

Digital technologies for efficient and resilient sea-land logistics: IT-based decision support systems to manage highway capacity at major gateway ports

The TQM Journal

301

Received 30 March 2025

Revised 31 December 2025

8 April 2026

Accepted 4 July 2026

Roberto Viviani

University of Genoa, Genoa, Italy

Francesco Parola and Antonella Ferri

Universitas Mercatorum, Rome, Italy, and

Luca Persico and Gabriele Pinna

University of Genoa, Genoa, Italy

Abstract

Purpose – The competitiveness of modern gateway ports increasingly depends on external factors beyond the port domain, such as the performance of hinterland connections. However, despite extensive research on port competitiveness, a theoretical gap persists regarding the role of road transport networks, whose efficiency and resilience remain a largely underexplored exogenous driver. This study contributes to addressing this gap by conceptualizing road-network performance through three analytical dimensions: traffic management, maintenance and infrastructure development. The study introduces a data-driven Decision Support System (DSS) architecture developed using Power Query and Power BI, thereby contributing to the existing methodological debate by illustrating how these analytical dimensions can be translated into a structured and data-driven assessment framework. The functioning of the DSS is illustrated through a structured simulation-based application using a synthetic dataset designed to reproduce realistic traffic dynamics.

Design/methodology/approach – The efficiency, resilience and overall quality of services provided by international supply chains focused on sea-land logistics increasingly depend on the ability to implement IT-based applications. In this perspective, several emerging digital technologies enable the development of IT-based DSS that operate through real-time data integration, offering timely and accurate information to a wide range of stakeholders.

Findings – Key findings reveal that even moderate reductions in infrastructure capacity due to roadwork sites can significantly deteriorate Levels of Service (LOS), especially during peak hours, impacting freight movements and port accessibility. The proposed DSS enables real-time monitoring, scenario comparison and predictive planning, offering concrete benefits across three strategic domains that emerge from the theoretical framing.

Research limitations/implications – Despite the original contribution provided, the present study is subject to some limitations that open up relevant avenues for future research. In particular, the current application relies on a synthetic dataset designed to illustrate the operational logic of the proposed DSS rather than to provide a full empirical validation of its performance. Future studies are called to perform simulations and analysis by applying real data concerning motorway infrastructural endowment and capacity, demand patterns and associated LOS. In addition, it could be worth testing the impact of critical events, including force majeure, that might provoke sudden limitations to capacity and/or heavy traffic perturbation across the port logistics chain, in order to assess the effectiveness of potential recovery mechanisms to be implemented by business operators. In this perspective, future empirical research grounded on real-world case studies could explicitly adopt structured design-oriented methodological approaches, such as Design Science Research Methodology, to iteratively test, refine and assess DSS artefacts under operational conditions, moving beyond the illustrative and exploratory scope of the present study.



© Roberto Viviani, Francesco Parola, Antonella Ferri, Luca Persico and Gabriele Pinna. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at <http://creativecommons.org/licences/by/4.0/>

The TQM Journal
Vol. 38 No. 11, 2026
pp. 301-322
Emerald Publishing Limited
e-ISSN: 1754-274X
p-ISSN: 1754-2731
DOI 10.1108/TQM-03-2025-0192

Practical implications – Overall, the proposed framework suggests that the adoption of IT-based DSS solutions can generate several benefits for a wide range of stakeholders involved in the management and utilization of highway infrastructures. For highway concessionaires (and public awarding authorities), the DSS serves as a powerful tool to enhance decision-making processes at multiple levels. Port authorities and logistics operators can benefit from the availability of such decision-support too. Reliable and efficient hinterland connectivity is essential for maintaining port competitiveness and expanding hinterland boundaries, and by reducing the risks of congestion-related delays, the DSS helps ensure that cargo flows can move seamlessly between ports and inland destinations. For public decision-makers and regulators, the availability of accurate data-driven information provides a solid foundation for informed policy and investment decisions. The DSS offers clear visibility into current infrastructure performance, helping to identify where new investments are most needed (such as the expansion of highway sections or the development of new connections). The benefits of the DSS extend to road users themselves, encompassing both B2B users, such as freight transport operators, and B2C users, including private vehicle drivers. For these users, improved travel conditions, reduced congestion and more predictable journey times translate into lower costs, greater reliability and an overall better travel experience. Finally, local communities and urban authorities play a key role in the broader ecosystem. The DSS contributes to mitigating the negative externalities associated with heavy port-related traffic, such as pollution, noise and urban congestion.

Originality/value – Hence, the study provides policy and managerial implications about the benefits of implementing IT-based DSS conceived to manage highway capacity efficiently, while offering insights to Port Authorities, regulators and road users for improving travel choices and mobility behaviors.

Keywords Gateway ports, Digital technologies, Highway capacity, Decision support system (DSS), Levels of service (LOS)

Paper type Research article

1. Introduction

Major gateway ports are complex logistics infrastructures, inserted in broad supply chains, that are called to synchronize massified maritime cargo flows with atomized inland flows. The growing economies of scale in mega-vessels imposed tremendous pressure on ports to deal with hinterland transportation concerns. Land-side infrastructure bottlenecks, urban traffic congestion, insufficient rail capacity and uneven cargo flow distribution during the day (peak versus off-peak) are just some of the critical concerns affecting port-related hinterland transportation (Notteboom and Rodrigue, 2005; Parola *et al.*, 2017; Pettit and Beresford, 2009). Notably, in most contexts, road transport is the prime logistics mode as it can ensure operational flexibility and logistics capillarity for coping with port traffic development, also in combination with rail (intermodality). Nevertheless, given the huge amount of cargo handled at major gateway ports, road transport implies the atomization of cargo flows and a massive frequency of arrivals/departures. Such maritime-related flows, often overlapping with private mobility, have a severe impact on motorway infrastructures, both around urban areas and corridors. In this regard, infrastructure criticalities occur when traffic demand exceeds the maximum service capacity of a particular motorway section, leading to several negative consequences, including slowdowns, congestion, increased travel times and reduced road safety (HCM, 2000; Roess and Prassas, 2014). In addition, this seriously undermines the sustainable development of the port, as its social acceptance is weakened by the critical issues that port activities generate in terms of negative externalities.

In this context, a wide range of policy and managerial responses can be envisaged to address congestion and hinterland inefficiencies, including physical infrastructure expansion, pricing and regulatory measures, as well as operational and technological interventions. Among these alternatives, this study deliberately focuses on the adoption of IT-based Decision Support Systems (DSS) as its primary analytical lens. This choice is motivated by the fact that, while infrastructure expansion typically requires long timeframes, high capital investments and complex administrative procedures, data-driven DSS solutions can be deployed more rapidly and can enhance the efficiency of existing infrastructures through real-time monitoring, predictive analytics and improved coordination among stakeholders (Lakshmanan and Anderson, 2001; Radzi *et al.*, 2023; Parola *et al.*, 2020).

The causes of these criticalities are multifaceted. A primary factor is the increase in vehicle density, particularly during peak hours, which exacerbates pressure on infrastructures; another factor is the inadequate infrastructural standards: winding routes, narrow roads and physical bottlenecks at highway entry and exit junctions hinder the regularity of traffic flows. Next to this, motorways need to implement light and heavy maintenance programs, which inevitably imply capacity restrictions with a negative impact on service levels. Additionally, unexpected events such as road accidents, bad weather conditions or road construction sites can cause sudden and unforeseen congestion. Finally, even ports themselves can generate massive logistics disruptions across the chain. In this regard, disruptions originating in one node of the supply chain may propagate across the entire network, in line with the well-known bullwhip effect described in logistics literature (Lee *et al.*, 1997). Port strikes, vessels' late arrivals, digital breakdowns at IT platforms, rough seas, shipping network disruptions because of wars, terrorist/pirate attacks and other catastrophic events translate into a tremendous misbalance between sea-land logistics, with inevitable profound perturbations that need days (or weeks) to be fully absorbed.

The effects of these criticalities produce traffic slowdowns affecting trucks and private cars, with a significant reduction in average speed and consequent inefficiencies across the logistics chain and mobility. Congestion occurs when traffic volumes exceed road capacity, causing vehicle build-ups to move slowly or remain stationary on lanes. Moreover, significant increases in travel times are observed, compromising travel planning and delivery punctuality, and creating discomfort for both private users and logistics operators. Such circumstances might undermine the competitiveness of the gateway port, especially if these drawbacks are frequent as well as broadly present within the hinterland network to be served (Van Klink *et al.*, 1998; Verbeke and Dooms, 2007; Veenstra *et al.*, 2012). Indeed, port competitiveness increasingly depends on the reliability and efficiency of inland connections, rather than solely on terminal performance (Notteboom and Rodrigue, 2005; Parola *et al.*, 2017; Hales *et al.*, 2016).

Notoriously, the empowerment of physical infrastructures (e.g. additional lanes, new junctions and road sections) takes a long time and huge financial and administrative efforts, leaving logistics problems unsolved in the short/mid-term. Infrastructure expansion processes are typically characterized by high investment costs, long planning horizons and complex regulatory procedures (Lakshmanan and Anderson, 2001; Radzi *et al.*, 2023). Conversely, superior efficiency in the exploitation of road infrastructures constitutes a prompt solution capable of optimizing the use of existing facilities, sharing information about the traffic status among users, improving traffic distribution and fluidity, and mitigating the impact of construction sites on the route. Addressing these challenges requires adopting advanced technological tools to proactively monitor and manage traffic to prevent or alleviate the negative impacts of infrastructure criticalities.

In line with this perspective, DSS represent a particularly suitable approach for managing complex and dynamic transport systems, as they enable the integration of heterogeneous data sources, support scenario analysis and facilitate coordinated decision-making among multiple stakeholders (Power, 2013; Loucks, 1995).

