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Innovative Approaches to Transport Challenges in Port Cities Based on Literature Review

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ABSTRACT: Port cities are critical nodes in global trade but face unique transport challenges issuing from their dual role as urban centres and maritime hubs. These challenges include congestion, pollution, and governance complexities, which intensify as global trade grows. Traffic bottlenecks caused by overlapping freight and urban mobility systems disrupt efficiency and elevate environmental and social concerns. Heavy-duty vehicles contribute significantly to CO2 emissions, while outdated infrastructure in older port cities exacerbates these issues. Technological innovations such as real-time traffic monitoring, Internet of Things (IoT), Artificial Intelligence (AI) and digital twins, are transforming how port cities manage logistics and reduce environmental impact. Green transport initiatives, including electric vehicles, intermodal hubs and clean energy systems, demonstrate the potential to reduce emissions and improve urban liveability. Collaborative efforts from governments like the EU-funded PORTIS project showcase how aligning the objectives of port authorities and urban planners can foster resilient, sustainable systems. This paper reviews innovative approaches to addressing transport challenges in port cities, emphasizing sustainable and technological solutions that integrate urban and port operations. The future of port cities lies in adopting integrated approaches that balance economic, environmental and social priorities, ensuring their evolution into efficient, sustainable hubs for global trade and urban life.

1 INTRODUCTION

Port cities are crucial to the global supply chain, serving as points of convergence for maritime and inland transportation systems. This strategic position, while vital for international trade, presents a range of transport-related challenges, with issues of congestion, environmental sustainability, and governance standing at the forefront (Merk, Thai-Thanh, 2013). The influx of goods moving through port cities leads to substantial congestion, both in the ports themselves and in the surrounding urban areas. Port-related traffic often overlaps with everyday city traffic, intensifying congestion and putting immense pressure on transport infrastructure. The issue is particularly severe in older port cities, where infrastructure may not have been designed to handle modern trade volumes (John-Alder, Whiteman, 2022). Heavy-duty vehicles transporting goods from ports to designated areas add further pressure to roads, which are often ill-equipped for the size and volume of vehicles involved. This congestion impacts not only the efficiency of goods movement but also the quality of life for city residents due to delays, noise, and increased accident risks (González-Laxe et al., 2023). In response to these challenges, some cities have adopted traffic management solutions to streamline transport flows between port zones and urban centres (Roberts et al., 2023). This approach has shown promise in pilot projects in cities like Antwerp and Trieste, where

integrated systems help reduce bottlenecks by improving coordination between transport networks and managing traffic in real-time (European Commission, 2020).

A major issue linked to transport congestion in port cities is also environmental pollution. The high volume of heavy-duty vehicles, combined with port operations, contributes significantly to CO_2 emissions and local air pollution (Hall, 2018). Ports are also often located in densely populated areas, which makes it challenging to balance the demands of a functioning port with the needs of the urban environment. Studies estimate that freight transport accounts for a large portion of CO_2 emissions in port cities, with heavy-duty trucks being a major contributor (Kotowska, Kubowicz, 2019). To address this, some cities are exploring greener transport options and low-emission zones. Expanding public transportation networks, promoting the use of electric or hybrid trucks for short-distance hauls, and implementing incentives for rail and inland waterway transport are strategies aimed at reducing the environmental impact of freight movement (Carpenter & Lozano, 2020). Port cities like Rotterdam and Hamburg have invested heavily in green corridors and intermodal logistics hubs that support these environmentally friendly modes of transport, hoping to make freight movements both cleaner and more efficient. These efforts reflect a growing emphasis on sustainability and innovation to tackle the complex transport challenges that port cities face (Gurzhiy et al., 2021).

