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Shipment Times and Shipment Costs: A Systematic Literature Review

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Abstract: Long-distance freight transport plays a critical role in supporting global trade and economic development, yet its increasing complexity has raised significant challenges related to efficiency, cost, reliability, and sustainability. This review paper provides a comprehensive and systematic synthesis of the literature on long-distance multimodal freight transport, with a particular focus on the representation of time and cost components within transport systems and modelling frameworks. The study integrates over one hundred academic and grey literature sources to examine the operational mechanics of freight transport chains, including transport chain configurations, terminal operations, transshipment processes, and system-level uncertainties.

A structured bibliometric and classification analysis is employed to categorise the literature across multiple dimensions, including geographical focus, transport modes, cargo types, and modelling approaches. The findings reveal a strong concentration of research in Europe and maritime-dominated logistics systems, with containerised freight receiving disproportionate attention compared to dry bulk, liquid bulk, and general cargo. Methodologically, optimisation-based models dominate the literature, while simulation, econometric, and hybrid approaches are gaining traction in addressing system complexity and uncertainty.

A key contribution of this review is the critical examination of how time and cost components are conceptualised and modelled across freight transport studies. The analysis demonstrates that while both dimensions are widely acknowledged, they are often treated in isolation or simplified within modelling frameworks. In particular, terminal dwell time, handling processes, and reliability are frequently underrepresented, despite their significant impact on overall system performance.

The report identifies key research gaps, including the limited integration of time–cost trade-offs, underrepresentation of non-containerised freight, and insufficient modelling of uncertainty and behavioural responses. Future research directions are proposed to advance the development of more comprehensive, data-driven, and operationally realistic freight transport models that better support policy and planning decisions in complex multimodal logistics systems.

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1. Introduction

1.1 Context of Long-Distance Goods Mobility

Long-distance goods mobility constitutes the backbone of modern economies, enabling spatial separation between production, consumption, and distribution at national, international, and intercontinental scales (Rodrigue, 2024; Tavasszy & de Jong, 2014). In Europe, freight transport systems support highly integrated supply chains spanning manufacturing clusters, logistics hubs, ports, and consumption centres. These systems increasingly rely on multimodal and intermodal transport chains, combining road, rail, maritime, and air transport to balance cost efficiency, speed, reliability, and environmental performance (Macharis & Bontekoning, 2004; SteadieSeifi et al., 2014).

Over the past two decades, the organisation and scale of freight transport have expanded substantially. Global container trade, the increased fragmentation of production, the growth of e-commerce, and expanded global value chains have driven higher volumes and more complex logistics patterns (Rodrigue, 2024; UNCTAD, 2022). In the European Union, total road freight transport performance (measured in tonne-kilometres) reached around 1,807 billion tonne-kilometres in 2023, reflecting sustained high volumes of long-distance road movements and international hauls (Eurostat, 2025). Further, maritime and road transport together accounted for approximately 93% of total freight transport performance in 2023, with maritime transport alone representing about two-thirds of tonne-kilometres and road transport accounting for roughly one-quarter (Eurostat, 2025; See Figure 1.1 for more details). These figures highlight the continued dominance of long-distance seaborne trade and the persistent importance of road haulage for intra-European freight movements.

This freight growth has been accompanied by increasing volatility and operational stress within transport systems. The post-2010 period, and particularly the years following the COVID-19 pandemic, exposed the vulnerability of long-distance supply chains to congestion, disruptions, and delays. Severe port congestion and extended vessel dwell times during 2021–2022 substantially increased door-to-door transport times and logistics costs for containerised freight, challenging the reliability of multimodal supply chains (T. Notteboom et al., 2021; UNCTAD, 2022). At the same time, air freight – while accounting for comparatively small share of tonne-kilometres – played a critical role in high-value and time-sensitive logistics, reinforcing the importance of time-based competition in long-haul goods mobility (Bowen, 2012; Kupfer et al., 2017).

This growth has not been uniform across modes or regions. Road transport remains to carry a large share of tonne-kilometres for in-land freight in most European countries, while rail and maritime maintain dominant roles for specific distance ranges, shipment sizes, and commodity types (e.g., bulk and containerised long-haul seaborne trade) (Liedtke, 2009; SteadieSeifi et al., 2014). Simultaneously, the share of intermodal and combined transport – where containers, swap-bodies, or trailers are shifted between road, rail and short-sea chains – has gained significant policy relevance, even if absolute modal shares have remained persistent in many

national contexts. Besides, freight transport has become a central concern of transport and climate policy due to its contribution to greenhouse gas emissions, congestion, noise, and infrastructure wear.

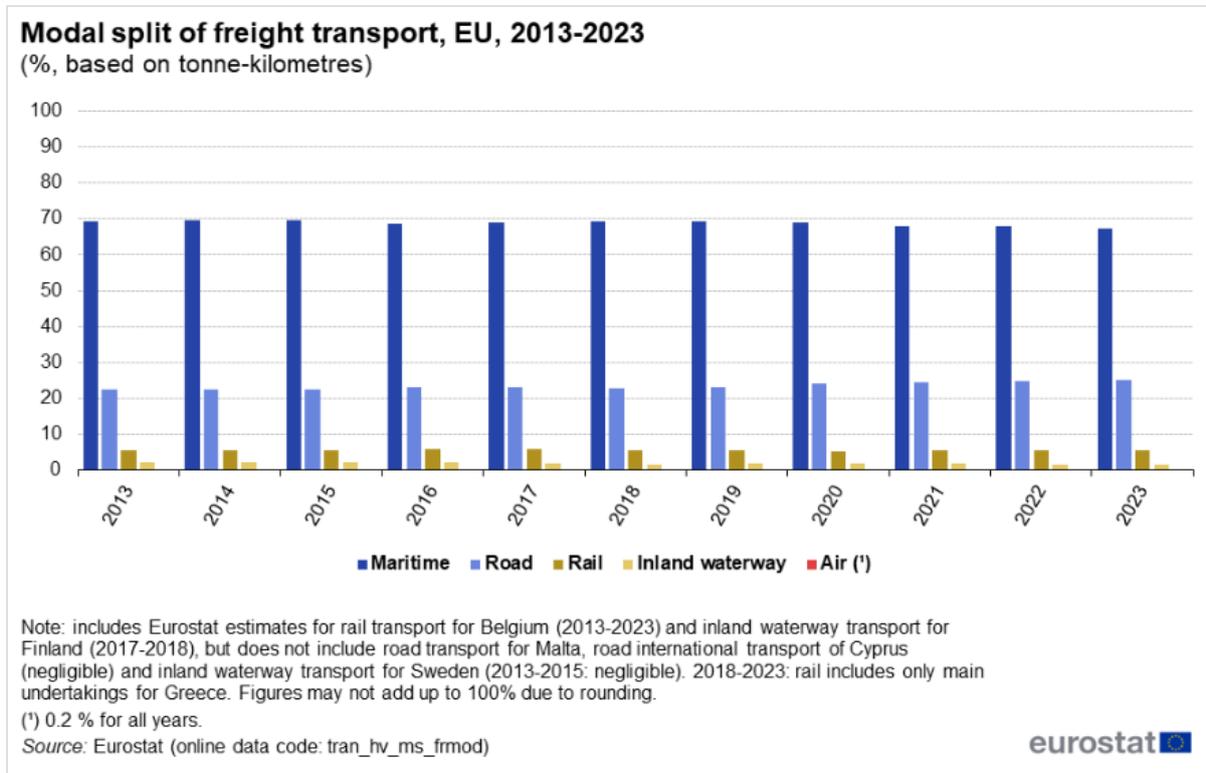


Figure 1.1. Modal split of freight transport, EU, 2013–2023
(%, based on tonne-kilometres)

Source: [Eurostat data](#)

European transport policy has responded by promoting modal shift, interoperability, and system integration, encouraging greater use of rail and inland waterways, improved port–hinterland connections, and more efficient multimodal logistics chains. Initiatives such as the Trans-European Transport Network (TEN-T), Motorways of the Sea, and digital freight corridors illustrate the emphasis on coordinated, cross-border freight systems (European Commission, 2011, 2020). However, despite these policy ambitions, road freight remains dominant for long-distance inland transport, and the expected efficiency and sustainability gains from multimodal solutions have often failed to materialise at scale. Further, empirical evidence suggests that the uptake of intermodal solutions remains constrained by additional handling costs, transshipment delays, and coordination challenges (Agamez-Arias & Moyano-Fuentes, 2017; Feo-Valero et al., 2011; Reis, 2019).

A key reason for this policy–outcome gap lies in the time and cost structures of freight transport. Decisions made by shippers, logistics service providers, and carriers are shaped not only by direct transport costs and in-vehicle travel times, but also by handling costs and times, transshipment delays, inventory holding costs, reliability penalties, and risks associated with uncertainty (Forkenbrock, 2001; Liedtke, 2009; Tavasszy & de Jong, 2014). Understanding how these components are conceptualised, measured, and modelled in the current literature is

therefore essential for explaining observed freight behaviour and for designing effective decision support systems in multimodal systems.

1.2 Long-Distance Freight Transport as a Decision-Making Problem

Freight transport differs fundamentally from passenger transport in that demand is derived from economic activity and embedded within complex supply chains rather than individual travel needs (Hesse & Rodrigue, 2004; Tavasszy & de Jong, 2014). Mode and route choices are typically made by firms or logistics intermediaries, often under contractual arrangements, and reflect multi-criteria optimisation rather than individual-level utility maximization. Long-distance goods mobility decisions involve trade-offs between:

- Transport and handling costs
- Door-to-door travel time
- Schedule reliability and delay risk
- Inventory and warehousing costs
- Service frequency and network connectivity
- Regulatory compliance and administrative burden

Multimodal and intermodal transport chains amplify these trade-offs. While combining modes can reduce line-haul costs or emissions, it introduces additional handling operations, coordination requirements, and exposure to delays at terminals, ports, and borders. Consequently, the generalised cost of freight transport often diverges substantially from simple distance-based cost measures (Tao & Zhu, 2020; Tavasszy & de Jong, 2014; Vannieuwenhuysse et al., 2003).

Multimodal and intermodal transport chains further augment the decision complexity. While combining modes can reduce line-haul costs or environmental costs, it introduces additional handling operations, coordination requirements, and exposure to delays at terminals, ports, and border-crossings (Agamez-Arias & Moyano-Fuentes, 2017; Macharis & Bontekoning, 2004; SteadieSeifi et al., 2014). Empirical studies demonstrate that transshipment time and cost penalties often counter potential efficiency gains, limiting the competitiveness of intermodal solutions for time-sensitive or high-value goods (Feo-Valero et al., 2011; Reis, 2019).

The literature has responded to this complexity through a wide range of modelling approaches, including aggregate and disaggregate freight demand models, network flow models, discrete choice models, optimisation frameworks, and simulation-based approaches (Hoff et al., 2010; Tao & Zhu, 2020; Wardman et al., 2016). These models differ significantly in how they represent time components (e.g. in-vehicle travel time, dwell time, waiting time, buffer time) and cost components (e.g. transport cost, handling cost, inventory cost, delay penalties). A systematic synthesis of these representations is currently lacking, particularly across modes and multimodal combinations.

1.3 The Imperative for Decision Support Systems (DSS)

Decision Support Systems (DSS) play a critical role in freight transport planning and operations, supporting decisions at strategic (network design), tactical (service configuration), and operational (routing and scheduling) levels (Hoff et al., 2010). For long-distance and multimodal freight transport, effective DSS must integrate:

- Detailed network representations across modes
- Realistic time and cost functions
- Treatment of uncertainty and stochastic delays
- Policy and regulatory constraints

However, many existing systems rely on simplified or deterministic assumptions, such as fixed travel times or average costs, which fail to capture congestion effects, stochastic delays, and operational variability (Liedtke, 2009; Tavasszy & de Jong, 2014). This simplification limits their ability to capture the true economic and operational drivers of multimodal freight decisions for long-distance and international freight chains, where delays at ports, terminals, and borders often dominate total transit time and cost (UNCTAD, 2022; UNECE, 2019).

Recent research has therefore emphasised the incorporation of uncertainty, robustness, and reliability into freight DSS. Approaches include stochastic optimisation, scenario analysis, and simulation-based evaluation, as well as adaptive routing concepts in intermodal and synchromodal transport systems (Agamez-Arias & Moyano-Fuentes, 2017; Reis, 2014, 2019; SteadieSeifi et al., 2014). A comprehensive review of how time and cost components have been treated in the literature is therefore essential for improving the theoretical foundations and practical applicability of freight DSS. Such a review also provides the basis for identifying gaps, inconsistencies, and opportunities for methodological advancement.