In light of the strategic role of such infrastructures, data plays a fundamental role in enhancing the efficiency, resilience and overall performance of complex transport networks. Highways, as critical connectors between ports and inland logistics hubs, require a continuous exchange of information with other land-based infrastructures to ensure smooth operations. The increasing availability of real-time and big data in transport systems is enabling more advanced forms of traffic monitoring and predictive analysis (Tyrogianni *et al.*, 2012; Zhang *et al.*, 2024).

In this sense, several emerging digital technologies enable the development of IT-based DSS, i.e. flexible and adaptive computer-based information systems (IS), developed for supporting the solution of management problems by utilizing data, providing an easy-to-use interface and allowing for decision makers' own insights (Power, 2013).

As argued by [Loucks \(1995\)](#), DSS are particularly suitable for supporting decision-making in complex systems where uncertainty, multiple stakeholders and scenario analysis play a central role, making them appropriate tools for addressing the challenges discussed in this paper.

In this perspective, IT-based DSS represent a promising class of tools for providing data-driven support to highway management and development, with potential long-term benefits for port competitiveness and hinterland connectivity. These systems serve two key long-term objectives: (1) enhancing the competitiveness of ports by optimizing their connectivity to inland logistics and (2) ensuring sustainability by minimizing the environmental and social impact of freight flows on the local economy and territory.

Despite the academic literature has extensively investigated the major drivers of port competitiveness, emphasizing the key role played by external dimensions such as the endowment of inland transport infrastructures and the efficiency of hinterland connectivity ([De Martino and Morvillo, 2008](#); [Kaliszewski et al., 2020](#); [Luo et al., 2022](#)), the function of road transport and the potential of IT-based DSS in boosting port performance have been largely neglected so far. Existing studies have predominantly focused on rail and intermodal solutions, leaving highway systems comparatively underrepresented in analytical frameworks ([Behdani et al., 2020](#); [Sdoukopoulos and Boile, 2020](#)). This brings to a first, largely overlooked, theoretical gap concerning how road network efficiency and resilience contribute to port competitiveness as exogenous drivers within maritime logistics literature.

Building upon this gap, the present study proposes a conceptual reframing in which road connectivity – interpreted through its efficiency and resilience – constitutes a critical yet underexplored component of port competitiveness.

Moreover, a second, methodological gap emerges from the limited integration of operational tools capable of translating these conceptual dimensions into measurable constructs for decision-makers. In this regard, this study introduces an IT-based DSS approach designed to support the systematic assessment of road capacity and service levels in port-hinterland corridors.

The paper introduces, through an inductive approach, the design and implementation of an IT-based DSS solution that leverages currently existing/available data to develop a data-feeding architecture in Power Query, which compares the actual highway capacity near leading gateway ports and relevant traffic volumes over a specific time frame.

In particular, the proposed DSS framework supports the analysis of the actual congestion levels associated with specific traffic volumes on individual highway sections. This provides insights into the quality of the Levels of Service (LOS) measured on the highway infrastructures, connecting gateway ports with their hinterlands ([Ferrari et al., 1982](#)). Such IT-based managerial architecture enables decision makers to explore key areas of optimization including: (1) day-to-day traffic management, (2) light and heavy maintenance programs and (3) timely infrastructural development. Finally, the paper provides policy insights and managerial implications for major stakeholders' categories, including various public decision-makers (i.e. awarding authorities, infrastructure planners, independent regulatory authorities and competent Ministries), motorways concessionaires, B2B and B2C users, and other societal and economic groups of interest (e.g. citizens, local industries, port firms, Port Authorities, etc.).

The remainder of the paper is organized as follows. [Section 2](#) introduces the notion of port competitiveness and outlines the theoretical gap, focusing on road infrastructure efficiency and resilience as underexplored exogenous drivers. This section also emphasizes the associated methodological limitations and presents the conceptual framework grounded in the three analytical dimensions of traffic management, maintenance programs and infrastructure development. [Section 3](#) develops the methodological framework, introducing the DSS architecture for highway performance assessment, presents the applied methodology and discloses the main

findings. Finally, [Section 4](#) discusses the theoretical and practical implications, before The TQM Journal concluding with [Section 5](#).

2. Literature review and research gap

2.1 Port competitiveness and road transport

In an increasingly interconnected and dynamic trade environment, port competitiveness is no longer determined solely by the efficiency of maritime operations within the terminal. Instead, it is increasingly shaped by exogenous factors, particularly those related to hinterland transportation. The efficiency, reliability and sustainability of port supply chains extend far beyond the physical boundaries of the port, making the seamless integration between maritime and hinterland cargo flows a critical success factor. In line with a consolidated strand of research on port competitiveness (e.g. [Notteboom and Rodrigue, 2005](#); [Notteboom and Yap, 2012](#); [Parola et al., 2017](#); [Yu et al., 2025](#)), hinterland accessibility and the performance of inland corridors are now widely recognized as decisive components of ports' competitive positioning. Yet most contributions have concentrated on rail-based solutions, leaving a substantial knowledge gap concerning the analytical mechanisms through which highway systems condition port performance.

Synchronizing inbound and outbound cargo flows is essential for ensuring that port operations are not only efficient in terms of handling capacity but also aligned with the frequency (inter-arrival times) and volume (capacity of the means of transport) requirements of the various transport modes serving the hinterland. In fact, one of the key challenges in achieving synchronized and seamless logistics is the complexity and diversity of hinterland cargo flows. Indeed, vessels are characterized by big volume sizes and a low frequency, whereas trains and, above all, trucks typically unveil a much lower transport capacity and frequent inter-arrival times. Such profound "asymmetry" imposes a tremendous "pressure" on ports and, in turn, on landside infrastructures ([Li et al., 2024](#)).

Road transport, holding a modal split (often) largely above 50%, is called to play a dominant role in connecting ports to their hinterlands due to its operational flexibility, faster transit times and cost-effectiveness. Even in long-distance freight distribution, road transport remains a preferred option, often complementing rail and inland waterway transport for last-mile logistics. Its ability to provide door-to-door service by adapting quickly to demand fluctuations gives it a competitive edge over other transport modes. This operational centrality strengthens the argument that highway performance represents a fundamental, yet insufficiently conceptualized, exogenous driver of port competitiveness.

The dependence on road transport presents several challenges to port areas, particularly in relation to urban development, societal acceptance and local value creation. Port-related truck flows often overlap with urban mobility, leading to increased congestion, environmental concerns and "conflicts" with local communities. Finding a balance between logistical efficiency and societal acceptance is a delicate issue that requires strategic planning and innovative solutions. In this regard, investments in IT-based DSS, real-time traffic management and capacity optimization strategies can mitigate the negative externalities of road transport while safeguarding port competitiveness.

Considering these dynamics, the integration of road transport into an optimized multimodal logistics network is essential for the long-term sustainability and competitiveness of ports ([Forte and Siviero, 2014](#)). However, despite the relevance of this sector, the literature still lacks a structured analytical account of the connectivity and resilience of highway systems as determinants of port performance, an aspect more thoroughly discussed in the next subsection.

2.2 Road connectivity and resilience as exogenous competitiveness drivers: the theoretical gap

Although efficiency in hinterland transportation requires coordinated and high-performing inland infrastructures, the literature addressing port-hinterland connectivity has tended to

privilege rail corridors and inland waterways, thereby underrepresenting the contribution of highways. This imbalance leaves the theoretical underpinnings of road-based connectivity and resilience only partially explored, despite their centrality in many port systems.

To address this gap, the present study proposes a conceptual reframing in which the performance of highway systems is viewed as an integral component of the exogenous determinants of port competitiveness. Within this perspective, road connectivity and the capacity of motorway networks to absorb, manage and recover from disruptions emerge as key channels through which ports preserve accessibility, stability and service reliability. Such a reframing requires clarifying the analytical dimensions through which highways influence port performance. As shown in [Figure 1](#), road connectivity and resilience are analytically articulated through three interrelated dimensions.

- i. Traffic management, capturing the ability of motorway networks to maintain fluid circulation under variable demand;
- ii. Asset maintenance, accounting for infrastructure condition, planned interventions and constraints generated by roadworks;
- iii. Infrastructure development, reflecting long-term investment decisions that shape future accessibility and corridor competitiveness.

The complexity of this system is further heightened by the ramifications of road networks, which, while ensuring broad logistical capillarity, also introduce critical inland junctures characterized by relevant cargo volumes and congestion risks. At these pivotal nodes/sections, even minor disruptions can trigger severe inefficiencies that might propagate along the entire supply chain. Within the conceptual logic proposed here, such disruptions undermine the stability of the three analytical dimensions identified above, thus directly affecting the capacity of ports to maintain regular inland flows.

Disruptions in inland supply chains can stem from two primary sources: (1) exogenous factors, such as extreme weather events, strikes, accidents or geopolitical tensions, and (2) endogenous factors, including poor infrastructure maintenance, suboptimal capacity planning or inefficient traffic management. Both types of disruptions can lead to substantial bottlenecks, slowing down cargo distribution and deteriorating port-hinterland connectivity. In addition to this, it's worth emphasizing that the negative impact of specific bottlenecks originating in

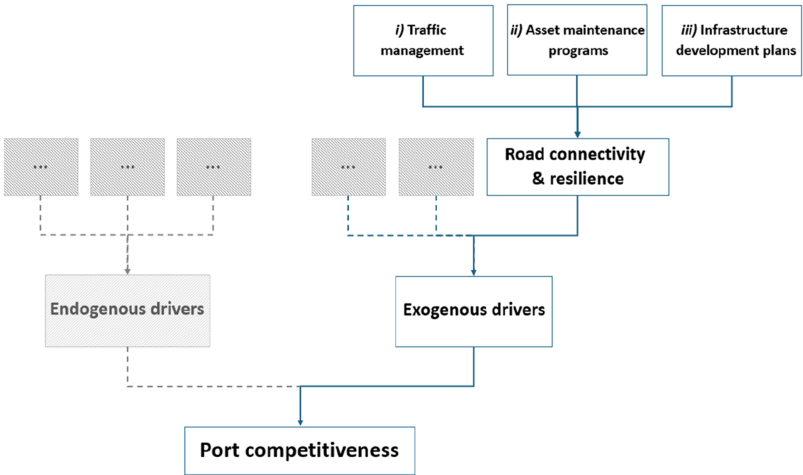


Figure 1. Conceptual framework. Source: Authors' elaboration

some logistics nodes or infrastructure sections might easily propagate across the entire supply chain. Such a cascading effect may be somewhat comparable to the bullwhip effect, first formalized by [Lee et al. \(1997\)](#) to describe the amplification of demand variability along multi-tier supply chains, and has since been widely applied in logistics and transport studies to explain how localized disruptions can propagate across interconnected networks. In port-hinterland systems, this mechanism may help interpret how congestion at a single inland node triggers cascading delays that deteriorate the stability of the entire corridor.