Building on these advancements, effective governance becomes critical in ensuring that such initiatives are successfully implemented and aligned with broader urban priorities. Effective governance is essential in addressing transport challenges in port cities, as these urban areas must manage a delicate balance between the operational needs of ports and the broader urban agenda. A common challenge in port city governance is the need for collaboration among various stakeholders, including municipal governments, port authorities, and private companies. The overlapping jurisdictions and interests can lead to fragmented approaches and policy conflicts, particularly when it comes to spatial planning and transportation priorities (D'Amico et al., 2021). An example of successful governance in this area is the European Commission's PORTIS initiative, which worked across several European port cities to promote integrated governance models and sustainable mobility solutions. This included efforts to connect public transit systems with port logistics, which helped reduce reliance on private cars and improved accessibility for workers and residents alike. Collaborative projects like these highlight the importance of multi-stakeholder engagement in creating sustainable, resilient transport frameworks for port cities (European Commission, 2020).

In addition to governance efforts, technological innovations are playing an interestingly pivotal role in addressing transport issues within port cities. These advancements complement policy initiatives by providing tools to enhance efficiency and sustainability. Digital tools, such as real-time traffic monitoring, predictive analytics, and automated freight management systems, are helping port authorities and municipalities to optimize the flow of goods and reduce congestion. For instance, automated scheduling systems can help coordinate freight movements, reducing peak load pressures on transport networks (Kosiek et al., 2021). Digital twins—virtual models of physical systems—are also gaining traction as a way to simulate and improve the interactions between port operations and urban mobility (Ilin et al., 2019). In addition to digital solutions, physical infrastructure improvements are underway in some cities. High-speed rail connections, expanded metro lines, and dedicated freight lanes are among the infrastructure upgrades that support more seamless, sustainable transport in port areas. Looking forward, the development of autonomous freight vehicles and drones for last-mile delivery also presents new possibilities for reducing road congestion and emissions in port cities (González-Laxe et al., 2023).

Addressing transport challenges in port cities is a multifaceted issue that requires an integrated approach. Congestion, pollution, and governance issues are intertwined, and effective solutions must balance the operational demands of ports with the needs of urban residents and environmental priorities. Successful approaches often combine sustainable transport modes, innovative governance frameworks, and advanced technologies to optimize transport flows and reduce the negative impacts of port activity on city life. As these strategies evolve, port cities have the opportunity to transform into cleaner, more efficient nodes within the global supply chain while maintaining liveable, sustainable urban environments for residents.

2 TRANSPORT CHALLENGES IN PORT CITIES

The duality of the port cities creates complex interactions between the operational needs of ports and the demands of urban mobility, often resulting in significant congestion, environmental strain, and governance challenges. The coordination of freight and passenger traffic within these cities leads to overlapping transport systems that can hinder efficiency and exacerbate negative externalities, such as increased emissions and reduced quality of life. According to independent research conducted by Olaf Merk and Dang Thai-Thanh, port cities experience unique pressures because of their dual roles as economic centres and community spaces. As port cities grow, congestion intensifies, fueled by increased freight activity alongside everyday urban traffic, exacerbating environmental and social challenges (Merk, Thai-Thanh, 2013). Similarly, Peter Hall highlights that port cities must balance industrial expansion with the livability of urban areas, a tension that often generates conflicts over space, pollution, and traffic management (Hall, 2018).

Understanding these challenges requires a multidimensional perspective, encompassing infrastructure limitations, regulatory frameworks, and the broader socio-economic impacts of transport inefficiencies. The growth in global trade and the increasing size and volume of goods moving through ports have only intensified these pressures, particularly in cities where historical infrastructure is ill-equipped to the modern demands. Moreover, the environmental footprint of freight transport highlights