1.4 Research Questions

Based on the above discussed background, this review is guided by the following research questions:

RQ1: How have time and cost components of long-distance freight transport been conceptualised and operationalised in the current state of literature?

RQ2: How do these representations differ across freight modes (road, rail, maritime, air) and multimodal (and intermodal) transport chains?

RQ3: What modelling methodologies have been employed to estimate, optimise, or simulate freight transport time and cost, particularly under uncertainties and delays?

RQ4: What are the key methodological and empirical gaps that limit current understanding and policy applications?

1.5 Scope and Contribution of the Review

This review focuses on long-distance goods mobility, encompassing domestic, international, and intercontinental freight movements. All major freight modes – road, rail, maritime, and air – are considered, with particular emphasis on multimodal and intermodal transport chains. While Europe constitutes the primary geographical focus, studies from other regions are included where they offer transferable insights or methodological innovations.

Methodologically, the study adopts a systematic scoping review approach, which is well suited to mapping heterogeneous literatures, clarifying key concepts, and identifying research gaps in complex and interdisciplinary fields (Arksey & O'Malley, 2005; Tricco et al., 2018). The review goes beyond descriptive summarisation by explicitly comparing time and cost structures across studies and linking them to modelling choices and policy implications.

The primary contribution of this report lies in:

- Developing a comprehensive taxonomy of time and cost components in long-distance freight transport
- Synthesising modelling approaches used to represent these components
- Identifying inconsistencies and blind spots in existing research
- Providing evidence-based directions for future research and DSS development

2. Methodological framework

Given the extent of transport modes, methodological approaches, and data sources involved, this report adopts a systematic scoping review approach as the most appropriate method to map, synthesize, and critically analyse the existing body of literature. This chapter outlines the methodology adopted to systematically review the literature on long-distance goods mobility, with particular emphasis on time and cost components in multimodal and intermodal freight transport.

2.1 Justification for the Systematic Scoping Review

Systematic scoping reviews are designed to examine the extent, range, and nature of research activity within the given field, particularly where the literature is heterogeneous in terms of methods, concepts, and disciplinary origins ((Arksey & O'Malley, 2005; Tricco et al., 2018). Unlike traditional systematic reviews or meta-analyses, scoping reviews do not seek to aggregate effect sizes or assess intervention effectiveness. Instead, they are well suited to identify how concepts are defined, how methodologies are applied, and where research gaps exist.

The literature on goods mobility exhibits substantial diversity. Studies vary widely in their treatment of freight modes (road, rail, maritime, air) and spatial scales (domestic, international, intercontinental) and spans across operations research (mathematical models), transportation economics (econometric cost functions), and public policy (infrastructure reports). A scoping review can handle this heterogeneity well and provide a robust and transparent approach as it

allows for the inclusion of these diverse evidence types – qualitative, quantitative, and theoretical – without the rigid “risk of bias” exclusion criteria.

2.2 Adoption of PRISMA-ScR and PRISMA-S

To ensure the review is reproducible, transparent, and rigorous, this review follows PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) and PRISMA-S (PRISMA Search Extension) guidelines for scoping reviews and reporting literature search strategies (Rethlefsen et al., 2021; Tricco et al., 2018).

Unlike standard PRISMA, which mandates a quality assessment of every study (often irrelevant for mathematical simulations), PRISMA-ScR focuses on the “Data Charting” process. This is crucial for this study, as the goal of this study is to extract and chart specific algorithmic approaches (e.g., “Genetic Algorithm”, “Ant Colony Optimization”) and time and cost components (e.g., “handling time”, “transshipment costs”) rather than assessing clinical outcomes. It provides a structured checklist for documenting the objectives, eligibility criteria, information sources, selection process, and synthesis methods used in scoping reviews. Its adoption ensures that the review process is systematic, auditable, and clearly reported.

PRISMA-S complements this framework by specifying best practices for documenting search strategies across databases, including search strings, filters, and date ranges. Given this review includes “grey literature” (e.g., European Commission, World Bank, UNCTAD reports), PRISMA-S is essential. It provides a specialized checklist for reporting searches in non-bibliographic sources and ensures that the “grey” search is not ad-hoc but as scientifically rigorous and reproducible as the academic search. Together, these frameworks enhance the credibility of the review and facilitate replication by other researchers.

2.3 Eligibility Criteria

2.3.1 Inclusion Criteria

The following inclusion criteria were applied:

- Topic relevance: Studies addressing long-distance goods mobility, freight transport, or logistics with explicit consideration of time and/or cost components.
- Transport modes: Road, rail, maritime, air, and any multimodal or intermodal combinations thereof.
- Spatial scale: Domestic, international, or intercontinental freight movements.
- Publication type: Peer-reviewed journal articles and high-quality grey literature (policy reports, technical reports, institutional studies).
- Time period: Publications from the year 2000 onwards.

2.3.2 Exclusion Criteria

Studies were excluded if they:

- Focused exclusively on passenger transport without transferable methodological insights.
- Addressed urban or last-mile freight only, without relevance to long-distance transport.
- Lacked any discussion or modelling of time, cost, delays, or reliability.
- Were opinion pieces, editorials, or non-technical commentary without methodological content.

2.3.3 Information Sources

The primary academic sources were: Web of Science (WoS), Scopus, and ScienceDirect. These databases were selected due to their comprehensive coverage of top-tier journals in transport economics, operations research, logistics, and geography. Together, they capture the majority of high-impact research relevant to freight transport modelling and analysis. Besides, to capture policy-relevant and practice-oriented knowledge, the review also included grey literature from authoritative institutions, including European Commission, International Transport Forum (ITF), Organisation for Economic Co-operation and Development (OECD), United Nations Conference on Trade and Development (UNCTAD), United Nations Economic Commission for Europe (UNECE), and World Bank amongst others. Consultancy reports were included selectively where they provided unique empirical insights or industry data not available in the academic publications.

2.3.4 Search Strategy

A structured search strategy was developed in line with PRISMA-S guidelines. Search strings combined keywords related to:

- Freight and goods transport (e.g., “freight transport”, “goods mobility”, “logistics”)
- Transport modes (e.g., “road”, “rail”, “maritime”, “air”, “multimodal”, “intermodal”)
- Time and cost dimensions (e.g., “travel time”, “transport cost”, “generalised cost”, “delay”, “reliability”)

Boolean operators and truncation were used to capture variations in terminology. Searches were limited to titles, abstracts, and keywords to ensure relevance. Where necessary, backward and forward citation tracking was employed to identify additional relevant studies.

2.3.5 Study Selection Process

The study selection process followed a multi-stage screening procedure:

- Identification: Records were retrieved from the selected databases and grey literature sources.
- Deduplication: Duplicate records were removed using reference management software.
- Title and abstract screening: Records were screened against the eligibility criteria.

- Full-text review: Remaining studies were assessed in detail for relevance and methodological content.

This process ensured a transparent and systematic narrowing of the literature to a corpus suitable for detailed analysis.

2.3.6 Data Extraction and Coding Framework

A structured data extraction framework was developed to capture key characteristics of each study. Extracted variables included:

- Publication year and source
- Geographic focus
- Transport modes considered
- Type of transport chain (unimodal, intermodal, multimodal)
- Time components modelled (e.g., in-vehicle time, handling time, waiting time, buffer time)
- Cost components modelled (e.g., transport cost, handling cost, inventory cost, delay penalties)
- Treatment of uncertainty and delays
- Modelling methodology (e.g., optimisation, discrete choice, simulation)

This coding framework enables consistent comparison across studies and forms the basis for the bibliometric and thematic analyses presented in subsequent chapters.

3. Bibliometric and descriptive analysis

This chapter provides a structured mapping of the academic and policy literature on long-distance goods mobility. The analysis identifies dominant research themes, methodological trends, geographical concentrations of research activity, and systematic gaps in the representation of freight transport systems. The chapter performs two complementary roles. First, it provides an empirical overview of the evolution and composition of the literature reviewed in this study. Second, it establishes the classification framework used throughout the subsequent analysis, enabling consistent comparison across studies that differ widely in methodological approach, geographic focus, transport mode, and cargo characteristics.

3.1 Method and classification

The analysis is based on a curated corpus of peer-reviewed journal articles and selected reports identified through the systematic search strategy described in Chapter 2. The final corpus includes studies published primarily in leading journals in transport research, logistics, operations research, and transportation geography.

The literature set was compiled using searches in major bibliographic databases including:

- Web of Science (WoS)
- Scopus
- ScienceDirect

Additional studies were identified through backward and forward citation tracking, ensuring that highly cited and methodologically influential papers were included even where database searches did not capture them directly. The resulting dataset represents a broad cross-section of the literature on long-distance freight transport, encompassing modelling studies, empirical analyses, simulation research, and operational case studies across multiple transport modes and geographical regions.

Each study included in the literature corpus was then processed to capture both bibliographic characteristics and substantive research attributes relevant to the objectives of this review. The classification process followed three stages:

- 1. Initial screening and metadata extraction:** basic bibliographic information such as publication year, journal source, and study location were recorded.
- 2. Content-based classification:** the abstract, methodology, and results sections of each study were examined to identify transport modes analysed, modelling approaches used, and the time and cost components considered.
- 3. Analytical categorisation:** each study was assigned to one or more categories across the defined dimensions, enabling cross-tabulation and comparative analysis.

Table 3.1 summarises the analytical dimensions used to classify the reviewed studies. These dimensions reflect key structural characteristics of freight transport research and correspond directly to the analytical themes explored in this report.

Table 3.1. Literature classification framework used in the review

Dimension	Categories used in classification	Purpose in the review
Publication characteristics	Year of publication, journal source	Identify temporal trends and disciplinary distribution
Transport mode	Road, Rail, Maritime, Air, Multimodal combinations	Examine modal coverage and identify research concentration
Transport configuration	Unimodal, Intermodal, Multimodal, Synchromodal	Unimodal, Intermodal, Multimodal, Synchromodal
Geographical focus	Europe, North America, Asia, Global / intercontinental, other regions, non-specific	Identify regional concentration of research and transferability of findings
Type of load	Containerised cargo, Dry bulk, Liquid bulk, General cargo, Unspecified	Evaluate cargo representation and detect container-centric modelling bias

Time components analysed	Line-haul travel time, Terminal handling time, Waiting / dwell time, Buffer or reliability time, Aggregate time	Examine how transport time is conceptualised in the literature
Cost components analysed	Line-haul transport cost, Handling cost, Inventory cost, Delay penalties, Generalised cost	Identify economic cost representations used in models
Modelling methodology	Econometric models, Network optimisation, Simulation models, Hybrid approaches, Data-driven / machine learning	Analyse methodological diversity and dominant modelling paradigms

3.2 Temporal evolution of the goods mobility literature

The literature shows a clear expansion over the past two decades, indicating growing policy attention to freight transport efficiency, multimodal logistics systems, and supply-chain resilience. Early research prior to the mid-2000s focused largely on network design, freight demand modelling, and unimodal transport analysis, particularly for road and rail freight. During the late 2000s and early 2010s, increasing attention was directed towards intermodal transport, containerisation, and terminal operations, coinciding with the expansion of global supply chains and container-based logistics systems.

From approximately 2015 onwards, the literature shows profound growth, particularly in studies addressing multimodal transport optimisation, freight system reliability, and digitalised logistics networks. More recent work has also expanded to incorporate data-driven modelling approaches, machine learning methods, and resilience analysis, suggesting both advances in data availability and the increasing importance of disruption management following major global supply-chain shocks.

Overall, the temporal distribution of publications indicates three broad phases in the development of freight transport research:

1. Foundation (2000–2008) – emphasis on freight demand modelling, cost analysis, and network optimisation.
2. Intermodal expansion (2009–2016) – growth of research on container logistics, port–hinterland transport, and multimodal network design.
3. Integrated systems (2017–present) – increasing focus on multimodal integration, reliability, digitalisation, and resilience of freight transport systems.

Table 3.2. Distribution of reviewed studies by publication period.

Period	Approximate share of studies	Dominant research themes
2000–2008	~15–20%	Freight demand modelling, network optimisation, road and rail freight

2009–2016	~35–40%	Intermodal transport, container logistics, port–hinterland connections
2017–2020	~20–25%	Multimodal modelling, terminal efficiency, supply-chain integration
2021–present	~20%	Resilience, data-driven modelling, disruption management

A thematic breakdown of publications over time reveals the increasing prominence of multimodal and intermodal transport studies. Early research was dominated by unimodal transport analysis, particularly road freight cost modelling and rail network optimisation. However, more recent years show a rapid increase in studies addressing multimodal transport chains, terminal operations, and logistics system resilience.