In this perspective, a congestion event implying traffic jams, extra-dwell times or transit times at a key inland junction does not merely affect the immediate logistics assets; instead, its impact spreads progressively over time, imposing even more severe slowing down on operations across the broader logistics system. The recovery process can take weeks or even months, as demonstrated during the COVID-19 pandemic, where port congestion in China had ripple effects on global supply chains long after the initial disruption had been resolved.

In summary, the theoretical gap addressed in this section concerns the absence of a structured conceptualization linking highway connectivity and resilience to port competitiveness, and the lack of a clear analytical framework capturing the three dimensions, traffic management, asset maintenance and infrastructure development, through which the highway system influences port performance. This gap motivates the methodological discussion developed in the next section.

2.3 Assessing highway performance for port-hinterland logistics: the methodological gap

The efficient management of highway infrastructures is crucial for maintaining seamless hinterland connectivity, ensuring logistics efficiency and preserving the competitiveness of port-hinterland supply chains. Highway networks serve as fundamental corridors linking ports to inland logistics hubs, supporting various flows of goods, commuters and tourists. However, the increasing complexity of these flows and the variability of demand bring significant challenges to maintaining acceptable service levels across the network.

Despite the vast corpus of transport engineering research on capacity analysis, highway performance modeling and LOS evaluation, existing methodologies have not been systematically applied to support port-related assessments. More specifically, no methodological contribution has operationalized the three analytical dimensions identified in [Section 2.2](#), traffic management, asset maintenance and infrastructure development, within a unified evaluation framework capable of linking highway performance to port competitiveness.

Under this perspective, a fundamental indicator for assessing highway performance is the LOS metric, as defined by the Highway Capacity Manual ([HCM, 2000](#)). LOS reflects the interaction between service supply and traffic demand, categorizing road performance from “free-flow” conditions (LOS “A”) to fully congested states (LOS “F”). Two main categories of factors influence highway capacity.

- “Static” supply factors, which include the physical characteristics of the infrastructure, such as lane width, curvature radius and technological systems;
- “Dynamic” supply factors, which relate to service management, including maintenance scheduling, adaptive traffic management (e.g. opening and closing of lanes and sections), differentiated toll pricing strategies and external disruptions such as road accidents and adverse weather conditions.

Traffic demand, on the other hand, is shaped by a variety of heterogeneous factors that influence user behavior. These can be broadly categorized as (1) logistics cargo flows, (2) commuting flows and (3) tourist flows.

Yet LOS has rarely been integrated into decision-support frameworks that inform port authorities or corridor managers about the consequences of congestion, maintenance or

infrastructural choices on port-hinterland logistics. The lack of such an integrated approach constitutes the methodological gap this study addresses.

The absence of operational tools connecting LOS evaluations to the three analytical dimensions of the conceptual framework limits the ability of decision-makers to anticipate bottlenecks, plan maintenance with minimal logistics disruptions and evaluate the long-term competitiveness of port corridors. These limitations justify the development of the DSS presented in [Section 3](#), which translates the theoretical constructs into an applied architecture.

3. The proposed IT-based DSS framework for port-hinterland highway performance assessment

3.1 Conceptual foundations of the DSS architecture

Building on the theoretical gap identified in [Section 2.2](#) and the methodological limitations highlighted in [Section 2.3](#), this section introduces an IT-based DSS designed to operationalize the analytical dimensions through which highway systems influence port competitiveness.

From a port perspective, the DSS is conceived as a decision-support tool capable of monitoring and anticipating highway service conditions that may affect the regularity, reliability and efficiency of cargo flows between port terminals and their hinterland markets.

While scholars increasingly recognize the decisive role of exogenous factors in determining the success or failure of ports, research has primarily focused on rail and barge transport. Highway infrastructures, by contrast, have lacked analytical instruments capable of capturing their contribution to port performance in a structured and data-driven manner. The DSS framework developed in this study directly responds to this limitation, offering a methodological architecture that mirrors the conceptual structure proposed earlier ([Section 2.2](#)).

The methodological contribution of this study lies in the development of a structured DSS framework aimed at assessing highway performance in terms of effective capacity utilization and LOS, with specific reference to motorway sections serving gateway ports and their hinterlands. In doing so, it provides an operational extension of the conceptual framework, enabling decision-makers to quantify how changes in highway conditions affect port accessibility and competitiveness.

Importantly, the study adopts an illustrative, proof-of-concept approach aimed at demonstrating the internal coherence and operational logic of the proposed DSS architecture, rather than providing empirical validation or performance benchmarking. In this perspective, the DSS should be interpreted as a methodological and analytical tool that enables structured observation, comparison and interpretation of highway capacity conditions under different operating scenarios.

This framework is built on the strategic exploitation of three distinct categories of data – historical, real-time and predictive – which together enable an overarching approach to deal with short- and long-term highway performance assessment and infrastructure management.

In particular, historical data that refers to past traffic volumes, asset condition records, maintenance logs and LOS performance serve as the foundation for benchmarking current infrastructure performance. These data allow decision-makers to identify long-term trends, recognize recurring congestion patterns and evaluate the effectiveness of previous maintenance strategies.

Real-time data, collected through smart sensors, GPS systems and satellite localization technologies, provide a continuous flow of up-to-date information on traffic conditions, vehicle composition (distinguishing between light vehicles, heavy trucks, port-related traffic, etc.), and any emerging disruptions (e.g. accidents, weather events, roadworks, strikes, etc.). This data stream supports immediate, timely interventions to maintain acceptable service levels and ensure traffic fluidity.

Finally, predictive data derived from forecasting models and simulation tools enable public and private stakeholders to anticipate future demand shifts and mitigate the risk of emerging

bottlenecks and capacity constraints. These insights are instrumental in informing long-term infrastructure planning, maintenance prioritization and investment decisions. By integrating these three data layers into a dedicated decision-support environment, the DSS translates the conceptual foundations of highway connectivity and resilience into an operational methodology. This approach not only addresses the methodological gap identified earlier but also provides concrete analytical tools for infrastructure managers and port authorities seeking to enhance the competitiveness of port-hinterland systems.

3.2 DSS architecture

Although academics agree on the most promising digital technologies for sea-land logistics in the future, a deeper analysis is required to disentangle the main business opportunities for highway infrastructures and enhance port competitiveness.

To reach these macro-objectives, in this section, a methodological approach is proposed that operationally translates the conceptual framework presented in Figure 1 into the IT-based DSS architecture illustrated in Figure 2. In this way, the DSS architecture captures key selected aspects of the highway performance dimension of the conceptual framework, while port competitiveness remains a conceptual reference dimension.

The first phase is to create an asset inventory system where the minimum observation unit should be identified, i.e. the elementary highway section. Then, for each section, several technical details are collected, including the number of lanes, the width of lanes, the presence of emergency lanes or not and the maximum speed allowed. Finally, the principles and criteria contained in the HCM 2000 have been applied to input data for estimating the theoretical capacity of each section of the highway infrastructure, in the absence of any form of congestion or physical limitations to the regular flow.

Indeed, the DSS proposed in Figure 2 is based on the difference between the theoretical capacity of the infrastructure, defined as the capacity derived from the technical construction characteristics of the roadway, and the effective capacity, which is influenced by management

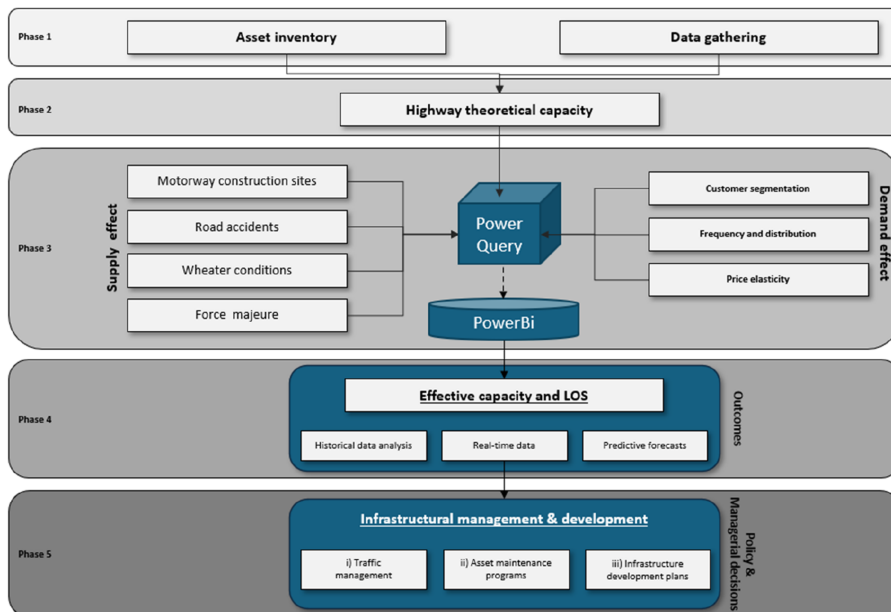


Figure 2. Proposed DSS architecture Source: Authors' elaboration

decisions of the highway concessionaire, unpredictable or partially predictable events and user behavioral choices.