the urgent need for sustainable and innovative solutions to ensure the viability of both ports and their surrounding urban environments. Several studies underscore the environmental and logistical burdens that come with heavy truck movements in port areas. Polish researchers Kotowska and Kubowicz note that road transport remains the dominant mode of hinterland cargo movement, which significantly contributes to CO_2 emissions and congestion (Kotowska, Kubowicz, 2019). According to the European Commission, heavy-duty vehicles are responsible for approximately a quarter of CO_2 emissions from road transport across the EU, making their impact on urban air quality and public health a pressing concern (European Commission, 2020). This environmental impact also intersects with economic demands. Interestingly enough, Spanish researchers emphasize that, while maritime transport is one of the most sustainable transport modes in terms of CO_2 emissions, the surrounding urban areas are deeply affected by port activities. As strategic locations for trade, port cities often face bottlenecks that can disrupt economic activity if left unmanaged. González-Laxe advocates for balancing economic priorities with social sustainability to maintain livable conditions for port city residents (González-Laxe et al., 2023). However, such efforts often face financial and logistical barriers, particularly in smaller port cities with limited resources. Research conducted by another Polish analysts confirms that the expansion of port cities into dense urban regions further complicates this issue, as port-related traffic merges with regular city traffic, causing significant congestion and increasing pollutant levels (Budzyński et al., 2017; Ziemska-Osuch, Guze, 2023). Similarly, researchers from Gdynia Maritime University (GMU) highlight that mobility challenges in port cities are not limited to freight transport but also extend to the commuting patterns of institutions locate within port areas. A case study on GMU reveals that the transport habits of its employees and students are not aligned with the principles of sustainable mobility, further exacerbating congestion and environmental concerns in the city. Authors argue that integrating institutional mobility plans with broader urban transport strategies is essential for reducing traffic burdens in port cities and enhancing their sustainability. This reinforces the need for a comprehensive approach that considers both freight logistics and everyday urban mobility in transport planning (Kaszuba et al., 2023).

Resilience and climate adaptation are further essential considerations. Piet Dircke, a leading climate adaptation expert, points out that ports face mounting pressures from climate change, including rising sea levels and extreme weather events. This has necessitated that ports not only address immediate congestion and pollution issues but also develop long-term adaptation strategies to protect infrastructure and maintain economic resilience. He suggests phased planning as a solution to integrate sustainability and resilience into port city development effectively (Dircke, 2022). Port governance also plays a crucial role in addressing these challenges. The Belgian professor in his book observe that while port authorities' autonomy has allowed for more rapid adaptation to logistical changes, it has also created spatial and policy conflicts between ports and cities. This research suggests that port and city authorities often operate with conflicting spatial visions, an issue that could be resolved by shifting focus from division to cooperation, planning the strengths and addressing the challenges of both entities together (Van Den Berghe, 2018). To tackle these issues, innovative approaches in governance and mobility have emerged. For instance, the EU-funded PORTIS project, cited by the European Commission, demonstrates a model for integrating sustainable mobility solutions across five major port cities. This initiative aims to reduce car dependency by implementing multi-modal transport hubs and strengthening collective transit between city and port. Such projects have shown that a comprehensive, data-driven approach can foster collaboration between port authorities and municipal governments, facilitating more efficient transport flows and reducing environmental impact (European Commission, 2020). Nonetheless, thee approaches must be adapted to varying regional contexts, as financial constraints and institutional fragmentation can hinder implementation.

Lastly, Anastasia Gurzhiy and Tony Roberts highlight the potential role of technological innovation in mitigating these challenges. They argue that digitalization, automation, and data-driven solutions can play an essential part in optimizing traffic management and streamlining cargo movement. These advancements could enable port cities to manage congestion more effectively, ensuring efficient movement of goods while minimizing the impact on local communities (Gurzhiy et al., 2021; Roberts et al., 2023). Technological innovation has long been regarded as a key driver of efficiency and transformation in complex systems, including urban and transport networks. Theories of innovation diffusion and technological determinism suggest that the adoption of new technologies can fundamentally reshape industries and societal practices by offering novel solutions to longstanding challenges. In the context of port cities, where intersection of urban life and industrial operations creates unique pressures, innovation can serve as a critical tool for balancing economic demands with environmental and social priorities. Even though, the successful deployment of these technologies depends on empirical validation of their effectiveness, financial feasibility and stakeholder acceptance.