The temporal evolution of the literature highlights several important patterns. First, research on freight transportation has increased substantially over the past two decades, reflecting both the growing economic importance of freight transport and the increasing complexity of global logistics networks. Second, the focus of research has progressively shifted from unimodal transport systems towards integrated multimodal logistics systems, with particular attention to ports, terminals, and intermodal corridors. Third, the most recent literature increasingly addresses uncertainty, disruption, and system resilience, showing lessons learned from major global supply-chain disruptions and the growing availability of high-resolution logistics data. These developments suggest that freight transport research is transitioning from a primarily cost-optimisation perspective towards a broader system performance and reliability perspective, a trend that is further explored in the modelling review presented in Chapter 5.

3.3 Geographical distribution of freight transport studies

Freight transport systems differ substantially across regions in terms of infrastructure availability, regulatory frameworks, logistics organisation, and modal shares. As a result, the geographical distribution of studies influences which operational characteristics and policy challenges are emphasised in the academic literature. Since the geographical focus of this report is concentrated to Europe, prominent part of the literature corpus reflects European policy initiatives aimed at promoting multimodal transport and sustainable freight mobility. European Union programmes such as the Trans-European Transport Network (TEN-T), combined transport policies, and research funding frameworks have stimulated a large body of research focusing on intermodal corridors, rail–road integration, port–hinterland logistics, and terminal operations. Consequently, many empirical and modelling studies examining multimodal freight transport systems are based on European case studies.

A significant share of studies also examines Asian freight transport systems, particularly in countries with rapidly expanding logistics networks and major container ports. Research in this region frequently focuses on port efficiency, maritime logistics networks, and rapidly growing freight corridors connecting industrial production centres with global export markets. These studies often emphasise maritime transport, port operations, and large-scale logistics

infrastructure. On the other hand, North-American studies often focus on rail freight systems, intermodal rail terminals, and long-distance truck transport. Due to the structure of freight markets in the United States and Canada, research in this region often highlights the role of private rail operators, long-haul trucking networks, and large inland logistics hubs.

In addition to region-specific studies, a notable portion of the literature adopts a multi-regional or global perspective, particularly in research on maritime shipping networks and air cargo logistics. These studies analyse international trade flows, global shipping routes, and intercontinental air freight networks, often using aggregated datasets covering multiple continents. Such work contributes valuable insights into the structure of global freight transport systems but may rely on simplified representations of local operational constraints.

A smaller subset of the literature uses schematic or hypothetical networks without a specific geographical case study. These studies are typically methodological in nature, focusing on optimisation models, simulation frameworks, or conceptual analyses. While such research contributes to methodological advancement, the absence of empirical context can limit the direct applicability of results to real-world freight systems.

3.4 Modal distribution of freight transport studies

The distribution of research across different freight transport modes provides important insights into the analytical priorities and biases present in the literature. Long-distance freight transport systems involve a combination of road, rail, maritime, and air transport modes, often organised in multimodal or intermodal chains. However, the extent to which each mode is represented in academic research varies considerably.

A substantial portion of the literature focuses on road freight transport, reflecting its dominant role in freight movements across many regions of the world. Road transport offers high operational flexibility, extensive network coverage, and relatively low entry barriers compared with other transport modes. Consequently, many studies analyse road-based freight systems in relation to routing optimisation, vehicle scheduling, freight demand modelling, and logistics network design. Research on road freight frequently examines issues such as travel time estimation, fuel costs, congestion effects, and operational efficiency in trucking networks.

Rail freight transport represents another important focus area within the literature, particularly in studies addressing long-distance freight corridors and intermodal transport systems. Rail transport is often analysed in relation to its potential to provide cost-efficient and environmentally sustainable alternatives to long-haul road transport. A large body of research investigates rail network design, rail capacity allocation, train scheduling, and the role of rail terminals in intermodal logistics systems. Rail freight studies are particularly prominent in European and North American contexts, where rail plays a significant role in long-distance freight transport.

Research on maritime freight transport is also well represented in the literature, largely due to the central role of maritime shipping in international trade. Maritime studies frequently focus

on container shipping networks, port efficiency, shipping route optimisation, and port–hinterland logistics connections. The dominance of containerised shipping in global trade has contributed to the strong presence of container-related modelling studies in the literature. Many of these studies analyse port operations, vessel scheduling, terminal handling processes, and maritime network structures.

In contrast, air freight transport is comparatively under-represented in the academic literature on freight transport modelling. Although air cargo plays a crucial role in transporting high-value and time-sensitive goods, the total volume of air freight is much smaller than that of road, rail, or maritime transport. As a result, relatively few studies examine air freight systems in detail. Existing research often focuses on airline cargo networks, airport logistics systems, hub-and-spoke network structures, and the role of air cargo in global supply chains.

In addition to studies focusing on individual transport modes, a growing share of the literature examines multimodal and intermodal freight transport systems. These studies analyse freight movements involving combinations of two or more transport modes, such as road–rail, road–maritime, rail–maritime, or road–air transport chains. Multimodal research often focuses on the integration of transport modes through logistics terminals, intermodal transfer operations, and coordinated scheduling across transport networks.

3.4.1 Modal representation and research biases

The modal distribution of studies reveals several structural patterns in the literature. First, road transport tends to receive considerable attention due to its operational flexibility and widespread use in freight logistics. Second, rail and maritime transport are frequently studied in the context of intermodal freight systems, where they serve as long-distance line-haul modes complemented by road transport for first-mile and last-mile operations. Third, the relatively limited representation of air freight studies suggests that this mode remains under-explored in the freight transport modelling literature, particularly in comparison with its strategic importance for time-sensitive logistics and global supply chains. This gap is particularly relevant for analyses of time-sensitive freight transport systems and integrated multimodal logistics chains involving air cargo.

Finally, the increasing presence of multimodal studies reflects a broader shift in freight transport research towards analysing integrated logistics systems rather than isolated transport modes. This shift aligns with policy initiatives aimed at improving freight system efficiency, reducing environmental impacts, and enhancing the coordination between different transport modes.

3.5 Modelling approaches in freight transport literature

The analytical methods used in the freight transport research have evolved considerably over the past two decades. Advances in computational capabilities, the increasing availability of logistics data, and the growing complexity of freight transport systems have contributed to the

development of diverse modelling approaches. These approaches vary in their analytical objectives, data requirements, and levels of operational detail. Understanding the methodological distribution of studies is therefore essential for interpreting the strengths and limitations of the existing literature. The modelling approaches used in freight transport research can be classified into five major categories: econometric and behavioural models, network optimisation models, simulation-based models, hybrid modelling frameworks, and data-driven approaches.

3.5.1 Econometric and behavioural models

Econometric models constitute an important class of analytical approaches used to examine freight transport behaviour, particularly in studies analysing mode choice, route selection, and logistics decision-making. These models typically rely on statistical techniques to estimate relationships between freight transport decisions and explanatory variables such as transport cost, travel time, reliability, shipment characteristics, and firm-level attributes.

Discrete choice models are commonly employed to analyse freight mode choice decisions, allowing researchers to estimate the relative importance of cost and time attributes across different transport alternatives. Such models are particularly useful for examining behavioural responses to policy interventions, infrastructure investments, and changes in logistics costs. However, econometric models often rely on aggregated data and may simplify operational constraints within freight networks.

3.5.2 Network optimisation models

Network optimisation models represent one of the most widely used approaches in freight transport research. These models aim to determine the optimal allocation of freight flows within transport networks while minimising total system costs or maximising operational efficiency. Optimisation models are frequently used to analyse problems such as freight network design, hub location, terminal placement, route planning, and multimodal transport configuration.

In multimodal freight research, optimisation models often represent freight systems as interconnected networks consisting of nodes (e.g., terminals, ports, distribution centres) and links (transport corridors). These models enable researchers to analyse how freight flows can be efficiently routed through multimodal networks while considering factors such as transport costs, handling costs, capacity constraints, and service frequency. Despite their analytical strength, optimisation models may rely on simplified assumptions regarding demand patterns, operational uncertainty, and behavioural decision processes.

3.5.3 Simulation-based models

Simulation approaches are increasingly used to capture the dynamic and stochastic nature of freight transport systems. Simulation models enable researchers to represent complex operational processes that may be difficult to analyse using analytical optimisation techniques.

For example, simulation methods can be used to examine terminal operations, container handling processes, vehicle movements within logistics facilities, and the interactions between different components of freight transport systems.

Discrete-event simulation is particularly common in studies analysing port terminals, intermodal transfer facilities, and logistics hubs. These models allow researchers to examine how operational decisions influence system performance, including congestion levels, waiting times, and resource utilisation. Simulation approaches are therefore well suited for analysing operational bottlenecks and evaluating alternative infrastructure or operational policies.

3.5.4 Hybrid modelling frameworks

In recent years, researchers have increasingly combined multiple modelling techniques to capture the multi-layered nature of freight transport systems. Hybrid models integrate elements of optimisation, simulation, and behavioural modelling in order to represent both network-level planning decisions and operational processes.

For example, hybrid modelling frameworks may combine econometric demand models with network optimisation algorithms, enabling researchers to examine how changes in transport costs or infrastructure investments influence freight flows within multimodal networks. Similarly, simulation components can be integrated into optimisation frameworks to capture operational uncertainties and system dynamics. Hybrid approaches therefore provide a more comprehensive representation of freight transport systems, although they often require extensive data and computational resources.

3.5.5 Data-driven and machine learning approaches

The increasing availability of large-scale logistics datasets has stimulated growing interest in data-driven modelling approaches. Machine learning methods are increasingly applied to analyse freight transport patterns, predict freight demand, estimate travel times, and identify congestion patterns within logistics networks.

These approaches are particularly useful when large volumes of operational data are available, such as GPS-based vehicle tracking data, port activity records, or air cargo shipment datasets. Data-driven methods can reveal complex patterns within freight transport systems that may not be easily captured by traditional modelling approaches. However, purely data-driven approaches may lack the structural interpretability required for policy analysis and infrastructure planning.

3.6 Representation of cargo types in freight transport research

Freight transport systems carry a wide range of commodities that differ substantially in their physical characteristics, handling requirements, economic value, and sensitivity to transport time and reliability. Despite this diversity, the representation of cargo types in freight transport

research remains uneven. A systematic classification of the reviewed literature reveals that the majority of modelling and empirical studies focus on containerised cargo, while other important freight categories, such as dry bulk, liquid bulk, and general cargo, receive comparatively limited attention. Table 3.3 summarises the representation of cargo types in the current literature.

This imbalance has important implications for interpreting the findings of the freight transport literature, particularly in relation to multimodal and intermodal transport modelling. Different cargo types exhibit fundamentally different time–cost trade-offs, handling processes, and logistics structures. Consequently, models calibrated primarily on containerised freight flows may not accurately represent the behaviour of other freight segments.

3.6.1 Containerised cargo

Containerised cargo represents the most extensively studied freight category in the literature. The widespread adoption of ISO containers since the late twentieth century has transformed global logistics systems by enabling standardised handling, rapid transshipment, and seamless integration across transport modes. These characteristics make containerised freight particularly well suited for analytical modelling, as containers can be treated as discrete and uniform transport units within network models.

As a result, a large share of research on multimodal transport, intermodal terminals, port–hinterland logistics, and synchronomodal transport systems focuses explicitly on container flows. Studies frequently examine container routing, port congestion, terminal handling processes, and inland distribution networks. The availability of relatively rich datasets—such as port statistics, shipping schedules, and container tracking data—has further reinforced the dominance of container-based analyses in the literature.

However, this concentration introduces a container-centric bias in freight transport modelling. Containerised cargo typically exhibits moderate time sensitivity and relatively predictable handling processes, which differ substantially from those associated with other freight types. Consequently, conclusions regarding the competitiveness of intermodal transport or the efficiency of multimodal chains may not be directly transferable to other cargo categories.

3.6.2 Dry bulk cargo

Dry bulk cargo includes commodities such as coal, iron ore, grain, and other raw materials transported in large quantities without packaging. These commodities typically exhibit low unit value relative to their weight and therefore emphasise minimisation of transport cost rather than transport time. Dry bulk freight is commonly transported using specialised vessels, rail wagons, or conveyor systems designed for large-volume movements.

In the academic literature, studies addressing dry bulk freight often focus on strategic network planning, infrastructure capacity, and commodity flow modelling rather than detailed analysis of multimodal transport chains. Because bulk commodities are usually transported in large

homogeneous shipments, the logistics systems involved are often simpler and involve fewer transshipment stages compared with containerised freight.