Factors that might reduce theoretical capacity can be classified into two main categories: (1) supply-related factors, which can be fully or, at least partially, managed by the highway concessionaire, and (2) demand-related factors, which derive from the demographics and the behavioral choices of highway B2B and B2C users.

On the supply side, several elements impact the effective capacity of the highway network; among these, construction sites are a major factor, as they reduce the number of available lanes and lower the maximum allowed speed limits in specific sections, leading to congestion and delays. Then, traffic accidents also might play a significant role, as they may temporarily block traffic, either partially or completely, thus challenging network resilience. Additionally, weather conditions, such as (heavy) rain, snow, wind or fog, affect driving speeds, contributing to a reduction in the expected capacity of the highway. Finally, force majeure events, including natural disasters, unforeseen operational challenges, or external incidents beyond the control of the highway operator, may occur, making it virtually impossible to implement preventive measures.

On the demand side, several other factors influence highway capacity. One above all is customer segmentation: indeed, motorway users are not all the same; they can be classified based on travel purposes and vehicle types. A key distinction is between B2B traffic, primarily composed of trucks used for heavy freight transport, and B2C traffic, which includes private cars used for personal mobility. Within the B2B segment, it is also crucial to differentiate between port-related trucks, which are directly linked to port logistics, and other freight trucks operating independently from port activities. The frequency and temporal distribution of trips also affect the available capacity, considering, for example, peak hours during the day as well as traffic distribution throughout the week or year, reflecting seasonal variations in demand. Moreover, price elasticity plays a crucial role in users' travel choices, capturing the sensitivity of demand to changes in toll prices or travel costs.

Once all the above data has been collected and imported into the Power Query platform, the third phase of the procedure starts with data cleaning and data quality assessment. Finally, when data have been processed and linked via unique keys, the dataset is ready to calculate the effective capacity compared to theoretical capacity, and to determine the corresponding LOS based on a reference benchmark.

LOS is a standardized metric applied to evaluate the operational efficiency and quality of highway infrastructures by analyzing traffic conditions, capacity utilization and user experience (Tian and Chen, 2009). HCM 200 defines six LOS from A to F, with LOS A representing the best operating conditions and LOS F the worst. According to HCM 2000, the main factors affecting the LOS are traffic volume, speed and flow rate, infrastructure theoretical capacity, geometric and physical conditions, traffic density, vehicle interactions and lane changes (customer behavior), environmental and weather conditions, presence and type of ramps, junctions and intersections and incidents and traffic disruptions.

Once the necessary calculated fields are added, the data are imported into Power BI, a tool that provides advanced capabilities for building interactive and customizable dashboards. The outcome of these dashboards represents the fourth phase, during which the actual capacity and related LOS are identified for each highway section. By monitoring how LOS values evolve in relation to effective capacity, it becomes possible to identify potential historical, current and future criticalities on specific highway sections, while providing timely monitoring and decision-support tools.

In particular, historical data analysis enables a comprehensive evaluation of past traffic conditions, road usage and service levels. This analysis reveals key insights regarding highway performance, identifying patterns and trends that are essential to measure the effective capacity of highways and determining LOS.

On the other hand, the DSS allows for making predictions on potential congestion, queuing and how these factors could affect traffic flow and LOS. This information plays a key role in

planning the optimization of construction sites, minimizing delays and enhancing traffic management strategies.

Finally, the real-time data are crucial for providing real-time updates to various stakeholders, including public authorities, local institutions as well as users. The real-time data, if provided in a structured and prompt way, can help in making informed travel plan decisions, improving the efficiency of highway networks, but also to optimize the timing and the technical contents of construction projects, and support policymakers at different levels.

Indeed, exchanging information with regulatory bodies, local institutions and the Port Authority is important to ensure coordination and address potential problems before they affect public or commercial users. This dialogue contributes to more effective management of transport infrastructure, ensuring smoother operations and reducing disruptions.

3.3 Data and implementation

To simulate the functioning of the proposed DSS architecture, a synthetic dataset was developed to reproduce realistic traffic dynamics on highway infrastructures. Although the dataset is synthetically generated, it is constructed starting from a limited real-world sample of traffic observations. In particular, the synthetic data preserve the key structural characteristics observed in the empirical sample, including the proportion of heavy and light vehicles, hourly traffic distribution patterns and typical daily and weekly variability. This approach ensures internal consistency while approximating some typical traffic patterns commonly observed in motorway networks.

The dataset shown in [Figure 3](#) simulates vehicle flows on a specific highway segment (denoted as the j -th section), capturing traffic volumes on an hourly basis for each day of the week. It distinguishes between light vehicles and heavy vehicles and covers a hypothetical observation period of 31 consecutive days (from July 1st to July 31st, 2023). The simulation incorporates daily and weekly traffic variation patterns derived from the empirical sample and ensuring realistic peak-hour dynamics and demand fluctuations.

Additional variables are incorporated to represent the theoretical capacity and reduced capacity due to roadworks on the same section. These capacity values are defined according to the standard thresholds outlined in the [HCM 2000](#) to ensure transparency and potential replicability. In particular, the theoretical maximum capacity was calculated by assuming that the simulated section includes two lanes per direction, each with a maximum capacity of 2,400 vehicles per hour, resulting in a total capacity of 4,800 vehicles per hour under normal operating conditions. On the other hand, the reduced capacity under roadwork conditions was determined by assuming that only one lane per direction is available, lowering the total section capacity to 2,400 vehicles per hour.

To enhance transparency and potential replicability, the main data-generation rules and assumptions are now explicitly defined. These include (1) the proportional distribution of vehicle categories (light versus heavy), (2) the temporal allocation of traffic volumes across hourly intervals and (3) the calibration of LOS thresholds based on standardized HCM classifications.

It is important to clarify that the synthetic dataset is not intended to provide a full empirical validation of the DSS performance. Rather, it is designed to illustrate the operational logic of the architecture and to demonstrate how variations in capacity and demand affect LOS outcomes under controlled scenarios.

Accordingly, the current application should be interpreted as a simulation-based demonstration of the DSS capabilities, not as an assessment of its predictive accuracy, reliability or superiority compared to alternative approaches. This limitation is acknowledged and will be further discussed in the Conclusions, where future research directions are outlined.

Based on these assumptions and using the LOS classification criteria derived from the HCM, traffic volume thresholds are computed to define the reference LOS for each section with and without roadwork sites ([Figure 4](#)).