Figure 1 presents six major challenges faced by port cities, which were identified by the researchers whose publications were used to develop this chapter. These challenges focus on congestion, air pollution, governance constraints, climate change, ageing infrastructure and noise pollution. This chapter drawing on a review of relevant literature, it examines the root causes of these issues and their impact on urban life, while setting the stage for the subsequent discussion of technological innovations as potential solutions. Through this exploration it is possible to provide a comprehensive understanding of the transport dynamics in port cities and the critical need for integrated, sustainable approaches to address these multifaced problems. In summary, port cities face intertwined challenges of congestion, environmental impact, and governance complexities. Addressing these issues requires a multifaceted approach involving sustainable mobility solutions, enhanced governance structures, and advanced technologies.

The cumulative insights from these researchers underline the need for integrated strategies that bridge the gaps between urban and port planning, aligning economic objectives with environmental and social priorities for a sustainable future in port cities.

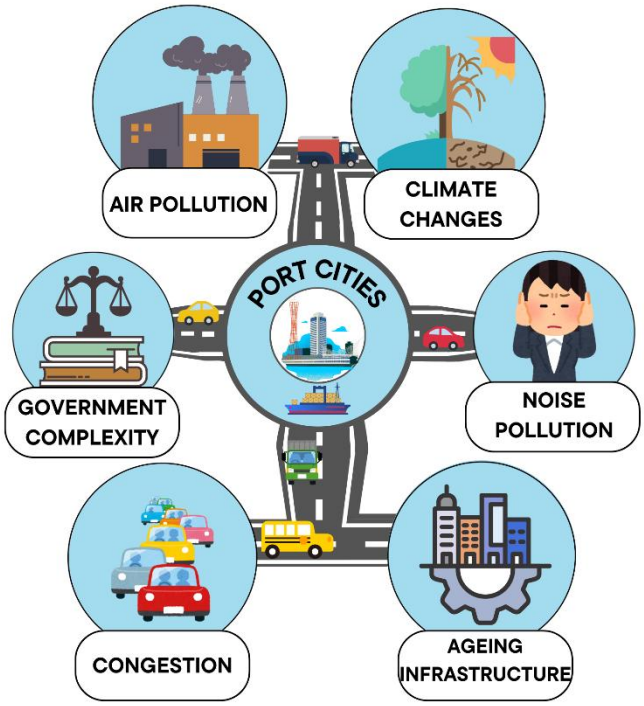

Figure 1. Main challenges faced by port cities. Source: Own elaboration.

3 TECHNOLOGICAL SOLUTIONS ADDRESSING TRANSPORT CHALLENGES

Technological innovations have become essential in tackling complex transport challenges, transforming how systems operate to improve efficiency, sustainability, and resilience. Advances in digital tools, automation, and data driven technologies allow stakeholders to address pressing issues such as congestion, pollution, and infrastructure strain. Initiatives such as Smart Cities and Intelligent Transport Systems (ITS) demonstrate how real-time data, predictive analytics, and automated processes can enhance traffic management, optimize mobility, and reduce environmental impacts. In port cities, where the overlap of freight and urban transport creates unique pressures, these technologies play a critical role in managing traffic flows, alleviating bottlenecks, and minimizing the environmental footprint of heavy transport operations. By integration such innovations, transport networks can respond more effectively to growing demands, ensuring smoother, more sustainable movement of goods and people. However, the practical implementation of these solutions requires further empirical validation, particularly regarding cost-effectiveness and scalability across different port contexts.