Nevertheless, bulk freight transport remains a crucial component of global logistics systems, particularly for energy and agricultural supply chains. The relatively limited representation of dry bulk freight in multimodal modelling studies represents an important gap in the literature.

3.6.3 Liquid bulk cargo

Liquid bulk cargo includes petroleum products, liquefied natural gas (LNG), chemicals, and other liquid commodities transported in tankers, pipelines, or specialised containers. Similar to dry bulk freight, liquid bulk transport emphasises cost efficiency and operational safety rather than rapid delivery. Transport systems for liquid bulk cargo are typically highly specialised and subject to strict regulatory requirements related to safety and environmental protection.

Research on liquid bulk freight is often concentrated in fields such as energy logistics, maritime transport economics, and pipeline network analysis. As a result, these studies frequently examine infrastructure capacity, safety management, and long-term supply chain planning rather than multimodal logistics optimisation.

Consequently, liquid bulk cargo is rarely represented explicitly in multimodal freight transport models. Instead, it is often implicitly included within aggregated freight demand datasets or excluded entirely from analyses focusing on containerised logistics systems.

3.6.4 General cargo

General cargo refers to freight that is neither containerised nor transported in bulk form. This category includes a wide range of goods such as palletised shipments, boxed products, packaged consumer goods, machinery, and other manufactured items. General cargo often involves relatively small shipment sizes and may require additional handling operations such as consolidation, sorting, and packaging.

From a logistics perspective, general cargo frequently moves through hub-and-spoke distribution systems, consolidation centres, and multimodal logistics hubs. Handling intensity and shipment fragmentation tend to be higher than for containerised or bulk freight, which can increase both handling costs and transit time variability.

Despite these distinctive characteristics, general cargo remains under-represented in freight transport modelling literature. Many studies implicitly assume containerisation or treat general cargo as part of aggregated freight flows without explicitly modelling its handling requirements.

Table 3.3. Representation of cargo types in freight transport literature

Cargo type	Typical transport characteristics	Common transport modes	Representation in literature
Containerised cargo	Standardised loading units, moderate time sensitivity	Maritime, road, rail, intermodal	Very high
Dry bulk	Large homogeneous shipments, low time sensitivity	Maritime, rail	Moderate
Liquid bulk	Specialised infrastructure, safety-sensitive	Maritime, pipeline, rail	Low
General cargo	Fragmented shipments, high handling intensity	Road, air, multimodal logistics	Low

3.7 Summary

The bibliometric and classification analysis presented in this chapter reveals several clear structural patterns in the literature on long-distance freight transport. Research activity has expanded significantly over the past two decades, reflecting growing academic and policy interest in multimodal logistics systems, intermodal transport corridors, and supply-chain resilience. The literature shows a strong geographical concentration in Europe, North America, and parts of Asia, where extensive logistics infrastructure and policy initiatives have stimulated empirical and modelling research. At the modal level, road transport and container-based maritime logistics dominate the literature, while air freight and certain specialised freight systems receive comparatively less analytical attention.

The analysis also highlights important methodological patterns. Network optimisation models and econometric approaches remain the most widely used analytical tools, particularly for analysing freight demand, network design, and mode choice. Simulation and hybrid modelling frameworks have become increasingly prominent in recent years, reflecting the need to capture operational complexity and uncertainty in freight transport systems. However, integration between behavioural, operational, and network-level modelling approaches remains limited, suggesting opportunities for methodological advancement.

Finally, the classification reveals several structural biases in the literature. Containerised cargo is heavily overrepresented compared with other freight categories such as dry bulk, liquid bulk, and general cargo. Further, many studies focus primarily on line-haul transport time and cost while underrepresenting terminal operations, dwell time, and reliability. These patterns indicate that existing research may not fully capture the operational realities of multimodal freight transport systems. Recognising these limitations provides important context for the detailed analysis of time–cost modelling approaches presented in Chapter 5.

4. Mechanics of Multimodal and Intermodal Freight Transport

4.1 Definitions and Overview: Intermodal, Multimodal, Co-modal, and

Synchromodal Freight Transport

The literature indicates that combining two or more types of transportation in a logistics network provides the means to move the freight from its point of origin to its destination economically and in a way that is operationally viable (Meng & Wang, 2011; Slack, 1990). The literature on long-distance goods mobility employs a variety of closely related terms – intermodal, multimodal, co-modal, and synchromodal freight transport – to describe transport chains that involve more than one mode. While these concepts are often used interchangeably in policy documents and even in academic work, they reflect distinct operational logics and levels of integration. Clarifying these definitions is essential for interpreting empirical findings and modelling approaches consistently across studies.

4.1.1 Intermodal freight transport

Intermodal freight transport refers to the movement of goods in a single loading unit (e.g., container, swap body, or trailer) using successive modes of transport without handling the goods themselves when changing modes (European Conference of Ministers of Transport, 1993). Another definition states intermodal transportation as the coordinated transport of freight in containers or trailers by means of a combination of road and rail modes, with or without a connection to the sea mode (Muller, 1995). The defining characteristic of intermodality is the physical separation of transport legs combined with standardised loading units, which enable transfers between modes such as road–rail, road–sea, or road–rail–sea chains (Macharis & Bontekoning, 2004; SteadieSeifi et al., 2014). Additionally, (D’Este, 1996) proposes that apart from specifying a loading unit to move the goods between the different modes of transport, in intermodal transportation it is quite necessary to have an appropriate administrative and legal environment in place, to have a technical, commercial and management framework defined for the movement of freight, and for effective measures to be taken to favour information sharing.

In intermodal systems, the sequence of modes is typically fixed at the planning stage, and modal transfers occur at dedicated terminals. As emphasised in the comprehensive review by (Agamez-Arias & Moyano-Fuentes, 2017), intermodal freight transport emerged historically as a response to increasing containerisation and the need to reduce cargo handling costs and damage. However, despite its operational advantages over break-bulk transport, intermodal freight remains sensitive to transshipment time, terminal congestion, and coordination failures, which can offset savings in line-haul costs.

4.1.2 Multimodal freight transport

Multimodal freight transport is a broader concept that refers to the use of two or more transport modes within a single transport chain, regardless of whether goods remain in the same loading unit throughout the journey. (UNCTAD, 2003) proposes that multimodal transport is the transportation of freight using at least two different modes of transportation, by virtue of a single contract, from one place located in a country in which the operator takes charge of the

goods, to a second place designated for their delivery in a different country, but does not highlight the need for a loading unit to be used for transportation. In contrast to intermodal transport, multimodality does not necessarily imply standardised units or terminal-based transfers, and may involve repacking, consolidation, or redistribution of goods at intermediate nodes (Islam et al., 2005; Rodrigue, 2024; SteadieSeifi et al., 2014).

From an operational perspective, multimodal freight systems encompass a wide spectrum of arrangements, ranging from loosely coordinated mode combinations to more integrated logistics solutions managed by a single service provider. (Agamez-Arias & Moyano-Fuentes, 2017) note that the distinction between intermodal and multimodal transport is often blurred in practice, particularly in policy discourse, yet remains analytically important when assessing time and cost accumulation along transport chains. Multimodal systems typically exhibit higher flexibility than strictly intermodal systems but may also involve additional handling operations and organisational complexity.

4.1.3 Co-modal transport

The concept of co-modal transport was introduced primarily in European transport policy to emphasise the efficient and complementary use of different transport modes, rather than prioritising a modal shift away from road transport per se (European Commission, 2011). According to (Verweij, 2011), co-modal transportation is the intelligent use of two or more modes of a consignor's or groups of consignors' transport in a distribution system – alone or in combination – to obtain the greatest benefit from each of the two modes in terms of global sustainability, with a flexible distribution network being the key to co-modality. In essence, co-modality focuses on optimising the overall transport system by exploiting the comparative advantages of each mode within an integrated framework.

Unlike intermodal or multimodal transport, co-modality is less a description of a specific transport chain configuration and more a policy-oriented principle. It seeks to promote combinations of modes that jointly minimise economic, environmental, and social costs. In the academic literature, co-modality is often referenced in discussions of policy objectives and system optimisation but is rarely operationalised explicitly in freight transport models (Macharis & Bontekoning, 2004; SteadieSeifi et al., 2014).

4.1.4 Sychromodal freight transport

Sychromodal freight transport represents a more recent evolution of multimodal thinking, characterised by dynamic and flexible mode choice during the execution of a transport chain. In sychromodal systems, the specific mode or route used for a shipment may be adjusted in real time based on network conditions, capacity availability, or service disruptions, rather than being fixed at the planning stage (SteadieSeifi et al., 2014; Verweij, 2011). For this, it is important that the network actors actively work together in coordinating the various logistics processes.

Synchromodality relies heavily on advanced information systems, coordination platforms, and contractual arrangements that decouple service requirements from specific modes. While still relatively limited in empirical implementation, the concept has gained prominence in European research and policy debates as a potential means of increasing resilience and efficiency in long-distance freight transport. However, as noted by (Agamez-Arias & Moyano-Fuentes, 2017), the operational complexity and institutional requirements of synchromodal transport pose significant challenges, particularly with respect to liability, pricing, and information sharing.

Table 4.1. Summary of definitions.

Term	Definition (key aspect)	Example/Note
<i>Multimodal</i>	Transport by ≥ 2 different modes (goods or container may transfer between modes).	A factory-to-store shipment using truck + rail.
<i>Intermodal</i>	As above but <i>same loading unit</i> throughout (no handling of goods between modes).	Container moved by truck \rightarrow ship \rightarrow truck.
<i>Co-modal</i>	Optimizing use of modes (on their own & combined) for sustainability.	Shipper chooses cheapest/green mix (e.g. truck + barge with minimal road).
<i>Synchromodal</i>	Dynamic, real-time multimodal planning; carriers can switch modes on-the-fly based on conditions.	Real-time re-routing: cargo shifted from delayed ship to train.

4.1.5 Conceptual implications for long-distance goods mobility

Distinguishing clearly between intermodal, multimodal, co-modal, and synchromodal freight transport is crucial for analysing the mechanics of long-distance goods mobility. Each concept implies different assumptions regarding planning horizons, coordination mechanisms, terminal operations, and exposure to delays. These differences have direct implications for how time and cost components accumulate along transport chains and for how such chains are represented in analytical and modelling frameworks.

In the context of this review, these concepts provide the foundational vocabulary for Chapter 4, which examines the operational mechanics of multimodal and intermodal freight transport, and for Chapter 5, which analyses how these mechanics are formalised in freight transport models.

4.2 Transport Chain Configurations and Interfaces

Transport chain configurations describe how goods move from shipper to consignee across spatial scales and modes. At the highest level, long-distance chains can be classified into recurring archetypes observed across European and global freight corridors (Rodrigue, 2024; SteadieSeifi et al., 2014).

4.2.1 Major transport chain archetypes

Door-to-door unimodal chains rely on a single transport mode throughout the journey, most commonly road haulage for inland freight. These chains minimise interfaces and coordination requirements but become cost-intensive over long distances due to fuel, labour, and external costs (Liedtke, 2009; Rodrigue, 2024).

Port-centric maritime chains (sea–road or sea–rail) dominate intercontinental and long-distance European freight. Containerised cargo is moved by deep-sea vessels between gateway ports, followed by inland distribution via road, rail, or short-sea feeders. Empirical studies consistently identify port dwell time, berth congestion, and hinterland connectivity as decisive determinants of total door-to-door transport time and logistics cost (T. E. Notteboom & Rodrigue, 2005; UNCTAD, 2022).

Road–rail intermodal corridor chains combine long line-haul rail services with road-based pre- and post-haulage. These chains benefit from lower per-tonne-kilometre costs and reduced emissions on the main leg but incur additional handling costs and schedule constraints at intermodal terminals, which increase buffer times and reduce flexibility (Macharis & Bontekoning, 2004; Reis, 2014).

Hub-and-spoke networks are characteristic of both rail freight and air cargo systems. In air freight, consolidation at hubs enables high-frequency long-haul services but concentrates time sensitivity at transshipment nodes, where handling efficiency and flight connectivity critically influence door-to-door performance (Bowen, 2012; Kupfer et al., 2017).

Short-sea shipping and feeder-based chains are widely used in European coastal and regional logistics systems to reduce long overland road hauls. While short-sea services offer competitive transport costs and environmental benefits, they typically extend transit times and expose shipments to additional handling and schedule coordination requirements (Rodrigue, 2024; UNCTAD, 2022).