Roadwork site	Date	Hour	From	To	From-To	Direction	Section	Light volumes	Heavy volumes	Total volumes	N. Lane	Speed limits	Theoretical capacity	LOS A	LOS B	LOS C	LOS D	LOS E	% LOS A	% LOS B	% LOS C	% LOS D	% LOS E
No	01/07/2023	0	sect_3	sect_4	sect_3 - sect_4	North	i-th section	226	43	269	1	60	4.300	980	1.540	2.433	3.603	4.300	1	0	0	0	0
No	01/07/2023	0	sect_5	sect_3	sect_5 - sect_3	North	i-th section	283	79	362	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	01/07/2023	0	sect_8	sect_9	sect_8 - sect_9	North	i-th section	207	75	282	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	01/07/2023	0	sect_9	sect_5	sect_9 - sect_5	North	i-th section	226	59	285	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	01/07/2023	0	sect_11	sect_12	ect_11 - sect_1	North	i-th section	200	51	251	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	01/07/2023	0	sect_12	sect_8	sect_12 - sect_8	North	i-th section	207	61	268	1	100	4.600	1.400	2.200	3.200	4.130	4.600	1	0	0	0	0
No	01/07/2023	0	sect_14	sect_15	ect_14 - sect_1	North	i-th section	125	33	158	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	01/07/2023	0	sect_15	sect_11	ect_15 - sect_1	North	i-th section	221	152	373	1	110	4.700	1.540	2.420	3.480	4.270	4.700	1	0	0	0	0
No	02/07/2023	0	sect_3	sect_4	sect_3 - sect_4	North	i-th section	719	38	757	1	60	4.300	980	1.540	2.433	3.603	4.300	1	0	0	0	0
No	02/07/2023	0	sect_5	sect_3	sect_5 - sect_3	North	i-th section	1102	77	1179	1	80	4.400	1.120	1.760	2.680	3.768	4.400	0	1	1	0	0
No	02/07/2023	0	sect_8	sect_9	sect_8 - sect_9	North	i-th section	1405	108	1513	1	80	4.400	1.120	1.760	2.680	3.768	4.400	0	1	0	0	0
No	02/07/2023	0	sect_9	sect_5	sect_9 - sect_5	North	i-th section	1112	50	1162	1	80	4.400	1.120	1.760	2.680	3.768	4.400	0	1	0	0	0
No	02/07/2023	0	sect_11	sect_12	ect_11 - sect_1	North	i-th section	736	130	866	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	02/07/2023	0	sect_12	sect_8	sect_12 - sect_8	North	i-th section	1038	53	1091	1	100	4.600	1.400	2.200	3.200	4.130	4.600	1	0	0	0	0
No	02/07/2023	0	sect_14	sect_15	ect_14 - sect_1	North	i-th section	388	29	417	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	02/07/2023	0	sect_15	sect_11	ect_15 - sect_1	North	i-th section	789	149	938	1	110	4.700	1.540	2.420	3.480	4.270	4.700	1	0	0	0	0
No	03/07/2023	0	sect_3	sect_4	sect_3 - sect_4	North	i-th section	117	24	141	1	60	4.300	980	1.540	2.433	3.603	4.300	1	0	0	0	0
No	03/07/2023	0	sect_5	sect_3	sect_5 - sect_3	North	i-th section	152	45	197	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	03/07/2023	0	sect_8	sect_9	sect_8 - sect_9	North	i-th section	87	62	149	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	03/07/2023	0	sect_9	sect_5	sect_9 - sect_5	North	i-th section	145	38	183	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	03/07/2023	0	sect_11	sect_12	ect_11 - sect_1	North	i-th section	136	0	136	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	03/07/2023	0	sect_12	sect_8	sect_12 - sect_8	North	i-th section	94	38	132	1	100	4.600	1.400	2.200	3.200	4.130	4.600	1	0	0	0	0
No	03/07/2023	0	sect_14	sect_15	ect_14 - sect_1	North	i-th section	64	7	71	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	03/07/2023	0	sect_15	sect_11	ect_15 - sect_1	North	i-th section	96	0	96	1	110	4.700	1.540	2.420	3.480	4.270	4.700	1	0	0	0	0
No	04/07/2023	0	sect_3	sect_4	sect_3 - sect_4	North	i-th section	137	46	183	1	60	4.300	980	1.540	2.433	3.603	4.300	1	0	0	0	0
No	04/07/2023	0	sect_5	sect_3	sect_5 - sect_3	North	i-th section	164	85	249	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	04/07/2023	0	sect_8	sect_9	sect_8 - sect_9	North	i-th section	71	107	178	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	04/07/2023	0	sect_9	sect_5	sect_9 - sect_5	North	i-th section	143	72	215	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	04/07/2023	0	sect_11	sect_12	ect_11 - sect_1	North	i-th section	34	19	53	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	04/07/2023	0	sect_12	sect_8	sect_12 - sect_8	North	i-th section	31	78	109	1	100	4.600	1.400	2.200	3.200	4.130	4.600	1	0	0	0	0
No	04/07/2023	0	sect_14	sect_15	ect_14 - sect_1	North	i-th section	32	21	53	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	04/07/2023	0	sect_15	sect_11	ect_15 - sect_1	North	i-th section	38	77	115	1	110	4.700	1.540	2.420	3.480	4.270	4.700	1	0	0	0	0
No	05/07/2023	0	sect_3	sect_4	sect_3 - sect_4	North	i-th section	252	69	321	1	60	4.300	980	1.540	2.433	3.603	4.300	1	0	0	0	0
No	05/07/2023	0	sect_5	sect_3	sect_5 - sect_3	North	i-th section	300	130	430	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	05/07/2023	0	sect_8	sect_9	sect_8 - sect_9	North	i-th section	104	111	305	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	05/07/2023	0	sect_9	sect_5	sect_9 - sect_5	North	i-th section	255	110	365	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	05/07/2023	0	sect_11	sect_12	ect_11 - sect_1	North	i-th section	142	26	168	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	05/07/2023	0	sect_12	sect_8	sect_12 - sect_8	North	i-th section	147	63	210	1	100	4.600	1.400	2.200	3.200	4.130	4.600	1	0	0	0	0
No	05/07/2023	0	sect_14	sect_15	ect_14 - sect_1	North	i-th section	76	8	84	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	05/07/2023	0	sect_15	sect_11	ect_15 - sect_1	North	i-th section	92	147	239	1	110	4.700	1.540	2.420	3.480	4.270	4.700	1	0	0	0	0
No	06/07/2023	0	sect_3	sect_4	sect_3 - sect_4	North	i-th section	176	17	193	1	60	4.300	980	1.540	2.433	3.603	4.300	1	0	0	0	0
No	06/07/2023	0	sect_5	sect_3	sect_5 - sect_3	North	i-th section	215	32	247	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	06/07/2023	0	sect_8	sect_9	sect_8 - sect_9	North	i-th section	158	131	289	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	06/07/2023	0	sect_9	sect_5	sect_9 - sect_5	North	i-th section	178	27	205	1	80	4.400	1.120	1.760	2.680	3.768	4.400	1	0	0	0	0
No	06/07/2023	0	sect_11	sect_12	ect_11 - sect_1	North	i-th section	100	0	100	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	06/07/2023	0	sect_12	sect_8	sect_12 - sect_8	North	i-th section	138	70	208	1	100	4.600	1.400	2.200	3.200	4.130	4.600	1	0	0	0	0
No	06/07/2023	0	sect_14	sect_15	ect_14 - sect_1	North	i-th section	96	15	111	1	90	4.500	1.260	1.980	2.880	3.910	4.500	1	0	0	0	0
No	06/07/2023	0	sect_15	sect_11	ect_15 - sect_1	North	i-th section	121	145	266	1	110	4.700	1.540	2.420	3.480	4.270	4.700	1	0	0	0	0
No	07/07/2023	0	sect_3	sect_4	sect_3 - sect_4	North	i-th section	346	46	392	1	60	4.300	980	1.540	2.433	3.603	4.300	1	0	0	0	0

Figure 3. Vehicle transits and infrastructure capacity dataset. Source: Authors' elaboration

From	to	N. lane	Speed limits	Theoretical capacity	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
sect_1	sect_2	2	120	4.800	1.680	2.640	3.680	4.400	4.800	> 4800
sect_6	sect_7	2	120	4.800	1.680	2.640	3.680	4.400	4.800	> 4800
sect_2	sect_10	2	120	4.800	1.680	2.640	3.680	4.400	4.800	> 4800
sect_10	sect_13	2	120	4.800	1.680	2.640	3.680	4.400	4.800	> 4800
sect_3	sect_4	2	60	4.300	980	1.540	2.433	3.603	4.300	> 4300
sect_5	sect_3	2	80	4.400	1.120	1.760	2.680	3.768	4.400	> 4400
sect_8	sect_9	2	80	4.400	1.120	1.760	2.680	3.768	4.400	> 4400
sect_9	sect_5	2	80	4.400	1.120	1.760	2.680	3.768	4.400	> 4400
sect_11	sect_12	2	90	4.500	1.260	1.980	2.880	3.910	4.500	> 4500
sect_12	sect_8	2	100	4.600	1.400	2.200	3.200	4.130	4.600	> 4600
sect_14	sect_15	2	90	4.500	1.260	1.980	2.880	3.910	4.500	> 4500
sect_15	sect_11	2	110	4.700	1.540	2.420	3.480	4.270	4.700	> 4700

From	to	N. lane	Speed limits	Reduced capacity	LOS A	LOS B	LOS C	LOS D	LOS E	LOS F
sect_1	sect_2	1	120	2.400	840	1.320	1.840	2.200	2.400	> 2400
sect_6	sect_7	1	120	2.400	840	1.320	1.840	2.200	2.400	> 2400
sect_2	sect_10	1	120	2.400	840	1.320	1.840	2.200	2.400	> 2400
sect_10	sect_13	1	120	2.400	840	1.320	1.840	2.200	2.400	> 2400
sect_3	sect_4	1	60	2.150	490	770	1.216	1.801	2.150	> 2150
sect_5	sect_3	1	80	2.200	560	880	1.340	1.884	2.200	> 2200
sect_8	sect_9	1	80	2.200	560	880	1.340	1.884	2.200	> 2200
sect_9	sect_5	1	80	2.200	560	880	1.340	1.884	2.200	> 2200
sect_11	sect_12	1	90	2.250	630	990	1.440	1.955	2.250	> 2250
sect_12	sect_8	1	100	2.300	700	1.100	1.600	2.065	2.300	> 2300
sect_14	sect_15	1	90	2.250	630	990	1.440	1.955	2.250	> 2250
sect_15	sect_11	1	110	2.350	770	1.210	1.740	2.135	2.350	> 2350

Figure 4. LOS for section. Source: Authors' elaboration

3.4 Main outcomes

The implementation of the DSS architecture through the Power BI platform enables the development of an interactive and data-rich dashboard that provides an overview of traffic dynamics and LOS across the simulated highway network. The visual interface is designed to support both operational and strategic decision-making by enabling a multi-layered exploration of traffic patterns and infrastructure performance.

As shown in Figure 5, the dashboard provides an overview of the DSS and its core functionalities. On the left side, a panel of filter buttons allows users to select the temporal

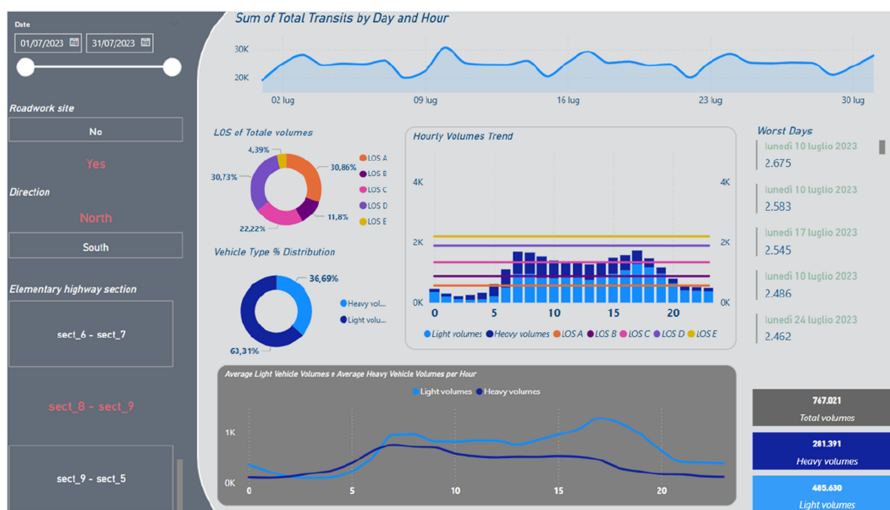


Figure 5. DSS platform overview. Source: Authors' elaboration

range, traffic direction and highway section of interest; once the desired inputs are selected, the central visual area populates with a series of key indicators that permits to the user to understand, among other thing, the total traffic flow and the daily average of light and heavy vehicles volumes with a focus on the distribution (%) of LOS levels observed within the selected timeframe and section.

