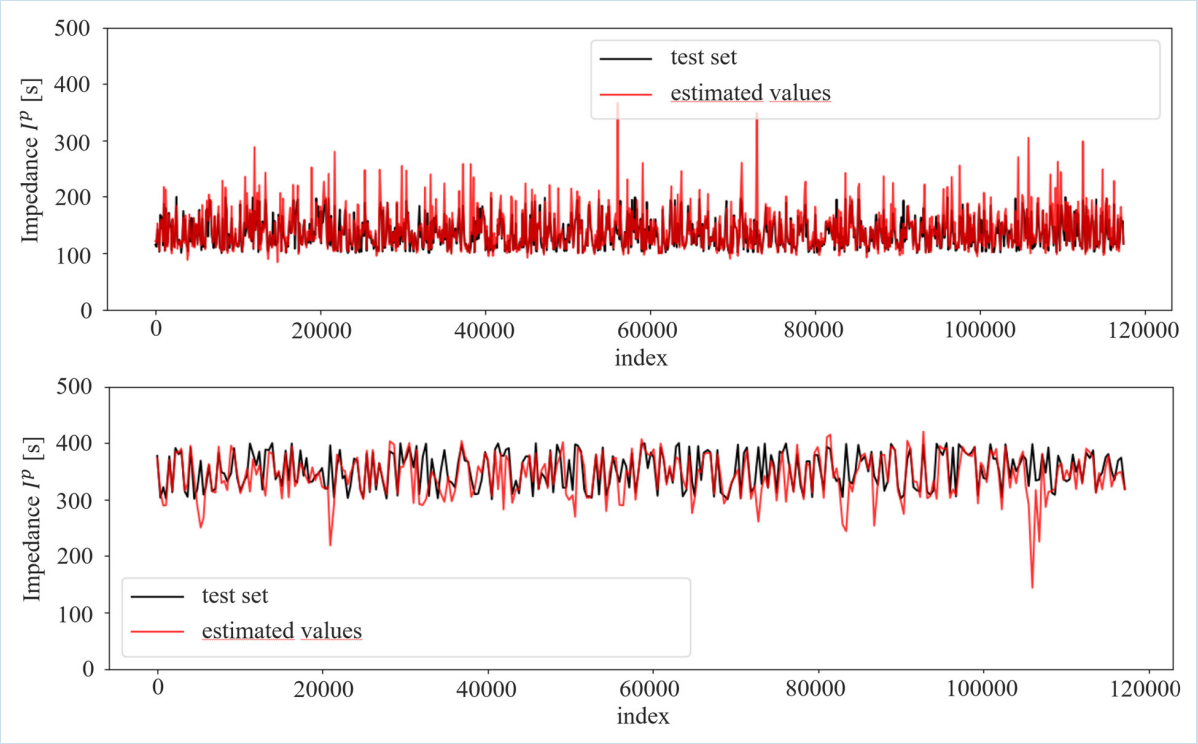


Figure 2. Evaluation of the RF model for impedance value ranges of 100–200 s and 300–400 s on the test dataset for route R1

Source: Made by authors.

The models performed more accurately in the more frequently represented lower impedance ranges, while errors increased under high impedance conditions associated with more extreme traffic states. For lower impedance ranges, MAE values were 14.5465 s, 38.8322 s, and 16.9108 s for R1, R2, and R3, respectively, increasing to 36.3267 s, 95.1188 s, and 102.4067 s in the higher impedance ranges. These results indicate that less frequent and more extreme traffic conditions remained more challenging to estimate.

5 DISCUSSION

The results show that microscopic simulation provides a controlled environment for systematically generating heterogeneous traffic state datasets. Its main advantage is not only the quantity of generated observations, but the ability to deliberately reproduce highly saturated and less frequent traffic conditions that may be insufficiently represented in real world patterns [4]. The results indicate that the selected traffic state variables contain sufficient information for estimating route impedance. Differences in predictive performance among routes further suggest that model accuracy depends on route specific traffic dynamics and network characteristics. The reduced accuracy observed in the high-impedance ranges is particularly relevant because these conditions represent the more extreme

traffic states that motivated the simulation based dataset generation. This finding indicates that the generation of extreme traffic states alone does not necessarily ensure equally accurate estimation across the complete operating range, particularly when such states remain less frequently represented or exhibit greater variability. From an operational perspective, such models can provide an additional information layer for centralised traffic management systems by transforming multiple traffic measurements into estimates of prevailing route performance [5, 24]. These estimates may support identifying deteriorating traffic conditions and subsequent decision making; however, the present approach addresses traffic state estimation rather than the implementation of traffic management actions themselves. Several limitations should be considered. The experiments were conducted on a generic reference network, and the generated data remain dependent on the assumptions and validity of the microscopic simulation model. Moreover, the random observation level split does not fully assess generalisation to unseen traffic scenarios. Because traffic variables were sampled at 1 Hz, consecutive observations may be strongly temporally correlated, allowing highly similar observations to occur in both the training and test subsets and potentially resulting in optimistic estimates of predictive performance.