Complex multimodal chains with multiple transfers (e.g. road–rail–sea–rail–road) arise in international logistics networks linking inland production regions to global markets. These chains are particularly vulnerable to cumulative delays and coordination failures, as each interface introduces additional time and cost components (Agamez-Arias & Moyano-Fuentes, 2017).

4.2.2 Terminal and interface typology

Interfaces are physical and institutional nodes where modes meet and where transport time and cost accumulation often accelerates (Hoff et al., 2010). Key interface types include deep-sea ports, inland rail terminals, air cargo hubs, dry ports, logistics parks, and border crossing points. Studies consistently show that terminal handling efficiency, gate processing times, and access congestion dominate door-to-door time variability in multimodal chains (Drewry, 2021; T. E. Notteboom & Rodrigue, 2005).

4.2.3 Interface processes and time–cost accumulation

Across transport chains, five interface processes are repeatedly identified as critical drivers of time and cost: (i) physical handling operations, (ii) documentation and customs clearance, (iii) consolidation and de-consolidation activities, (iv) scheduling coordination and transfer waiting, and (v) equipment and capacity constraints. Empirical evidence indicates that dwell time and waiting at terminals often exceed pure in-vehicle travel time on individual legs, particularly for containerised freight (UNCTAD, 2022).

4.2.4 Unitisation, equipment, and first/last-mile effects

Standardised loading units, particularly ISO containers, have enabled faster and more reliable intermodal transfers by reducing cargo re-handling and damage risks (Rodrigue, 2024). However, first- and last-mile drayage frequently erodes the cost advantages of long-haul rail or maritime legs, especially where terminal congestion and access delays are significant (Hoff et al., 2010; Reis, 2014).

4.2.5 Implications for modelling and decision support

The configuration of transport chains and the performance of interfaces have direct implications for freight transport modelling. Realistic decision support systems must explicitly represent transshipment times, handling costs, buffer times, and equipment constraints, rather than focusing solely on line-haul transport costs and average travel times (Crainic & Laporte, 1997; SteadieSeifi et al., 2014). These requirements provide the conceptual bridge between the mechanical analysis in Chapter 4 and the modelling methodologies reviewed in Chapter 5.

4.3 Terminal Operations, Transshipment, and Dwell Time

Terminal operations constitute the critical operational core of multimodal and intermodal freight transport systems. Empirical and modelling studies consistently show that delays and cost overruns in long-distance freight chains are more frequently generated at terminals than along line-haul links, particularly in containerised and intermodal transport (Hoff et al., 2010; T. E. Notteboom & Rodrigue, 2005). This section synthesises how the literature conceptualises terminal operations, transshipment processes, and dwell time, and how these elements shape door-to-door transport performance.

4.3.1 Structure of terminal operations

Freight terminals perform three fundamental functions: (i) interface handling between transport modes, (ii) temporary storage and buffering, and (iii) administrative and control processes. In container terminals, these functions are organised through berth operations, yard operations, and gate operations, each with distinct time and cost characteristics (T. E. Notteboom & Rodrigue, 2005).

Berth operations involve vessel berthing, crane assignment, and quay crane productivity, typically measured in moves per crane-hour. Berth congestion and crane allocation strategies strongly influence vessel turnaround time and schedule reliability.

Yard operations encompass container stacking, reshuffling, and internal transport between quay and gate. Yard congestion and suboptimal stacking strategies can significantly increase internal handling time and labour costs.

Gate operations regulate truck entry and exit, where queueing, documentation checks, and security procedures often generate substantial waiting times, particularly during peak periods.

Comparable functional distinctions are observed in inland rail terminals and air cargo terminals, where loading/unloading, sorting, and dispatch operations define terminal throughput and turnaround time (Hoff et al., 2010; Kupfer et al., 2017).

4.3.2 Transshipment processes and handling time

Transshipment refers to the transfer of freight units between modes or vehicles within a terminal. Handling time is influenced by terminal layout, handling technology (e.g. reach stackers, gantry cranes, automated guided vehicles), labour organisation, and information systems (Hoff et al., 2010). In intermodal rail terminals, transshipment typically involves lift-on/lift-off operations between rail wagons and trucks, with handling times that are relatively predictable but sensitive to peak congestion and equipment availability (Macharis & Bontekoning, 2004).

In air cargo terminals, transshipment and handling are highly time-critical due to tight flight schedules and the high value of transported goods. Studies emphasise that minutes lost in sorting or security screening can translate into substantial value losses and missed connections in express freight networks (Kupfer et al., 2017).

4.3.3 Dwell time and its determinants

Dwell time refers to the total time a freight unit spends within a terminal from arrival to departure. It includes pure handling time as well as waiting time arising from scheduling mismatches, congestion, and administrative procedures. Empirical port studies demonstrate that dwell time often accounts for a dominant share of total door-to-door transit time, particularly for containerised imports (UNCTAD, 2022).

Key determinants of dwell time identified in the literature include:

Capacity utilisation and congestion, where high yard occupancy ratios lead to longer reshuffling times and reduced operational efficiency (T. E. Notteboom & Rodrigue, 2005).

Service synchronisation, especially the alignment of vessel, train, and truck schedules, which determines waiting time between successive transport legs (StadieSeifi et al., 2014).

Customs and regulatory procedures, which introduce non-physical delays that vary significantly across countries and institutional settings (UNECE, 2019).

Information availability and coordination, where lack of real-time visibility increases uncertainty and buffer times (Agamez-Arias & Moyano-Fuentes, 2017).

4.3.4 Cost implications of terminal operations

Terminal-related costs arise from handling charges, storage fees, demurrage and detention penalties, and indirect costs associated with inventory holding and unreliability. While handling charges are often explicitly priced, dwell-time-related costs are frequently implicit and borne by shippers through increased inventory costs and reduced service reliability (Feo-Valero et al., 2011).

The literature highlights that these costs are not linear with time. Beyond certain thresholds, congestion-induced delays trigger stepwise cost increases through penalty fees, premium services, or the need for alternative routing, amplifying the economic impact of terminal inefficiencies (Drewry, 2021; Hoff et al., 2010).

4.3.5 Implications for long-distance freight performance

From a system perspective, terminal operations act as bottlenecks that constrain the effective performance of multimodal freight networks. Even when line-haul transport is fast and cost-efficient, poor terminal performance can negate these advantages. Consequently, several studies argue that investments in terminal capacity, automation, and digitalisation may yield higher marginal returns in terms of time and cost reduction than equivalent investments in line-haul infrastructure (T. E. Notteboom & Rodrigue, 2005; UNCTAD, 2022).

For modelling and decision support applications, this implies that dwell time and terminal handling processes must be explicitly represented rather than absorbed into average travel times. Failure to do so risks systematically underestimating the true generalised cost of multimodal and intermodal freight transport, particularly for time-sensitive and high-value goods.

4.4 Reliability, Variability, and Delay Propagation in Multimodal Freight Chains

This section synthesizes system-level, operational, and modelling perspectives on complexity, uncertainty and delays in multimodal and intermodal freight systems. Building on Sections 4.1, 4.2, and 4.3, it explains how local disruptions at interfaces and terminals propagate through transport chains, generating reliability shortfalls and non-linear economic costs. The goal is to make explicit the mechanisms through which local disruptions translate into system-level reliability shortfalls and economic costs.

4.4.1 System-level complexity and institutional uncertainty

Long-distance multimodal freight systems are widely characterised as complex socio-technical systems involving numerous heterogeneous actors—shippers, freight forwarders, carriers, terminal operators, infrastructure managers, and public authorities—whose decisions are weakly coordinated and often governed by separate contractual and regulatory regimes (Rodrigue, 2024; Tavasszy & de Jong, 2014). This institutional fragmentation introduces structural uncertainty that is qualitatively different from random operational disturbances. Cross-border freight chains in particular face heterogeneous customs procedures, safety regulations, labour rules, and documentation requirements, which generate non-physical delays and increase variance in door-to-door transport times (European Court of Auditors, 2023; UNECE, 2019).

Policy and governance studies at the European level show that intermodal freight initiatives frequently underperform due to misaligned incentives between infrastructure managers, terminal operators, and transport service providers, even where physical infrastructure capacity is sufficient (ITF, 2019; Macharis & Bontekoning, 2004). Recent empirical assessments of TEN-T and combined transport policies confirm that institutional barriers and coordination failures remain among the dominant sources of unreliability in long-distance freight transport (European Court of Auditors, 2023). Digital interoperability, such as single-window customs, terminal community systems, and shared booking platforms, is consistently identified as a key mitigation mechanism, although adoption remains uneven and governance frameworks are still evolving (Bastiaansen et al., 2020; Hofman, 2019; Zajac et al., 2025).

4.4.2 Physical and operational sources of variability

At the operational level, uncertainty arises from a wide range of physical processes across terminals, ports, rail yards, and airports. Empirical port and terminal studies consistently show that handling and dwell times exhibit substantial variability driven by berth congestion, crane breakdowns, yard reshuffling, chassis and wagon shortages, labour availability, and adverse weather conditions (Akakura, 2023; Drewry, 2021; T. E. Notteboom & Rodrigue, 2005). Simulation-based analyses demonstrate that dwell-time distributions are often highly skewed, with a small share of terminal calls accounting for a disproportionate share of total delay minutes (Kourounioti et al., 2016; Pham & Nguyen, 2022; Saini & Lerher, 2024).

Rail-intermodal chains are particularly sensitive to operational variability because of fixed timetables and rolling-stock circulation constraints. Missed terminal slots or delayed train arrivals can propagate through wagon rotations and crew schedules, amplifying initial disturbances at the network level (Kramarz et al., 2022; Minbashi et al., 2024). In air cargo systems, tight connection windows and security screening requirements introduce additional sources of variability, making air–road and air–rail interfaces highly sensitive to small operational disruptions (Kupfer et al., 2017; Lei & Mu, 2024).

4.4.3 Delay propagation mechanisms in intermodal chains

The literature distinguishes between local, corridor-level, and network-wide delay propagation mechanisms. Local propagation occurs within terminals, where congestion or equipment failures increase queueing and handling times for subsequent operations (T. E. Notteboom & Rodrigue, 2005). Corridor-level propagation arises when delays on one leg (e.g. a late vessel arrival) cause missed connections to scheduled rail or feeder services, forcing freight to wait for the next departure or to be rerouted (Chen et al., 2016; Delbart et al., 2021). At the network level, hub-and-spoke structures amplify these effects, as delays at major gateways affect a large number of downstream shipments (Rodrigue, 2024).

Classical stochastic delay-propagation models developed in the rail and air transport literature, e.g. (Carey & Kwieciński, 1994) have been increasingly adapted to freight and intermodal contexts. Recent studies combine empirical data and simulation to show that buffer times and slack are essential for maintaining reliability, but excessive buffering reduces asset utilisation and increases inventory costs, creating a fundamental trade-off between efficiency and robustness (Büker & Seybold, 2012; Giusti et al., 2019).

4.4.4 Economic consequences of unreliability and time variability

Unreliability in multimodal freight transport generates both direct and indirect economic costs. Direct costs include demurrage and detention charges, additional handling fees, overtime labour, and premium payments for priority services. Indirect costs arise through increased inventory holding, higher safety stock requirements, missed delivery windows, contractual penalties, and loss of service quality (Andersson et al., 2017; Feo-Valero et al., 2011; Liedtke, 2009).

A growing body of empirical work demonstrates that the cost of unreliability is non-linear. Beyond critical delay thresholds, shippers face stepwise increases in cost due to penalties, expedited transport, or production disruptions (Binsuwadan et al., 2022; Drewry, 2021). Studies focusing on high-value and time-sensitive goods – such as air cargo, perishables, and intermediate manufacturing inputs – show particularly high willingness to pay for reliability, reinforcing the importance of modelling time variability separately from average travel time (Kupfer et al., 2017; Liu et al., 2019).

4.4.5 Modelling approaches for uncertainty and delay

The treatment of uncertainty varies substantially across modelling approaches and planning levels. At the strategic level, stochastic and robust optimisation models are used to design freight networks, locate terminals, and allocate capacity under disruption risk (Crainic et al., 2014; Delbart et al., 2021). These models typically represent uncertainty through scenarios, probability distributions, or chance constraints, and seek solutions that balance expected cost with robustness.

At the tactical and operational levels, discrete-event simulation (DES) is widely applied to analyse terminal operations and to estimate dwell-time distributions under alternative resource

configurations (Chhetri et al., 2025; Kourouniotti et al., 2016; Pham & Nguyen, 2022). Hybrid simulation–optimisation frameworks combine DES with metaheuristics or mathematical programming to support real-time rescheduling and disruption management in intermodal chains (Hrušovský et al., 2021; Lei & Mu, 2024).