In Figure 6, a more detailed view is presented, focusing on a single day and a specific highway section. The bar chart shows the hourly trend of traffic flow throughout a single day and identifies the corresponding LOS experienced by users under the assumption of no construction works on the selected section. This visualization illustrates that traffic demand may fluctuate and how infrastructure performance could vary accordingly under the simulated conditions.

Figure 7 replicates the same data as Figure 6 but takes on a new scenario in which the selected highway section is affected by a construction site that reduces the number of available lanes from two to one. In this case, the DSS updates the LOS calculations based on the new reduced theoretical capacity.

A comparison between Figures 6 and 7 clearly highlights the impact of reduced infrastructure capacity due to roadworks. For example, while users traveling between 7:00 and 10:00 and 14:00 and 18:00 experience LOS B or C under normal conditions, the same traffic volumes, when simulated under reduced-capacity conditions, result in a deterioration to LOS D and E. This shift reflects a significant decline in service quality and overall infrastructure performance. Notably, the graph titled “LOS of Total Volumes” displays the hourly distribution of service levels, revealing that 8.33% of users travel under LOS E conditions and 37.5% under LOS D, further confirming the congestion effects generated by lane restrictions. Such deterioration of service levels may represent a potential constraint for circulation, especially in those motorway networks characterized by a traffic mix with a relevant share of heavy vehicles, like in the proximity of seaports and densely populated urban areas. The impact of critical traffic conditions on some motorway stretches on the regular in/outflow of trucks to/from port gates might be disruptive, even imposing the slowdown of terminal and berth operations.

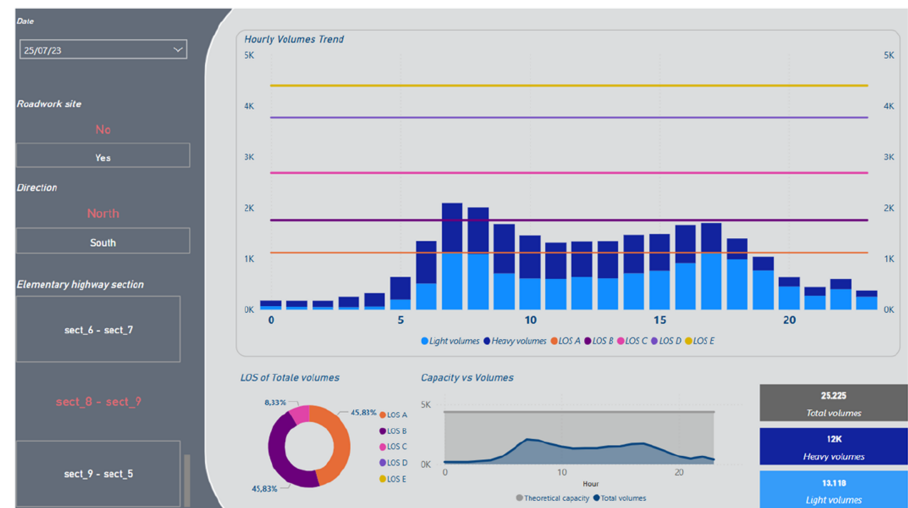


Figure 6. DSS platform – LOS breakdown. Source: Authors’ elaboration

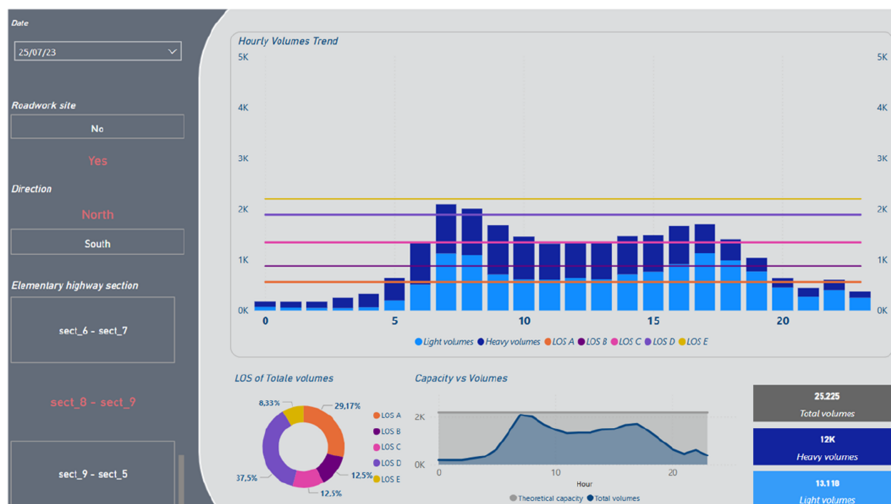


Figure 7. DSS platform – LOS with capacity restrictions. Source: Authors' elaboration

3.5 Expected benefits for managerial decision

The proposed DSS platform, grounded on emerging digital technologies, highlights a number of managerial and policy implications associated with the adoption of data-driven decision-support tools for highway and port-hinterland traffic management. The integration of these technologies through user-friendly software solutions such as Power Query and Power BI illustrates how a flexible and scalable decision-support environment can be developed to support a variety of stakeholders, including service providers, regulators, infrastructure concessionaires, B2B logistics operators, B2C users and policymakers. The proposed DSS architecture illustrates how decision-support tools can contribute to more informed approaches to highway capacity management and traffic flow efficiency, with implications for both short-term operational effectiveness and long-term resilience of port-hinterland transport corridors.

As shown in [Figure 8](#), the DSS architecture supports three main strategic objectives.

3.5.1 Traffic management optimization. One of the key strengths of the proposed DSS is the ability to integrate both historical traffic data and real-time information, providing a comprehensive overview of traffic volumes across individual highway sections. This dual-layered approach enables decision-makers to monitor fluctuations in traffic demand with a high degree of accuracy. Through the analysis of critical time slots, such as peak hours or periods of intense port-related activity, the system can promptly highlight potential bottlenecks before they evolve into severe service disruptions.

Furthermore, the DSS allows for a detailed differentiation between various types of vehicle flows, particularly distinguishing between light and heavy vehicles, including port-related trucks, commuter traffic and private cars. This “granular” breakdown of traffic composition is essential to identify which categories of users are more vulnerable to congestion risks and require tailored management interventions.

Additionally, the system's capacity to capture seasonal trends and variations in traffic flows supports more flexible and dynamic planning processes. By recognizing recurrent patterns (such as increased tourist traffic during holidays or elevated freight volumes during peak trading periods), managers can proactively deploy strategies to mitigate pressure on infrastructure and maintain acceptable service levels throughout the observation period. A greater consciousness about traffic evolution and potential service level deterioration may also

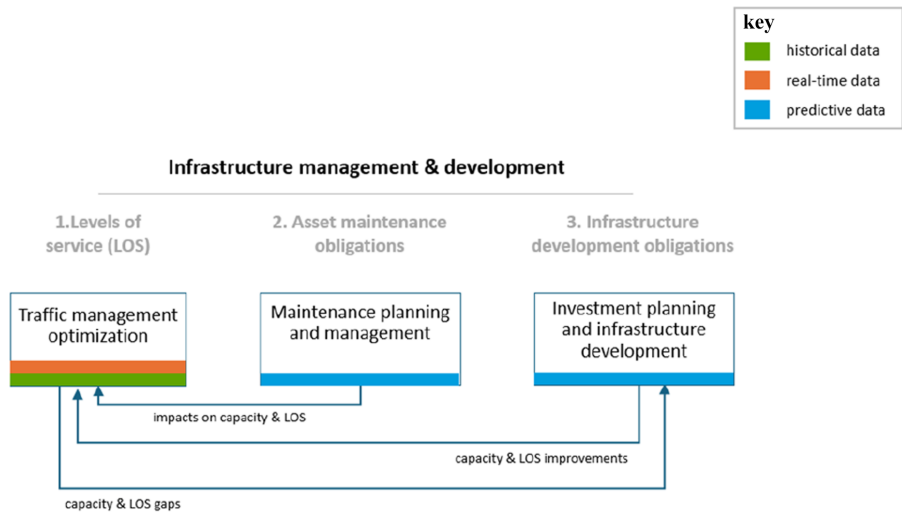


Figure 8. DSS and main managerial decisions. Source: Author' elaboration

stimulate a more effective and prompter disclosure of information by the concessionaire to users that, in turn, could decide to re-route their itinerary or even postpone travel. In particular, truckers could benefit from more effective route optimizations because in such a way they can preserve the operational integrity of assets rotation during the day, performing the minimum mileage which is necessary for ensuring the achievement of the economic break-even.

3.5.2 Maintenance planning and management. Another critical area where the DSS can provide relevant support is in the domain of maintenance planning and lifecycle management of highway assets. The system combines real-time data feeds with long-term historical performance records, enabling infrastructure managers to make informed decisions regarding the scheduling and calibration of both ordinary and extraordinary maintenance activities. This capability is crucial for minimizing the disruptive effects of necessary interventions such as tunnel refurbishments, lane repairs or other infrastructural upgrades. By strategically planning these activities, it is possible to reduce their impact on daily traffic flow and preserve the overall LOS.

Moreover, the proposed DSS offers valuable insights into the progressive obsolescence of infrastructure assets, allowing concessionaires and operators to anticipate future maintenance needs and ensure that the infrastructure is returned at the end of the concession period in the same condition in which it was received.

Importantly, the system also helps prevent uncoordinated or overlapping maintenance works, which could otherwise worsen congestion. By aligning maintenance schedules with actual demand patterns and LOS benchmarks, executives can achieve a more balanced and efficient use of highway capacity by optimizing traffic management across various time intervals during the day.