6 CONCLUSION

This research developed a simulation based methodology for generating structured traffic state datasets for ML route performance estimation. Systematic variation of traffic demand, temporal profiles, route distributions, and stochastic conditions resulted in 150 simulation cases and 587082 observations for each of the three investigated routes. Eight regression algorithms were evaluated. Random Forest for R1 and R2 and XGBoost for R3 achieved the strongest overall performance, with R^2 values of 0.9321 (RMSE of 28.50 s), 0.8288 (RMSE ofo 60.08 s), and 0.9048 (RMSE of 30.62 s), respectively. The findings demonstrate the potential of microscopic simulation as a controllable and reproducible source of heterogeneous traffic-state data for ML estimation and centralised traffic management decision support. The proposed approach specifically addresses the traffic state estimation layer, providing a methodological basis for transforming systematically generated traffic data into information relevant for subsequent decision support processes. Future research should evaluate the methodology on calibrated real-world networks, integrate simulated and observed traffic data, and assess model generalisation and transferability through scenario-based validation in which complete traffic-demand conditions are excluded from model training.

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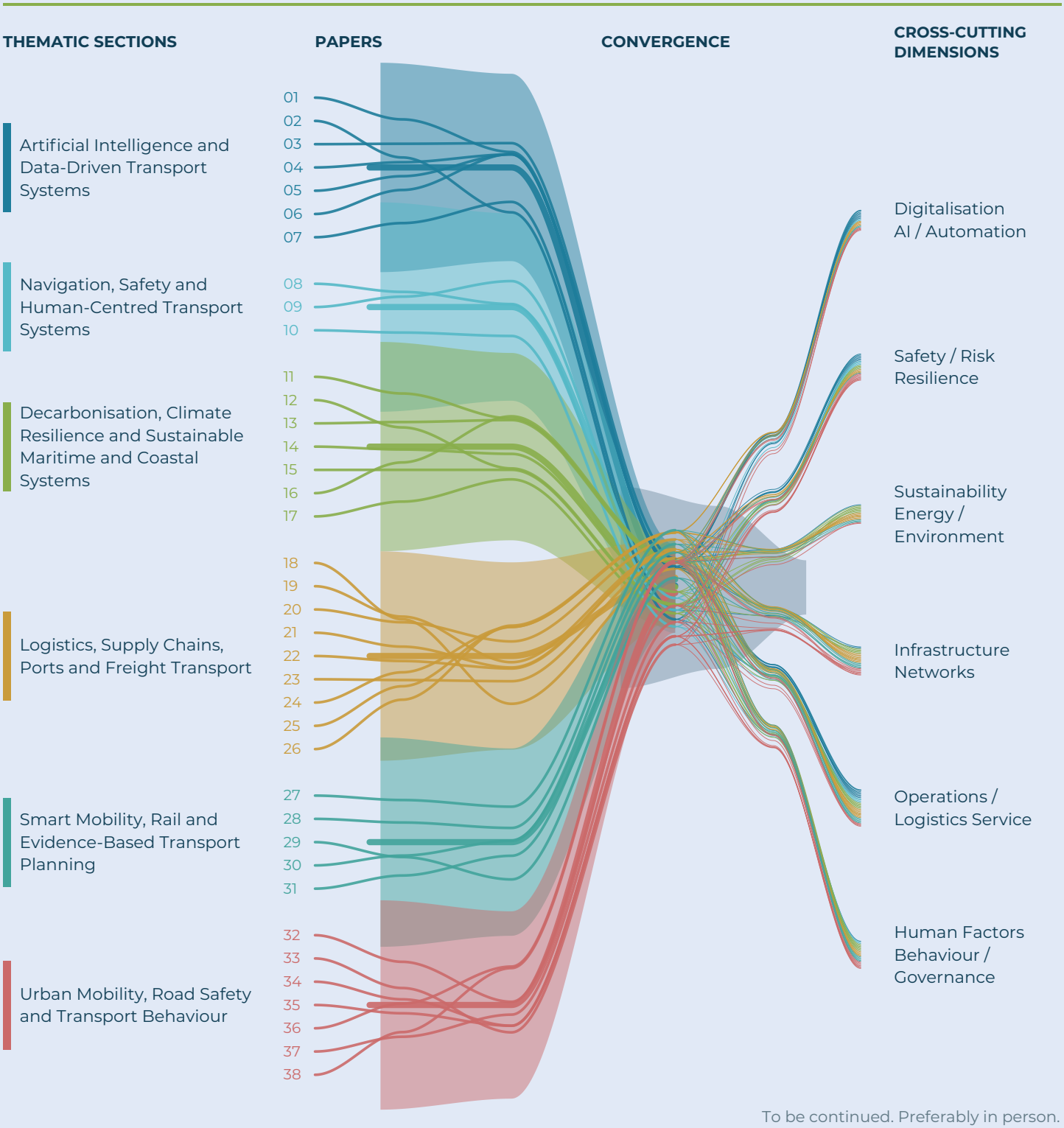
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