More recently, data-driven and machine-learning approaches have been introduced to predict delays and arrival times using high-frequency operational data. Applications include freight train delay prediction, port congestion forecasting, and air cargo arrival-time estimation, often as inputs to downstream optimisation or decision-support models (Chhetri et al., 2025; Lee et al., 2024; Minbashi et al., 2024). While promising, these approaches remain constrained by data availability and transferability across regions and modes.

4.4.6 Data limitations, empirical gaps, and policy relevance

Despite rapid methodological progress, empirical research on uncertainty and delays in multimodal freight transport remains constrained by data limitations. Public datasets typically provide aggregate indicators of performance, while event-level terminal and shipment data are proprietary and fragmented (Eurostat, 2025; World Bank, 2023). As a result, many models rely on stylised assumptions or case-specific datasets, limiting generalisability (Pham & Nguyen, 2022).

From a policy and operational perspective, the literature consistently highlights the high leverage of interventions targeting terminals and interfaces. Investments in terminal automation, digital coordination platforms, and regulatory simplification often yield greater reductions in door-to-door transport time and variability than equivalent investments in line-haul infrastructure (T. E. Notteboom & Rodrigue, 2005; UNCTAD, 2003, 2022). These findings underscore the importance of integrating uncertainty and delay explicitly into freight transport analysis and decision support.

5. Modelling Methodologies

This chapter critically reviews the modelling methodologies applied to long-distance freight transport across road, rail, maritime, and air modes. It integrates methodological classifications with evidence on how time, cost, uncertainty, and type of load are represented, and highlights systematic modelling biases and implications for policy and decision support.

5.1 Conceptual classification of freight transport models

This section establishes a multi-dimensional classification framework that structures the subsequent review. Rather than organising models solely by mathematical technique, the framework differentiates studies by purpose, scale, transport configuration, and type of load (Crainic & Laporte, 1997; SteadieSeifi et al., 2014; Tavasszy & de Jong, 2014). This approach enables meaningful comparison across heterogeneous literatures and exposes systematic gaps in the modelling of long-distance goods mobility.

5.1.1 Classification by modelling purpose

Freight transport models serve distinct decision-making purposes, commonly grouped into strategic, tactical, and operational levels (Crainic & Laporte, 1997; Hoff et al., 2010). Strategic models address long-term decisions such as network design, terminal location, and infrastructure investment, typically relying on aggregated representations of demand, average travel times, and linear or piecewise-linear cost functions (de Jong et al., 2004; Tavasszy & de Jong, 2014). Tactical models support medium-term planning, including service design, capacity allocation, and contract planning, and often introduce limited representations of variability (Liedtke, 2009). Operational models focus on short-term routing, scheduling, and disruption management, requiring detailed representations of time, resource constraints, and uncertainty (Hoff et al., 2010; Hrušovský et al., 2021).

The literature shows a strong correspondence between modelling purpose and the treatment of time and cost. Strategic models frequently rely on aggregated travel times and linear cost functions, whereas operational models increasingly employ stochastic, simulation-based, or data-driven approaches to capture dwell time, waiting, and delay propagation. Air freight models are more prevalent at the tactical and operational levels due to tight schedules and high time sensitivity, while bulk freight is predominantly analysed at the strategic level (Kupfer et al., 2017; Tavasszy & de Jong, 2014).

5.1.2 Classification by spatial and temporal scale

Models also differ by spatial coverage and temporal resolution. Spatially, studies range from domestic and corridor-based analyses to international and intercontinental networks (Rodrigue, 2024). Maritime and air freight models naturally operate at international scales, whereas road and rail models are often national or regional (Kupfer et al., 2017; T. E. Notteboom & Rodrigue, 2005). Temporally, models may be static (single-period, average conditions), dynamic (time-dependent demand or capacity), or real-time (adaptive routing and rescheduling) (Delbart et al., 2021; SteadieSeifi et al., 2014).

Long-distance multimodal models that integrate maritime or air legs typically operate at coarser temporal resolutions, reflecting data limitations and planning horizons. In contrast, terminal simulation and air cargo scheduling models employ fine-grained temporal detail (Durdak, 2013; Lei & Mu, 2024; Minbashi et al., 2024). This divergence complicates comparison of time and cost outcomes across studies and reinforces the need for explicit classification.

5.1.3 Classification by transport configuration

A further distinction concerns the transport configuration represented in models: unimodal, intermodal, multimodal, or synchromodal (Macharis & Bontekoning, 2004; SteadieSeifi et al., 2014). Unimodal models, particularly for road freight, dominate early demand-modelling and cost-analysis literature (de Jong et al., 2004; Tavasszy & de Jong, 2014). Intermodal models

typically focus on road–rail or road–sea chains and explicitly represent terminals and transshipment costs (Bontekoning et al., 2004; Reis, 2014, 2019; Yu & Jiang, 2024). Multimodal models encompass a broader set of mode combinations but often retain fixed mode sequences. Sychromodal models introduce dynamic mode choice during execution, requiring advanced information systems and flexible contracts (StadieSeifi et al., 2014; M. Zhang & Pel, 2016).

Despite increasing policy attention to sychromodality, the modelling literature remains heavily concentrated on fixed intermodal configurations, with limited empirical validation of dynamic mode switching. Air freight is commonly integrated into multimodal models only for high-value or time-critical cargo, reinforcing a selective treatment of modes (Kupfer et al., 2017; M. Zhang & Pel, 2016).

5.1.4 Classification by type of load: descriptive mapping and modelling biases

Type of load is a critical yet inconsistently treated dimension in freight transport modelling. A descriptive mapping of the literature reveals four broad categories: containerised cargo, dry bulk, liquid bulk, and general (non-containerised) cargo, with many studies either implicitly assuming containers or leaving cargo type unspecified.

Containerised freight dominates intermodal and multimodal modelling. The prevalence of ISO containers, standardised handling processes, and data availability has led to a strong concentration of optimisation, simulation, and sychromodal studies on container flows (Agamez-Arias & Moyano-Fuentes, 2017). These models typically incorporate terminal handling time, dwell time, and inventory-related costs, making them well suited to analysing intermodal competitiveness and reliability.

Dry bulk freight (e.g. coal, ores, grain) is primarily represented in strategic cost and capacity models, often focusing on rail–water or rail–road chains. Time is frequently treated as an average parameter, and stochastic delay modelling is rare. Liquid bulk freight (e.g. oil, chemicals, LNG) appears mainly in specialised studies addressing safety, risk, and infrastructure capacity, with limited integration into general intermodal modelling frameworks.

General cargo, including palletised, boxed, and loose goods, is the least consistently represented category. While such cargo often exhibits high handling intensity and variability, it is typically subsumed under containerised assumptions or addressed indirectly in consolidation and hub-location models. This results in systematic under-representation of handling-induced delays and labour-intensive cost structures.

These patterns reveal clear modelling biases. The dominance of container-focused models risks overestimating the feasibility and performance of intermodal solutions for other load types. Conversely, the limited treatment of bulk and general cargo constrains the applicability of modelling results to a narrow subset of real-world freight flows. Recognising these biases is essential for interpreting comparative results and for identifying priorities for future research.

Table 5.1 provides the summary of the conceptual classification of freight transport models discussed in this chapter.

Table 5.1. Conceptual classification of freight transport models

Classification dimension	Main categories	Typical emphasis in literature	Key gaps
Modelling purpose	Strategic / Tactical / Operational	Strategic and tactical dominate	Limited operational realism in long-distance models
Spatial scale	Domestic / International / Intercontinental	Maritime and air at global scale	Weak integration across scales
Transport configuration	Unimodal / Intermodal / Multimodal / Sychromodal	Intermodal (road–rail, road–sea)	Limited empirical synchronomodal studies
Type of load	Containerised / Dry bulk / Liquid bulk / General cargo	Strong container bias	Under-modelling of bulk and general cargo
Time treatment	Deterministic / Stochastic / Reliability-based	Deterministic averages common	Deterministic averages common
Cost treatment	Linear / Generalised / Non-linear	Transport cost focus	Inventory and penalty costs often omitted

5.2 Machine Learning Integration in Network and Routing Models

The most significant and paradigm-shifting advancement in contemporary logistics modelling is the integration of Machine Learning (ML) to bridge the vast gap between static mathematical functions and dynamic, real-world operations (Deineko et al., 2024; Tsolaki et al., 2023).

Expected time of arrival and Delay predictions: Predicting the precise arrival time of intermodal freight is notoriously difficult due to the unexplainable, “black box” nature of maritime transit and the compounded risks of multi-stage transshipment (Tsolaki et al., 2023). Recent studies have demonstrated that aggregate learning methods, specifically Random Forest Regression, XGBoost, and LightGBM, vastly outperform traditional statistical models in predicting delivery timeliness across complex networks (Purnomo et al., 2025; Tsolaki et al., 2023), LightGBM, for instance, has proven highly effective in predicting short-term arrival delays in freight rail operations by rapidly processing vast datasets (Minbashi et al., 2024). Furthermore, advanced hybrid approaches – such as combining Decision Tree Regression with the Firefly Algorithm for simultaneous hyperparameter tuning and automated feature selection – have achieved astonishing accuracy rates exceeding 98 percent ($R^2=0.987$) in forecasting logistics delays (Xiang et al., 2026). Feature importance analyses within these models consistently isolate specific parameters – such as physical distance, prior reliability performance, train composition (weight and length), and real-time departure delays – as the most heavily weighted predictors of downstream arrival delays (Pineda-Jaramillo & Viti, 2023; Purnomo et al., 2025).

Network Flow Estimation (Deep Gravity Models): Understanding massive, macro-level freight flows is an absolute prerequisite for micro-level routing optimization. Researchers are increasingly applying Deep Gravity Models – a novel, physics-informed deep learning framework – to predict the spatial interaction and volume of heavy truck and maritime traffic across global networks (Song et al., 2024; Yang et al., 2023). By analysing massive GPS trajectory datasets and utilizing transformer neural networks to map highly non-linear dependencies between economic mass (e.g., regional GDP, port throughput) and transport friction (physical distance, transit cost), Deep Gravity models have achieved substantial, double-digit percentage improvements in predictive accuracy over traditional spatial gravity models (Song et al., 2024; Yang et al., 2023). This leap in capability enables highly precise multi-port liner routing and highly accurate intercity truck mobility forecasting.

Table 5.2. Summary of Machine Learning models in the literature

ML model	Primary application	Key performance advantages	References
Random Forest / XGBoost	Terminal delay prediction, delivery ETA forecasting.	High accuracy (approx. 65-97%), effectively handles non-linear operational factors, identifies key feature weights.	(Purnomo et al., 2025; Tsolaki et al., 2023)
LightGBM / CatBoost	Short-term arrival delay prediction for rail freight.	Fast training on large datasets, highly accurate for rail departure/arrival forecasting, identifies train weight/length impacts.	(Pineda-Jaramillo & Viti, 2023; Purnomo et al., 2025)
Graph Attention Networks (GAT)	Special delay propagation across rail/intermodal networks.	High interpretability, uses attention mechanisms to apply diverse weights to distinct delay influence factors.	(Huang et al., 2024)
Deep Reinforcement Learning (DRL)	Dynamic synchromodal routing and real-time shipment matching.	Continuous learning from stochastic environments, enables mode-free booking and real-time rerouting under uncertainty.	(Y. Zhang et al., 2023)
Deep Gravity Networks	Macro-level origin-destination flow estimation, multi-port routing.	Physics-informed, uses transformers to capture long-term dependencies, vastly outperforms traditional gravity models.	(Song et al., 2024; Yang et al., 2023)
Decision Trees + Firefly Algorithm	Hyperparameter tuning and feature selection for delays.	Achieves near 98% accuracy ($R^2=0.987$), reduces overfitting, lowers computational resource requirements.	(Xiang et al., 2026)

5.3 Representation of time components in freight transport models

This section provides a comprehensive overview of how time is estimated, decomposed, and operationalised in long-distance freight transport models by critically examining how different time components influence freight mode choice, system performance, and operational decision-making across road, rail, maritime, and air transport.

5.3.1 Methods for estimating freight transport time

Empirical freight studies employ several distinct approaches to estimate transport time; each associated with specific strengths and biases. First, observed or realised time measurements derived from GPS traces, AIS vessel data, train logs, and terminal operating systems are increasingly used to capture actual door-to-door performance. Such data-driven approaches allow researchers to distinguish between scheduled and realised times and to quantify variability and tail delays. Recent port and terminal studies using operational logs and process mining demonstrate that realised dwell times often deviate substantially from planned benchmarks, with strong right-skewed distributions (Hassan & Gurning, 2020; Lee et al., 2024; Saini & Lerher, 2024).