3.5.3 Investment planning and infrastructure development. Beyond day-to-day operations, the present DSS can also play a strategic role in supporting investment planning and infrastructure development. Its predictive capabilities, based on historical data analysis and traffic demand trends, offer a robust foundation for identifying future capacity constraints and infrastructural weaknesses in specific portions of the network. Through this forward-looking approach, the DSS supports public awarding authorities and private concessionaires in assessing the potential need for new highway sections, the addition of extra lanes or the upgrade of existing junctions. These investment decisions can be closely aligned with the

evolving logistics landscape, including port facilities expansion and the commercial enlargement of the associated hinterland markets to be served, taking into account factors such as the persistent growth of freight volumes or the demand for higher average travel speeds.

In this way, the DSS can become an indispensable tool for shaping long-term policy strategies aimed at strengthening hinterland connectivity, fostering port competitiveness and ensuring that infrastructure development keeps pace with both economic and technological advancements.

Overall, the proposed framework suggests that the adoption of IT-based DSS solutions can generate several benefits for a wide range of stakeholders involved in the management and utilization of highway infrastructures.

For highway concessionaires (and public awarding authorities), the DSS serves as a powerful tool to enhance decision-making processes at multiple levels. By providing real-time data and predictive insights, it enables more efficient traffic management, helping to prevent congestion and ensuring smoother traffic flow. At the same time, the system supports the strategic planning of maintenance activities (both ordinary and extraordinary), allowing operators to schedule interventions in a way that minimizes disruption and extends the life cycle of infrastructure assets. In addition, a prompt identification of future capacity constraints due to demand growth and/or heavy maintenance programs may lead to more conscious and suitable expansion plans (e.g. additional lanes, etc.) for empowering network resilience and preserving long-term service levels. In the long run, this clearly translates into better asset management and a more sustainable use of resources.

Port authorities and logistics operators also can benefit from the availability of such decision-support tools. Reliable and efficient hinterland connectivity is essential for maintaining port competitiveness and expanding hinterland boundaries, and by reducing the risks of congestion-related delays, the DSS helps ensure that cargo flows can move seamlessly between ports and inland destinations. This contributes to greater predictability in logistics operations, which is crucial for supporting import/export activities and meeting tight delivery schedules.

For public decision-makers and regulators, the availability of accurate data-driven information provides a solid foundation for informed policy and investment decisions. The DSS offers clear visibility into current infrastructure performance, helping to identify where new investments are most needed (such as the expansion of highway sections or the development of new connections). Moreover, by aligning infrastructural developments with actual traffic trends and long-term mobility objectives, decision-makers can promote not only greater efficiency but also the sustainability of the transport network. Indeed, regulators could also include in the criteria for toll calculation the quality of motorway infrastructures and the service levels assured to users.

The benefits of the DSS extend to road users themselves, encompassing both B2B users, such as freight transport operators, and B2C users, including private vehicle drivers. For these users, improved travel conditions, reduced congestion and more predictable journey times translate into lower costs, greater reliability and an overall better travel experience.

Finally, local communities and urban authorities play a key role in the broader ecosystem. The DSS contributes to mitigating the negative externalities associated with intense port-related traffic, such as pollution, noise and urban congestion. By fostering more balanced and efficient traffic flows, it supports the coexistence of port activities with local mobility needs, helping to build societal acceptance and promoting a more sustainable integration of logistics infrastructures within urban environments.

Taken together, these elements illustrate how the proposed DSS architecture can support a variety of managerial and policy-oriented decisions across the port-hinterland transport system. The broader theoretical implications of this framework, as well as its relationship with the existing literature on port competitiveness and hinterland connectivity, are further discussed in the following section.

4. Theoretical and practical implications

4.1 Theoretical implications

This study offers a theoretical contribution by repositioning road transport efficiency and resilience as central exogenous drivers of port competitiveness, an area that has remained largely underdeveloped in maritime logistics research.

Building on established contributions on port competitiveness and hinterland connectivity (e.g. [Notteboom and Rodrigue, 2005](#); [Parola et al., 2017](#); [Sdoukopoulos and Boile, 2020](#)), the paper extends this debate by explicitly incorporating highway system performance – traditionally overlooked in favor of rail and intermodal solution – into the set of exogenous determinants shaping port performance.

While prior studies have emphasized rail corridors, inland terminals and intermodal integration, the role of road-based infrastructures has remained under-conceptualized despite its operational relevance in many port systems. By addressing this imbalance, the paper contributes to the debate on port competitiveness by highlighting the role of highway performance as a measurable exogenous determinant.

Specifically, the proposed framework refines the conceptualization of road-based connectivity within port systems by articulating three analytically distinct yet interdependent dimensions that structure the performance of highway systems serving gateway ports. First, the dimension of traffic management captures the system's capacity to handle fluctuating demand, absorb peak loads and preserve acceptable service levels despite the high variability associated with port-related truck flows. In line with prior studies on operational efficiency and service reliability in port systems ([Parola et al., 2017](#)), this dimension highlights how port competitiveness can be interpreted not only as port terminal productivity but also as the dynamic behavior of inland traffic networks.

Second, the maintenance dimension adds a temporal and resilience-oriented layer to the conceptualization of exogenous competitiveness drivers. Road infrastructure is not a static asset, as its effective capacity evolves over time due to planned interventions, unexpected disruptions and the progressive deterioration of physical components. Consistent with emerging research on infrastructure resilience and supply chain disruptions (e.g. [Behdani et al., 2020](#)), incorporating maintenance dynamics into the analytical framework highlights how infrastructure resilience directly influences the reliability and stability of port-hinterland logistics.

Third, the infrastructure development dimension anchors long-term competitiveness in the structural evolution of inland corridors. Investment decisions – such as lane additions, junction upgrades and new sections – shape the strategic alignment between port growth trajectories and the capacity of surrounding transport networks. This perspective aligns with existing research on port regionalization and hinterland expansion ([Notteboom and Rodrigue, 2005](#)), emphasizing how inadequate road infrastructure may constrain the spatial and economic reach of ports.

By integrating these three dimensions, the study offers a structured and theoretically grounded conceptualization of road connectivity as an exogenous determinant of port competitiveness. Moreover, the nexus between this theoretical framework and the DSS methodology reinforces the analytical coherence of the contribution: the same dimensions structuring the theoretical gap also shape the methodological outputs, thereby ensuring internal consistency. In doing so, the paper encourages future research to explore causal interactions between roadway performance, supply chain resilience, port terminal operations and hinterland market accessibility, namely domains that have been acknowledged but insufficiently theorized in the existing literature.

4.2 Practical implications

Indeed, the results of this study clearly demonstrate that the implementation of IT-based DSS brings tangible advantages to a wide range of stakeholders involved in the management and utilization of highway infrastructures.

For highway concessionaires (and public awarding authorities), the DSS serves as a powerful tool to enhance decision-making processes at multiple levels. By providing real-time data and predictive insights, it enables more efficient traffic management, helping to prevent congestion and ensuring smoother traffic flow. At the same time, the system supports the strategic planning of maintenance activities (both ordinary and extraordinary), allowing operators to schedule interventions in a way that minimizes disruption and extends the life cycle of infrastructure assets. In addition, a prompt identification of future capacity constraints due to demand growth and/or heavy maintenance programs may lead to more conscious and suitable expansion plans (e.g. additional lanes, etc.) for empowering network resilience and preserving long-term service levels. In the long run, this clearly translates into better asset management and a more sustainable use of resources.

Port authorities and logistics operators also stand to benefit significantly from the deployment of DSS. Reliable and efficient hinterland connectivity is essential for maintaining port competitiveness and expanding hinterland boundaries, and by reducing the risks of congestion-related delays, the DSS helps ensure that cargo flows can move seamlessly between ports and inland destinations. This contributes to greater predictability in logistics operations, which is crucial for supporting import/export activities and meeting tight delivery schedules.

For public decision-makers and regulators, the availability of accurate data-driven information provides a solid foundation for informed policy and investment decisions. The DSS offers clear visibility into current infrastructure performance, helping to identify where new investments are most needed (such as the expansion of highway sections or the development of new connections). Moreover, by aligning infrastructural developments with actual traffic trends and long-term mobility objectives, decision-makers can promote not only greater efficiency but also the sustainability of the transport network. Indeed, regulators could also include in the criteria for toll calculation the quality of motorway infrastructures and the service levels assured to users.

The benefits of the DSS extend to road users themselves, encompassing both B2B users, such as freight transport operators, and B2C users, including private vehicle drivers. For these users, improved travel conditions, reduced congestion and more predictable journey times translate into lower costs, greater reliability and an overall better travel experience.

Finally, local communities and urban authorities play a key role in the broader ecosystem. The DSS contributes to mitigating the negative externalities associated with heavy port-related traffic, such as pollution, noise and urban congestion. By fostering more balanced and efficient traffic flows, it supports the coexistence of port activities with local mobility needs, helping to build societal acceptance and promoting a more sustainable integration of logistics infrastructures within urban environments.

5. Conclusions and further research

The study introduces an innovative approach by applying emerging DSS technologies for managing critical issues in sea-land logistics, emphasizing potential common benefits for service providers, regulators and end users. Beyond its illustrative application, the paper provides a dual contribution by addressing a theoretical gap in the conceptualization of road-based exogenous drivers of port competitiveness and by proposing a methodological architecture that can be operationalized to assess highway efficiency and resilience through simulated scenarios.

On the methodological side, the manuscript presents and operationalizes an IT-based DSS architecture capable of integrating historical, real-time and predictive inputs to estimate capacity and LOS under alternative operating conditions.

The proposed DSS framework supports the assessment of real congestion levels associated with specific traffic volumes on individual highway sections. This enables the measurement of the quality of the LOS on various highway sections, connecting gateway ports with their

hinterlands. By linking the three analytical dimensions identified in the theoretical framework – traffic management, maintenance planning and infrastructure development – the study demonstrates the internal coherence between the conceptual contribution and the methodological architecture.