Smart technologies are revolutionizing port operations by streamlining logistics, improving decision-making, and increasing efficiency. The Internet of Things (IoT) connects port infrastructure, allowing for real-time tracking of cargo, monitoring equipment and optimizing storage space. Artificial Intelligence (AI) analyses vast amounts of data to predict traffic congestion, automate scheduling, and reduce delays in cargo handling. Big Data enables port managers to identify trends, detect inefficiencies and make better-informed operational decisions. Polish researchers argue that IoT and AI are pivotal in creating Smart Ports, improving both logistics and communication between different stakeholders (Kosiek et al., 2021). Similarly, analysts from Tunisia and Morocco emphasizes the importance of real-time data systems in modernizing port supply chains, making transport processes more efficient and predictable (Bessid et al., 2021). Another Africans provide a specific case study on Tangier Med Port, demonstrating how IoT applications such as real-time tracking, automated systems and optimized container stacking significantly improve operational efficiency and competitiveness (Bouhlal et al., 2022). Additionally, German researchers also underscore the transformative role of digital technologies, identifying three generations of digital evolution in ports and highlighting trends such as predictive analytics and automated decision-making systems (Heilig et al., 2017).

The transformation of traditional ports into Smart Ports represents a crucial shift in modern maritime logistics, driven by the need for greater efficiency, sustainability and technological integration. Researchers gave delved into this transition, focusing on the challenges of implementation and the critical factors that contribute to its success. The shift toward Smart Ports is further explored in studies analysing implementation challenges and success factors. Polish researcher Karaś identifies the complexities of selecting and deploying intelligent systems, particularly in North Sea ports, as they strive to align with smart port trends (Karaś, 2020). Meanwhile, Canadian analysts outline the evolution of ports into Industry 4.0 ready ecosystems, proposing characteristics and domains necessary for successful integration (Belmoukari et al., 2023). Spanish researchers extend this discussion, examining the pillars of Industry 4.0, including IoT, cybersecurity and data analytics, also highlighting their varying levels of maturity in the maritime industry (de la Peña Zarzuelo et al., 2020).

Ports are also recognized as critical players in promoting sustainability through the adoption of green technologies and innovative operational frameworks. Norwegian scientists categorize tools and technologies that address port sustainability, emphasizing the need for empirical research to support decision-making (Bjerkan & Seter, 2019). English researchers further discuss sustainability performance metrics, identifying trends in green operations and highlighting challenges in achieving consistent sustainability assessments across ports (Lim et al., 2019). While green innovations such as electrification, alternative fuels, and emission control technologies offer promising solutions, their large-scale implementation remains hindered by high upfront costs and regulatory inconsistencies.

When examining the state of innovation in specific regions, researchers have noted varying levels of adaptation and maturity. Brazilian analysts highlight the gradual transformation of Brazilian ports, where innovations such as cloud computing and drone technology are being adopted, although inconsistently.

This uneven progression reflects broader challenges in integrating new technologies into existing port infrastructures, including funding limitations and resistance to change (Cunha et al., 2023). Similarly, Chinese scientists explore the global implementation of IoT in ports, emphasizing its role in automating operations and the challenges of testing and calibrating sensing systems across diverse settings (Yang et al., 2018). By synthesizing these perspectives, it is clear that technological innovations are central to addressing transport challenges in ports. However, the pace of implementation, effectiveness of adaptation, and alignment with sustainability goals vary significantly, reflecting the diverse conditions and priorities across global port systems such as including financial viability, institutional support, and workforce adaptation. Ports with stable government support and long-term investment strategies are more likely to fully integrate smart technologies, while those in developing regions may require additional policy incentives and financial assistance.

Table 1. Overview of Smart Port Technologies and their global implementation.