Second, stated preference (SP) and mixed SP–RP approaches have often been applied to estimating the behavioural relevance of time and reliability in freight decision-making. Large-scale SP surveys with shippers and carriers have been used to estimate values of freight travel time savings (VFTTS) and values of reliability (de Jong et al., 2014), explicitly separating in-vehicle time, waiting time, and schedule delay components. Empirical results consistently show that reliability and waiting-related components often carry higher marginal disutility than pure line-haul travel time, particularly for containerised and high-value cargo (Binsuwadan et al., 2022; Shams, Jin, et al., 2017; Tao & Zhu, 2020; Vallender et al., 2023).

Third, econometric and statistical estimation using revealed operational data has been applied to infer time effects indirectly, for example through freight mode choice models or regression-based delay analyses. Such studies demonstrate that ignoring time variability leads to biased elasticity estimates and overvalues the competitiveness of slower but cheaper modes (Fulzele et al., 2019; Jung et al., 2019; Mandouri et al., 2026).

Finally, simulation-based and predictive approaches, including discrete-event simulation and machine-learning models, are increasingly used to estimate time components where direct observation is incomplete. Simulation studies of container and inland terminals quantify how yard policies, resource allocation, and congestion translate into handling and dwell time, while predictive models estimate arrival or dwell distributions for operational planning (Hassan & Gurning, 2020; Minbashi et al., 2024; Srisurin et al., 2022).

5.3.2 Various time components in freight transport

Across empirical studies, freight transport time is consistently decomposed into several components: line-haul travel time, terminal handling time, dwell and waiting time, buffer time, and delay recovery time. Evidence shows that while line-haul time dominates mean transit time

for unimodal road and rail transport, terminal-related components dominate variability and unreliability in intermodal and maritime chains.

Operational analyses of containerised freight reveal that terminal dwell time frequently exceeds pure handling time by an order of magnitude, reflecting customs clearance, documentation, equipment availability, and coordination failures (Hassan & Gurning, 2020; Lee et al., 2024). Empirical port studies report median import container dwell times of 1–3 days at well-performing terminals, with long tails extending beyond 7–10 days during congestion or disruption periods (BTS, 2026; UNCTAD, 2025).

Rail freight studies similarly show that while scheduled running times are relatively stable, missed slots and terminal connection failures produce disproportionate delays that propagate across the network (Minbashi et al., 2024; Pineda-Jaramillo & Viti, 2023). In air freight, by contrast, flight time variability is minimal, but connection reliability at hubs and ground handling capacity strongly influence total transit time (IATA, 2020; Lange & Bier, 2019; Lu & Chung, 2023).

5.3.3 Effects of time attributes on freight mode choice

A substantial body of empirical mode choice literature demonstrates that time-related attributes significantly influence freight transport decisions. Discrete choice models based on SP and RP data consistently find that increases in travel time and waiting time reduce the probability of choosing rail and maritime modes relative to road for medium-distance flows, while reliability improvements can partially offset longer average transit times (Jung et al., 2019; Tao & Zhu, 2020).

Meta-analytical evidence indicates that the estimated value of freight travel time varies widely across studies but is systematically higher for time-sensitive shipments and containerised cargo than for bulk commodities (Binsuwadan et al., 2022). Importantly, several empirical studies show that reliability often matters more than mean time, with shippers willing to pay substantial premiums to reduce variability and avoid extreme delays (Tao & Zhu, 2020; Vallender et al., 2023).

For intermodal transport, empirical results suggest that additional terminal time and unreliability constitute a major barrier to mode shift. Even when line-haul rail or maritime segments are cost-competitive, the cumulative effect of transshipment time and uncertainty reduces the attractiveness of intermodal options, particularly for high-frequency or just-in-time supply chains (Jung et al., 2019; Kramarz et al., 2022; Mandouri et al., 2026).

5.3.4 Operational impacts of time components

Beyond mode choice, time components have direct implications for freight system operations. Empirical terminal studies show that longer dwell times reduce asset utilisation, increase congestion, and exacerbate delay propagation across interconnected networks (Hassan & Gurning, 2020; Srisurin et al., 2022). Studies on demurrage and detention demonstrate that

prolonged dwell times generate non-linear operational and financial impacts, incentivising behavioural responses such as early pick-up, mode switching, or re-routing (Kim & Cho, 2024; Kołacz et al., 2024).

In rail and maritime systems, delay propagation studies highlight how small initial disturbances can cascade through tightly coupled schedules, increasing system-wide unreliability (Büker & Seybold, 2012; Minbashi et al., 2024; Pineda-Jaramillo & Viti, 2023). Air cargo operations exhibit similar amplification effects at hub airports, where missed connections lead to long waiting times due to limited onward capacity (Ishiguro et al., 2025; Lange, 2019; Lange & Bier, 2019).

In summary, comparative evidence across modes indicates clear structural differences in time performance. Road transport offers the shortest door-to-door times for short and medium distances but exhibits high variability due to congestion and regulatory constraints. Rail and maritime transport provide lower average costs for long distances but incur significant terminal-related time penalties and reliability risks. Air freight delivers the shortest line-haul times but is highly sensitive to network connectivity and ground handling performance.

Load type further conditions these effects. Containerised cargo is highly sensitive to terminal dwell and waiting time, while dry bulk freight exhibits lower time sensitivity and more stable handling processes. Liquid bulk is affected primarily by safety and inspection delays, whereas general cargo experiences high handling intensity and consolidation-related waiting. Empirical evidence on non-containerised cargo remains limited, highlighting a major gap in the literature.

5.3.5 Quantitative comparison of time components across modes

A key contribution of empirical freight studies lies in providing order-of-magnitude estimates of different time components, enabling comparison across modes and intermodal configurations. While exact values vary by corridor, terminal, and period, a synthesis of results across multiple empirical analyses reveals consistent patterns.

Line-haul time. Road freight studies report effective long-distance travel speeds of approximately 50–70 km/h under free-flow conditions, declining substantially under congestion or regulatory constraints (Jung et al., 2019; Vallender et al., 2023). Rail freight line-haul speeds in Europe typically range between 30–50 km/h when averaged over long distances and accounting for scheduled stops and pathing constraints (Minbashi et al., 2024). Deep-sea maritime transport exhibits average effective speeds of 15–25 knots (28–46 km/h), but the absolute duration of long-haul maritime legs often spans 2–4 weeks for intercontinental flows (UNCTAD, 2022, 2025). Air freight line-haul times are shortest in absolute terms, with intercontinental flight segments typically completed within 8–15 hours, although these represent only a fraction of total door-to-door time (IATA, 2020).

Terminal handling and dwell time. Empirical terminal studies provide relatively consistent quantitative evidence. For containerised freight, pure handling time (quay crane, yard moves, gate operations) is typically measured in hours, whereas total dwell time is measured in days.

Studies based on terminal operating system data report median import container dwell times of 1–3 days at well-performing terminals, with upper quartiles often exceeding 5–7 days, and extreme cases surpassing 10–14 days during congestion or disruption (Hassan & Gurning, 2020; Lee et al., 2024; UNCTAD, 2025). Inland rail terminals generally exhibit shorter dwell times, typically 0.5–2 days but missed connections can extend waiting times significantly (Minbashi et al., 2024; Srisurin et al., 2022).

Intermodal transfer penalties. Empirical comparisons between unimodal and intermodal chains indicate that each additional transshipment typically introduces a time penalty of 0.5–2 days, depending on terminal efficiency and service frequency (Jung et al., 2019; Mandouri et al., 2026). These penalties arise not from handling itself, but from waiting for scheduled departures and buffer times introduced to manage unreliability.

Reliability and variability. Quantitative analyses consistently show that variability is dominated by terminal-related components rather than line-haul movement. For containerised maritime chains, studies report coefficients of variation for dwell time that are 2–4 times larger than those for sailing time (Hassan & Gurning, 2020; Lee et al., 2024). Rail freight delay studies similarly indicate that a small share of disrupted connections accounts for a disproportionate share of total delay minutes, confirming the importance of tail-risk rather than average delay (Minbashi et al., 2024; Pineda-Jaramillo & Viti, 2023).

Mode and chain comparisons. When comparing complete door-to-door times, empirical evidence suggests that unimodal road transport is typically fastest for distances up to 300–500 km, while intermodal road–rail or road–sea chains become competitive only beyond longer distances and for less time-sensitive cargo. However, even at long distances, additional terminal time often offsets line-haul advantages, explaining the persistent dominance of road transport in many corridors (Jung et al., 2019; Vallender et al., 2023).

Table 5.3. Empirical ranges (in order of magnitude) of freight time components by mode

Mode	Line-haul time	Terminal handling time	Typical dwell / waiting time	Dominant source of variability
Road (long-haul)	Hours–1–2 days	<1 hour	Minimal	Congestion, driver hours
Rail	Days	2–6 hours	0.5–2 days	Missed slots, terminal coordination
Road–rail	Days	4–10 hours (2 terminals)	1–3 days	Transfer waiting, schedule mismatch
Maritime (deep-sea)	Weeks	6–24 hours	1–5 days (median; long tail)	Port congestion, documentation
Road–sea–road	Weeks	8–30 hours (2–3 terminals)	2–6+ days	Port dwell and feeder reliability
Rail–maritime–rail	Weeks	8–24 hours (ports + rail terminals)	2–5 days	Port–rail interface coordination

Road–air–road	Hours–1–2 days	2–8 hours (air cargo terminals)	<1 day	Hub connectivity, security, handling
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Table 5.3 summarises indicative time magnitudes and dominant sources of variability across modes, synthesised from multiple empirical studies. These quantitative comparisons highlight that terminal dwell and intermodal transfer time frequently outweigh differences in pure line-haul speed, particularly for containerised freight. Consequently, models that compare modes solely on in-vehicle travel time risk misrepresenting real-world performance.

5.4 Representation of cost components in freight transport

This section reviews how cost components are represented, quantified, and compared in modelling studies of long-distance freight transport and explicitly relates cost structures to transport modes, multimodal chain configurations, and types of loads.

5.4.1 Decomposition of freight transport cost components

Across the literature, freight transport costs are decomposed into a set of recurring components, although terminology and aggregation levels vary considerably (Forkenbrock, 2001; Liedtke, 2009; Tavasszy & de Jong, 2014). Empirical and modelling studies typically distinguish between:

1. **Line-haul transport costs**, including fuel or energy, labour, vehicle or vessel operation, and infrastructure charges.
2. **Transfer and handling costs**, covering terminal transfer costs, loading and unloading, lifting, sorting, storage, and terminal access charges.
3. **Inventory holding costs**, reflecting the capital tied up in goods during transport and storage.
4. **Delay-related and penalty costs**, such as demurrage, detention, contractual penalties, and premium charges for expedited services.

Empirical evidence shows that while line-haul costs dominate total transport expenditure for unimodal road freight, terminal- and delay-related costs can account for a substantial share of total generalised cost in intermodal chains, particularly for containerised freight (Feo-Valero et al., 2011; Reis, 2014). The standard objective function in the optimisation models generally seeks to minimise the total system cost (C_{total}), which is formulated as a summation of continuous and discrete cost parameters (Chupin et al., 2025; Lebedeva & Poltavskaya, 2020; Popa et al., 2025; M. Zhang et al., 2015).

The generalised cost objective function is typically structured as follows:

$$Z = \sum_{(i,j) \in A} (C_{ij}^{transport} \cdot x_{ij}) + \sum_{i \in N} (C_i^{handling} \cdot y_i) + C^{inventory} + C^{emissions}$$

In this formulation, the parameters are defined as:

x_{ij} is a binary decision variable indicating whether the specific continuous network arc between node i and node j is selected for transportation (1 if selected, 0 otherwise).

y_i is binary variable representing the utilisation of a transshipment terminal at node i .

$C_{ij}^{transport}$ is a link-specific operational costs including fuel, crew labour, vehicle depreciation, infrastructure access charges, and tolls. These costs exhibit concave structures; due to large economies of scale, the marginal unit cost of transporting container decreases significantly as total shipment volume increases on a specific rail or maritime link.

$C_i^{handling}$ is a terminal transfer costs which captures the heavy micro-level transshipment penalties at intermodal nodes, including gantry crane operations, gate fees, chassis supply, and temporary yard storage.

$C^{inventory}$ depicts in-transit holding costs, the economic value of time. Because rail and maritime transit times are generally longer and more variable than road-only transport, the financial capital corresponds to transit of goods increases interest and depreciation costs that must be mathematically accounted for in a true door-to-door cost comparison.