The simulation results confirm that highway congestion and capacity reductions represent a major constraint for port-related flows, particularly in networks characterized by substantial heavy-vehicle traffic. These conditions may significantly undermine the regularity of truck in/outflows from terminals, potentially slowing down operations and weakening port performance. Overall, the paper offers relevant policy and managerial implications for highway concessionaires, regulators, port authorities and logistics operators, showing how DSS-based approaches can strengthen highway resilience, improve port-hinterland connectivity and support more informed planning and coordination. It should be emphasized, however, that the proposed DSS does not directly measure port competitiveness. Rather, it provides a structured tool for assessing highway performance dynamics, which represent a relevant exogenous determinant of port competitiveness.

Despite the original contribution provided, the present study is subject to some limitations that open up relevant avenues for future research. In particular, the current application relies on a synthetic dataset designed to illustrate the operational logic of the proposed DSS rather than to provide a full empirical validation of its performance.

Future studies are called to perform simulations and analysis by applying real data concerning motorway infrastructural endowment and capacity, demand patterns and associated LOS. In addition, it could be worth testing the impact of critical events, including force majeure, that might provoke sudden limitations to capacity and/or heavy traffic perturbation across the port logistics chain, in order to assess the effectiveness of potential recovery mechanisms to be implemented by business operators. The mitigation of operational disruptions, also avoiding their quick propagation throughout the entire network, is a relevant business objective that should be further investigated by applying innovative DSS managerial architectures.

In this perspective, future empirical research grounded on real-world case studies could explicitly adopt structured design-oriented methodological approaches, such as Design Science Research Methodology, to iteratively test, refine and assess DSS artefacts under operational conditions, moving beyond the illustrative and exploratory scope of the present study. Such an approach would be particularly suitable in contexts where longitudinal data availability and close interaction with infrastructure managers allow for repeated cycles of design, evaluation and refinement. Additional research may also explore comparative applications of the proposed framework across different port-hinterland contexts, governance settings and traffic compositions, in order to investigate how structural, institutional and demand-side differences shape the role of road infrastructure efficiency and resilience in port competitiveness.

References

- Behdani, B., Wiegman, B., Roso, V. and Haralambides, H. (2020), "Port-hinterland transport and logistics: emerging trends and Frontier research", *Maritime Economics and Logistics*, Vol. 22, pp. 1-25, doi: [10.1057/s41278-019-00137-3](https://doi.org/10.1057/s41278-019-00137-3).
- De Martino, M. and Morvillo, A. (2008), "Activities, resources and inter-organizational relationships: key factors in port competitiveness", *Maritime Policy and Management*, Vol. 35 No. 6, pp. 571-589, doi: [10.1080/03088830802469477](https://doi.org/10.1080/03088830802469477).
- Ferrari, P., Treglia, P., Cascetta, E., Nuzzolo, A. and Olivotto, P. (1982), "A new method for measuring the quality of circulation on motorways", *Transportation Research Part B: Methodological*, Vol. 16 No. 5, pp. 399-418, doi: [10.1016/0191-2615\(82\)90021-2](https://doi.org/10.1016/0191-2615(82)90021-2).

- Forte, E. and Siviero, L. (2014), "Competitiveness and sea-rail intermodality in the Ro-Ro service market of Italian ports", *International Journal of Transport Economics*, Vol. 41 No. 2, pp. 255-278.
- Hales, D., Lee Lam, J.S. and Chang, Y.T. (2016), "The balanced theory of port competitiveness", *Transportation Journal*, Vol. 55 No. 2, pp. 168-189, doi: [10.5325/transportationj.55.2.0168](https://doi.org/10.5325/transportationj.55.2.0168).
- HCM (2000), *Highway Capacity Manual*, Transport Research Board.
- Kaliszewski, A., Kozłowski, A., Dąbrowski, J. and Klimek, H. (2020), "Key factors of container port competitiveness: a global shipping lines perspective", *Marine Policy*, Vol. 117, 103896, doi: [10.1016/j.marpol.2020.103896](https://doi.org/10.1016/j.marpol.2020.103896).
- Lakshmanan, T.R. and Anderson, W.P. (2001), "Infrastructure capacity", in Button, K.J. and Hensher, D.A. (Eds), *Handbook of Transport Systems and Traffic Control*, Emerald Group Publishing, Leeds, Vol. 3, pp. 209-228, doi: [10.1108/9781615832460-013](https://doi.org/10.1108/9781615832460-013).
- Lee, H.L., Padmanabhan, V. and Whang, S. (1997), "The bullwhip effect in supply chains", *Sloan Management Review*, Vol. 38 No. 3, pp. 93-102.
- Li, N., Wang, Z., Lin, X. and Sheng, H. (2024), "Prediction of delivery truck arrivals at container terminals: an ensemble deep learning model", *Maritime Economics and Logistics*, Vol. 26 No. 4, pp. 658-684, doi: [10.1057/s41278-024-00304-1](https://doi.org/10.1057/s41278-024-00304-1).
- Loucks, D.L. (1995), "Developing and implementing decision support systems: a critique and a challenge", *Journal of the American Water Resources Association*, Vol. 31 No. 4, pp. 571-582, doi: [10.1111/j.1752-1688.1995.tb03384.x](https://doi.org/10.1111/j.1752-1688.1995.tb03384.x).
- Luo, M., Chen, F. and Zhang, J. (2022), "Relationships among port competition, cooperation and competitiveness: a literature review", *Transport Policy*, Vol. 118, pp. 1-9, doi: [10.1016/j.tranpol.2022.01.014](https://doi.org/10.1016/j.tranpol.2022.01.014).
- Notteboom, T.E. and Rodrigue, J.P. (2005), "Port regionalization: towards a new phase in port development", *Maritime Policy and Management*, Vol. 32 No. 3, pp. 297-313, doi: [10.1080/03088830500139885](https://doi.org/10.1080/03088830500139885).
- Notteboom, T. and Yap, W.Y. (2012), "Port competition and competitiveness", *The Blackwell Companion to Maritime Economics*, pp. 549-570.
- Parola, F., Risitano, M., Ferretti, M. and Panetti, E. (2017), "The drivers of port competitiveness: a critical review", *Transport Reviews*, Vol. 37 No. 1, pp. 116-138, doi: [10.1080/01441647.2016.1231232](https://doi.org/10.1080/01441647.2016.1231232).
- Parola, F., Satta, G., Buratti, N. and Vitellaro, F. (2020), "Digital technologies and business opportunities for logistics centres in Maritime Supply Chains", *Maritime Economics and Management*, Vol. 48 No. 4, pp. 461-477.
- Pettit, S.J. and Beresford, A.K.C. (2009), "Port development: from gateways to logistics hubs", *Maritime Policy and Management*, Vol. 36 No. 3, pp. 253-267, doi: [10.1080/03088830902861144](https://doi.org/10.1080/03088830902861144).
- Power, D.J. (2013), *Engineering Effective Decision Support Technologies: New Models and Applications: New Models and Applications*, IGI Global.
- Radzi, A.R., Rahman, R.A. and Doh, S.I. (2023), "Decision making in highway construction: a systematic review and future directions", *Journal of Engineering, Design and Technology*, Vol. 21 No. 4, pp. 1083-1106, doi: [10.1108/jedt-06-2021-0306](https://doi.org/10.1108/jedt-06-2021-0306).
- Roess, R.P. and Prassas, E.S. (2014), "The fundamental concept of level of service", in *The Highway Capacity Manual: a Conceptual and Research History. Springer Tracts on Transportation and Traffic*, Springer, Cham, Vol. 5, pp. 49-76, doi: [10.1007/978-3-319-05786-6_3](https://doi.org/10.1007/978-3-319-05786-6_3).
- Sdoukopoulos, E. and Boile, M. (2020), "Port-hinterland concept evolution: a critical review", *Journal of Transport Geography*, Vol. 86, 102775, doi: [10.1016/j.jtrangeo.2020.102775](https://doi.org/10.1016/j.jtrangeo.2020.102775).
- Tian, Y.-J. and Chen, H. (2009), "Evaluation of truck highway service quality based on user satisfaction degree", *Second International Conference on Intelligent Computation Technology and Automation*, Springer, Changsha, pp. 180-183.

- Tyrogianni, H., Halkias, B., Politou, A. and Kotzampassi, P. (2012), "The Attica tollway operations authority KPI performance system", *Procedia - Social and Behavioral Sciences*, Vol. 48, pp. 2999-3008, doi: [10.1016/j.sbspro.2012.06.1267](https://doi.org/10.1016/j.sbspro.2012.06.1267).
- Van, K. and van den Berg, G.C. (1998), "Gateways and intermodalism", *Journal of Transport Geography*, Vol. 6 No. 1, pp. 1-9, doi: [10.1016/s0966-6923\(97\)00035-5](https://doi.org/10.1016/s0966-6923(97)00035-5).
- Veenstra, A., Zuidwijk, R. and van Asperen, E. (2012), "The extended gate concept for container terminals: expanding the notion of dry ports", *Maritime Economics and Logistics*, Vol. 14 No. 1, pp. 14-32, doi: [10.1057/mel.2011.15](https://doi.org/10.1057/mel.2011.15).
- Verbeke, A. and Dooms, M. (2007), "Integrating the extended gateway concept in long-term strategic seaport planning: a European case study", *Conference proceedings of the Van Horne Institute's*, pp. 28-29.
- Yu, H., Gong, Y. and Liu, J. (2025), "A systematic literature review on port competitiveness", *International Journal of Logistics Research and Applications*, Vol. 28 No. 7, pp. 720-744, doi: [10.1080/13675567.2023.2187355](https://doi.org/10.1080/13675567.2023.2187355).
- Zhang, Y., Zhou, X., Wan, F. and Wang, Q. (2024), "Evaluation of highway transportation service quality based on big data", *International Conference on Industrial IoT, Big Data and Supply Chain (IIoTBDSC)*, Wuhan, pp. 166-171.

Corresponding author

Roberto Viviani can be contacted at: roberto.viviani@edu.unige.it