Technology	Application in ports	Effects and benefits	Examples of implementation
Internet of Things	Real-time container tracking, port infrastructure monitoring, process automation	Increased efficiency, error reduction, improved coordination of operations	Tangier Med Port (Morocco)
Artificial Intelligence	Logistic optimization, cargo flow prediction, big data analysis	Reduced handling time, better forecasting, automated decision making	Port of Rotterdam (Netherlands)
Big Data	Analysis of vessel, cargo and workforce movement data	Enhanced operation planning, bottleneck identification, efficient resource allocation	Port of Hamburg (Germany)
Cybersecurity	Protection of IT systems, safeguarding cargo and logistic data	Reduced risk of cyberattacks, increased trust among business partners	Port of Singapore (Singapore)
Green Technologies	Reducing CO2 emissions, using renewable energy, green terminals	Lower environmental impact, improved image of ports as eco-friendly	Port of Los Angeles (USA)
Cloud Technologies	Data storage and analysis in the cloud, real-time information access	Reduced IT costs, greater operational flexibility, easier access to data	Port of Santos (Brazil)
Drone technologies	Monitoring infrastructure, inspecting operations in hard-to-reach areas	Improved monitoring of infrastructure condition, increased safety	Port of Lisbon (Portugal)

Source: Own elaboration.

To provide a comprehensive overview, the table above summarizes previously mentioned, key technologies, their applications, and the benefits they bring to modern port operations, supported by real-world examples from all around the globe. The integration of advanced technologies in ports has become a cornerstone of modern maritime logistics, addressing critical challenges. From IoT and AI to green innovations and cybersecurity, these tools are revolutionizing how ports operate, enabling smarter, more agile and environmentally conscious systems. The implementation of these technologies varies across the regions, reflecting differences in infrastructure readiness and strategic priorities, but the overarching trend points towards a unified goal of creating Smart Ports that align with Industry 4.0 principles. Moving forward, a greater emphasis on empirical studies and quantitative data will be essential to determine the most effective pathways for Smart Port development.

4 THE FUTURE OF TECHNOLOGY IN PORT CITIES

The future of technology in port cities is poised to revolutionize the way these urban-maritime hubs operate, transforming them into highly efficient, interconnected and intelligent ecosystems. As digitalisation accelerates, emerging technologies are set to redefine logistics, urban planning and sustainable efforts in port cities. This chapter delves into how innovations such as IoT, AI and blockchain alongside advanced data analytics, will shape the next generation of port cities by enhancing efficiency, improving environmental sustainability, and fostering a seamless integration between urban and maritime environments. Understanding these trends will be key to developing strategies that ensure port cities remain competitive and livable in the years ahead.

Port cities, as dynamic hubs of trade, urban development, and environmental stewardship, are leveraging advanced technologies to address their unique challenges and opportunities. Ciciriello et al. underscore the importance of adopting an integrated approach to sustainable planning that integrates economic performance evaluations with socio-environmental assessments. This comprehensive perspective aligns port cities development with the Sustainable Development Goals, ensuring balanced growth while respecting urban and maritime ecosystems (Ciciriello et al., 2024). Such integration is not merely a theoretical ideal but a pressing necessity, as the rapid expansion of global trade and urbanization intensifies the strain on port city infrastructure and resources. Similarly, Kong and Liu emphasize that modern port cities must establish interactive relationships between urban and industrial functions, promoting multifunctional regions where production, logistics, trade and research coexist (Kong & Liu, 2021). This integrated approach strengthens the connection between port systems and their surrounding cities fostering both economic and environmental sustainability.

While sustainability remains a cornerstone of port city development, its success requires more than just adopting new technologies. Kong and Liu highlight how clean energy integration, efficient logistics networks and low-carbon technologies are central to balancing economic growth with environmental responsibility. Hong Kong exemplifies this balance, with its successful policies incentivizing clean energy adoption and reducing emissions (Kong & Liu, 2021). D'Amico et al., however, caution against over-reliance on technology at the expense of social and

environmental considerations. They advocate for a balanced and inclusive approach that not only addresses logistical challenges but also prioritizes community well-being, ensuring that technological advancements align with broader societal and ecological goals (D'Amico et al., 2021). This perspective underscores the importance of a comprehensive approach that values both technological innovation and the human and environmental contexts in which it is applied. However, a more critical approach to sustainable technology adoption is required – one that considers economic disparities between global ports and acknowledges potential unintended consequences.

While smart technologies promise greater efficiency and automation, their implementation presents significant obstacles, particularly in governance and infrastructure. Zheng et al. highlight the potential of renewable energy systems, interactive visual tools, and the Historical Urban Landscape (HUL) approach in optimizing urban and port interactions (Zheng et al., 2020). These tools combined with circular economy principles that transform waste into valuable resources, significantly contribute to the ecological and economic sustainability of port cities, yet they require long-term investment and institutional alignment to be effective. Beškovnik and Bajec build on this by introducing the concept of a smart port-city ecosystem, where IoT platforms, big data analytics and machine-to-machine communication harmonize urban and port operations. Cities like Hamburg, Antwerp and Rotterdam demonstrate the potential of IoT dashboards to monitor productivity, reduce environmental impacts and improve urban mobility, creating a more cohesive and efficient urban-maritime interface (Beškovnik & Bajec, 2021). However, while these leading ports are making progress, many mid-sized and developing port cities lack the financial and organizational capacity to replicate such models. These examples illustrate that smart technologies are not only tools for operational efficiency but also key enablers of broader systemic transformations, allowing port cities to adapt to the demands of a rapidly changing global trade landscape while fostering resilience and sustainability. Nevertheless, without targeted investment, policy support, and scalable implementation strategies, the benefits of smart technologies may remain concentrated in well-funded ports, widening the gap between leading maritime hub and smaller, resource-constrained port cities.

The ongoing digital revolution is further transforming logistics and operations in port cities. Acciaro et al. describe how technologies such as AI, blockchain, and automation enable the seamless movement of goods across intermodal networks. The concept of the Physical Internet (PI) illustrates a globally integrated logistics system where real-time data sharing optimizes cargo movement, reduces delays, and enhances supply chain transparency (Acciaro et al., 2020). D'Amico et al. expand on this by discussing the role of digital platforms like artificial reality, drones and blockchain in optimizing container management and environmental monitoring. These technologies not only improve operational efficiency but also enhance real-time data access, enabling better decision-making and stakeholder collaboration. A notable example is Qingdao's fully automated terminal, where AI-driven systems and robotics have lowered labor costs and significantly increased operational efficiency (D'Amico et al., 2021). However, while these innovations hold great potential, their widespread adoption is often hindered by high implementation costs, cybersecurity concerns, and the need for regulatory harmonization. As the pace of digitalization accelerates, these factors will play a crucial role in determining whether technological advancements lead to widespread efficiency gains or deepen inequalities between technologically advanced and lagging port cities.

Beyond logistics management, the benefits of digitalization are increasingly addressing long-standing urban challenges in port city operations. Urban congestion and transportation inefficiencies continue to pose significant obstacles, yet intelligent traffic management and autonomous technologies offer promising solutions. Garduño et al. highlight AI-driven traffic systems, such as those in Hamburg, which predict congestion patterns, guide vehicles to less congested routes, and reduce CO2 emissions. Similarly, real-time truck guidance systems and advanced parking technologies further streamline operations, minimizing delays and enhancing the integration of port and city functions. Autonomous truck platoons, implemented in Rotterdam and Singapore, exemplify how logistics innovations can reduce fuel consumption and emissions while improving safety and efficiency (Garduño et al., 2020). While these advancements contribute to a more efficient and sustainable urban environment, their large-scale implementation remains dependent on regulatory adaptation, infrastructure investment, and public acceptance. These developments illustrate that technology is not merely optimizing supply chains but also reshaping urban mobility in port cities, ensuring that they remain both livable for residents and globally competitive trade hubs.

As these insights illustrate, the future of port cities depends on the effective integration of technology, sustainability, and governance, rather than technological advancements alone. While digital platforms, clean energy solutions and smart urban planning are reshaping port cities into more efficient and resilient hubs, their success relies on strategic investment, regulatory adaptation and stakeholder cooperation. The challenges of scalability, financial constraints and social acceptance must be addressed to ensure that innovation benefits all port cities, not just leading global hubs. By adopting comprehensive strategies that balance economic growth, environmental responsibility and social equity, port cities can navigate the complexities of digital transformation while securing a sustainable and competitive future.

5 CONCLUSIONS

Port cities face a complex set of challenges arising from their dual role as centres of trade and urban activity. Transport challenges are central to these dynamics, as the interplay between freight and urban mobility systems creates significant bottlenecks and inefficiencies. The overlapping nature of port and urban transport networks not only intensifies

congestion but also complicates the movement of goods and people, requiring a delicate balance between operational efficiency and urban livability. Addressing these interconnected challenges is essential to ensuring that port cities can support the demands of global trade without compromising the quality of urban life. However, to develop truly effective solutions, a stronger empirical foundation is needed to assess the real-world applicability of proposed measures across diverse port city contexts.

The pressing need for environmental stewardship has spurred the adoption of green technologies, cleaner energy solutions, and sustainable logistic practices. Transport-related emissions, particularly from heavy-duty vehicles, remain one of the primary sources of air pollution in port cities, underscoring the urgency of transitioning to low-carbon transport systems. Cities such as Rotterdam and Hamburg exemplify the success of these initiatives aimed at integrating green corridors and intermodal logistic hubs, demonstrating how the alignment of technological advancements with sustainability goals can significantly mitigate emissions and improve air quality. Nonetheless, the implementation of such initiatives is often constrained by financial limitations, political criteria, and disparities between larger, well-funded ports and smaller, resource-limited port cities. A deeper analysis of these barriers would be beneficial to ensure that sustainable mobility strategies are scalable and adaptable across different urban-maritime environments.

Effective governance also plays a significant role in addressing the transport challenges of port cities, particularly the need to coordinate stakeholders and harmonize the objectives of port authorities and urban planners. The overlapping jurisdictions of various actors often lead to fragmented strategies which can exacerbate traffic inefficiencies and hinder the implementation of cohesive transport policies. Collaborative frameworks, such as the PORTIS project, highlight the potential for integrated governance models to align policy, optimize mobility, and foster equitable urban growth. By focusing on inclusive and data-driven approaches, governance strategies can help overcome transport bottlenecks and enhance the overall efficiency of port-city systems. However, the success of such initiatives depends on overcoming institutional resistance to change, conflicts of interest between stakeholders, and the varying level of regulatory maturity across different port regions. More in-depth exploration of governance mechanisms, including case studies of successful multi-stakeholder coordination, could provide a clearer roadmap for implementation.

Technological advancements are equally transformative in solving transport-related issues. Innovations such as Internet of Things, Artificial Intelligence and real-time analytics are reshaping how port cities manage traffic flows and logistics. These tools enhance traffic management systems, reduce congestion, and promote the integration of smart systems to address the growing demands on transport infrastructure. By streamlining cargo flows and improving last-mile delivery through innovations like autonomous vehicles and predictive analytics, technology is proving instrumental in reducing transport delays and emissions. These advancements not only resolve immediate logistical challenges but also provide a foundation for more resilient transport networks in port cities. Although, the practical deployment of these technologies is often met with operational challenges, such as high initial investment costs, cybersecurity concerns, and workforce adaptation issues. Future research should explore quantitative assessments of cost-benefit trade-offs associated with these technologies to provide more concrete evidence of their long-term viability.

Looking ahead, the future of port cities lies in adopting integrated strategies that integrate technological, environmental, and governance innovations to address their transport challenges. The seamless synergy between urban and maritime ecosystems will allow port cities to evolve into sustainable, resilient hubs capable of meeting the demands of global trade while improving the quality of life for their residents. Nevertheless, the extent to which these strategies can be successfully implemented will depend on a combination of empirical validation, interdisciplinary collaboration, and adaptive policy-making. By tackling transport inefficiencies, reducing congestion, and implementing sustainable mobility solutions, port cities can transform into models of innovative and sustainable development.

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