$C^{emissions}$ is the monetised cost of environmental externalities. Depending on the model, this is calculated either through a deterministic direct carbon tax, stochastic cap-and-trade credit pricing, or the shadow pricing of pollutants (CO_2 , NO_x , SO_x). Please note that environmental externalities are not investigated in this review.

Time functions as constraints: Time acts as a strict, binding constraint within these optimization models. The temporal evolution of the freight through the network is tracked using accurate time update constraints:

$$t_j \geq t_i + \frac{d_{ij}}{v_{ij}} + t_i^{dwell} \quad \forall (i,j) \in A \text{ such that } x_{ij} = 1$$

Here, t_i is the departure time from node i , d_{ij} is the physical distance of the arc, v_{ij} is the mode-specific velocity, and t_i^{dwell} encompasses all waiting, loading, shunting, and unloading dwell times at the interface nodes.

5.4.2 Line-haul transport costs

Empirical studies and policy appraisal guidelines provide relatively consistent order-of-magnitude ranges for line-haul transport costs, usually expressed in monetary units per tonne-kilometre (€/tkm). Road freight in Europe typically exhibits the highest unit costs, with reported values commonly in the range of €0.04–0.10 per tkm, reflecting fuel prices, labour costs, and regulatory constraints (ITF, 2019; Marzano et al., 2022; Vallender et al., 2023). Rail freight generally offers lower line-haul costs for long distances, with typical estimates between

€0.02–0.05 per tkm, depending on train length, utilisation, and access charges (ITF, 2019; Liedtke, 2009; Marzano et al., 2018).

Deep-sea maritime transport exhibits the lowest unit line-haul costs, often reported below €0.01–0.02 per tkm for containerised cargo on major routes, although these averages mask substantial variability across ship sizes and market conditions (Atkins Beng, 2023; UNCTAD, 2025). Air freight, by contrast, is characterised by extremely high line-haul costs, frequently exceeding €1.50 per tkm, reflecting high operating costs and limited capacity, and is therefore confined to high-value and time-sensitive goods (Bowen, 2012; Kupfer et al., 2017).

5.4.3 Terminal, handling, and transshipment costs

Terminal and handling costs constitute a critical differentiating factor between unimodal and intermodal freight transport. Empirical port and terminal studies report container handling charges typically in the range of €100–300 per lift or per container, depending on terminal type, automation level, and region (T. E. Notteboom & Rodrigue, 2005; UNCTAD, 2025). Inland rail terminals exhibit comparable magnitudes for lift-on/lift-off operations, although costs vary with throughput and equipment utilisation (Macharis & Bontekoning, 2004).

In intermodal chains, each transshipments introduces additional handling and administrative costs, which modelling studies often represent as fixed penalties per transfer. Empirical analyses indicate that these costs can offset a significant share of the line-haul cost advantage of rail or maritime transport, particularly for medium-distance flows (Feo-Valero et al., 2011; Reis, 2014). For air freight, ground handling and security screening charges represent a non-negligible cost component, further reinforcing the mode's focus on high-value shipments (Kupfer et al., 2017).

5.4.4 Inventory holding and time-dependent costs

The inclusion of inventory holding costs link time directly to monetary cost. Inventory costs are typically modelled as a function of cargo value, interest rates, and transit time, and are particularly important for high-value goods and long-distance transport (Forkenbrock, 2001; Tavasszy & de Jong, 2014). Empirical studies show that inventory costs can rival or exceed pure transport costs for time-sensitive and high-value shipments, explaining the willingness of shippers to pay premiums for faster or more reliable modes.

Several modelling studies demonstrate that ignoring inventory costs biases mode choice results in favour of slower modes, especially maritime transport. When inventory costs are included, the generalised cost of slow but cheap modes increases substantially, narrowing the apparent cost gap with faster alternatives (Feo-Valero et al., 2011; Liedtke, 2009).

5.4.5 Delay-related, reliability, and penalty costs

Delay-related costs arise from deviations from planned schedules and include demurrage and detention charges, contractual penalties for late delivery, and additional labour or handling expenses. Empirical evidence from port and shipping studies indicates that demurrage and detention charges can escalate rapidly beyond free-time thresholds, introducing non-linear cost structures into freight transport models (Drewry, 2021; UNCTAD, 2025).

Reliability-related costs are often incorporated indirectly through values of reliability or schedule delay penalties in generalised cost formulations. Studies consistently find that shippers are willing to pay substantial premiums to reduce variability, particularly in multimodal and intermodal contexts where delays propagate across chains (Shams, Asgari, et al., 2017; Tao & Zhu, 2020; Vallender et al., 2023). These findings underscore the importance of modelling reliability as a distinct cost component rather than subsuming it into average transport cost.

5.4.6 Comparative cost structures across modes

This review reveals systematic difference in cost structures. Unimodal road transport exhibits high variable costs but low fixed and terminal costs, making it competitive for short and medium distances. Rail and maritime transport offer lower line-haul costs but incur higher fixed and terminal costs, reducing their competitiveness for smaller volumes or shorter distances (Liedtke, 2009; Reis, 2014).

In intermodal chains, the accumulation of terminal and transshipment costs often explains why cost advantages emerge only above certain distance thresholds. Empirical modelling studies identify break-even distances of several hundred kilometres for road–rail intermodal transport, depending on terminal efficiency and cargo type (Feo-Valero et al., 2011; Santos et al., 2015). Air freight chains exhibit the opposite pattern, with extremely high line-haul and handling costs justified only by very high cargo values or extreme time sensitivity (Kupfer et al., 2017).

5.4.7 Cost implications by type of load

Cost structures vary markedly by type of load. Containerised cargo benefits from standardised handling and transparent pricing, making it the dominant focus of intermodal cost models. Dry bulk freight typically exhibits low unit transport costs and low time sensitivity, with cost models emphasising economies of scale and infrastructure capacity rather than terminal handling (Liedtke, 2009). Liquid bulk freight incurs additional safety and compliance costs, which are rarely integrated into general freight models but are significant in practice (Rodrigue, 2024).

General cargo often faces higher handling and consolidation costs yet remains under-represented in modelling studies. This omission can lead to systematic underestimation of costs in multimodal chains involving non-containerised goods, reinforcing the container bias identified in [Section 5.1.4](#).

Table 5.4 below summarises the indicative ranges of various freight costs as discussed in previous subsections.

Table 5.4. Empirical ranges (in order of magnitude) of freight cost components by mode

Mode	Line-haul cost (€/tkm)	Terminal & handling cost	Inventory & time-related cost relevance	Dominant cost drivers
Road	€0.04–0.10	Low (<€50 per shipment stop)	Moderate for high-value goods	Fuel, labour, tolls, regulation
Rail	€0.02–0.05	Moderate (€100–250 per loading unit)	Low–Moderate	Train utilisation, access charges
Road–rail	€0.02–0.05 (main leg)	High (€200–500 per container, 2 terminals)	Moderate–high	Terminal lifts, schedule coordination
Maritime (deep-sea)	<€0.01–0.02	High (€200–400 per container)	High due to long transit time	Vessel size, port charges
Road–sea–road	<€0.02 (sea leg)	Very high (€400–700 per container)	High	Port handling, dwell, feeder links
Rail–maritime–rail	<€0.02 (sea) / €0.02–0.05 (rail)	Very high (€400–800 per container)	High	Port–rail interface efficiency
Road–air–road	>€0.50–1.50	High (€300–800 per shipment)	Very high	Fuel, security, ground handling

5.5 Integrated time-cost trade-offs in freight transport

This section synthesises the findings of Section 5.2 and 5.3 to critically examine how time and cost jointly shape freight transport decisions, and how their interaction is (mis)represented in existing modelling approaches. Instead of treating time and cost as independent attributes, the reviewed literature demonstrates that their interaction is non-linear, mode-specific, and highly sensitive to terminal performance, reliability, and type of load.

5.5.1 Time–cost trade-offs across modes: empirical regularities

Across empirical studies, a consistent time–cost gradient is observed across freight modes. Road transport occupies a middle ground, combining moderate line-haul costs with relatively short door-to-door times and minimal terminal penalties, which explains its persistent dominance in inland freight markets despite higher per-kilometre costs (Jung et al., 2019; Liedtke, 2009). Rail and maritime transport, by contrast, offer substantially lower line-haul costs but impose longer transit times and higher terminal-related costs, particularly in intermodal configurations (Feo-Valero et al., 2011; Reis, 2014).

Air freight represents the extreme end of the range, with very high line-haul and handling costs justified only where the value of time, reliability, or service criticality outweighs monetary considerations (Bowen, 2012; Kupfer et al., 2017). Empirical mode choice models consistently show steep cost elasticities for air freight and strong sensitivity to time reductions, reinforcing its niche role in long-distance goods mobility.

Importantly, the literature shows that these trade-offs are not linear. Small reductions in terminal dwell time can generate disproportionately large reductions in generalised cost for intermodal chains, whereas equivalent investments in line-haul speed often yield marginal benefits (T. E. Notteboom & Rodrigue, 2005; UNCTAD, 2025).

5.5.2 Intermodal chains: when low cost becomes high generalised cost

A repetitive empirical finding is that intermodal and multimodal chains frequently fail to deliver the expected cost advantages predicted by simplified models. Studies comparing unimodal road transport with road–rail or road–sea alternatives demonstrate that while line-haul costs are lower, additional handling, dwell time, and unreliability increase the generalised cost, particularly for time-sensitive shipments (Feo-Valero et al., 2011; Jung et al., 2019).

Break-even analyses reveal that intermodal cost advantages emerge only above certain distance and volume thresholds and are highly sensitive to terminal efficiency. When dwell times exceed benchmarks (e.g. 1–2 days at inland terminals or 2–3 days at ports), inventory and delay-related costs rapidly erode savings from lower transport rates (Liedtke, 2009; Reis, 2014).

5.5.3 Reliability as the missing link between time and cost

One of the strongest conclusions emerging from the literature is that reliability mediates the relationship between time and cost. Empirical studies show that shippers do not respond only to mean travel time but to the distribution of outcomes, particularly the risk of extreme delays (Tao & Zhu, 2020; Vallender et al., 2023).

Models that incorporate values of reliability or schedule delay penalties consistently outperform those based solely on average time and cost. However, many freight models still rely on deterministic or mean-value representations, leading to systematic underestimation of the generalised cost of intermodal transport (Liedtke, 2009; Tavasszy & de Jong, 2014). This modelling bias is particularly problematic in policy appraisal, where intermodal projects may appear economically attractive on paper but underperform in practice.

5.5.4 Type of load and heterogeneity in time–cost sensitivity

The interaction between time and cost varies substantially by type of load, yet this heterogeneity is often insufficiently represented in freight models. Containerised cargo exhibits moderate to high time sensitivity and benefits from standardised handling, making it the

primary focus of intermodal optimisation studies (Agamez-Arias & Moyano-Fuentes, 2017; Macharis & Bontekoning, 2004).

Dry bulk freight typically exhibits low time sensitivity and strong cost orientation, with shippers prioritising low unit transport costs over speed. For such cargo, slow but cheap modes such as rail and maritime transport are often optimal, even when dwell times are significant (Liedtke, 2009). Liquid bulk freight introduces additional safety and regulatory costs, which interact with time through inspection and clearance delays but remain poorly integrated into general freight models (Rodrigue, 2024).

General cargo, including palletised and non-containerised goods, often combines relatively high handling intensity with moderate time sensitivity. The literature suggests that ignoring this category biases conclusions in favour of container-centric intermodal solutions and underestimates the true cost of multimodal transport for heterogeneous freight flows (Hoff et al., 2010; Tavasszy & de Jong, 2014).

5.5.5 Systematic modelling biases and their consequences

Synthesising the reviewed studies reveals several systematic modelling biases. First, many models overemphasise line-haul transport costs while underrepresenting terminal, handling, and delay-related costs. Second, time is frequently modelled as a deterministic average, ignoring variability and tail risk. Third, type-of-load heterogeneity is often omitted or oversimplified, limiting the transferability of results.

These biases tend to overestimate the competitiveness of intermodal and multimodal solutions, particularly in policy-oriented studies aiming to promote modal shift. Empirical evidence from realised freight operations suggests that without substantial improvements in terminal performance and coordination, the predicted time–cost advantages of intermodal transport are unlikely to materialise (T. E. Notteboom & Rodrigue, 2005; UNCTAD, 2025).

5.6 Policy implications for long-distance freight movement

5.6.1 From link-based to node-based policy priorities

A key implication of the reviewed literature is that policy interventions focused predominantly on line-haul infrastructure are unlikely to deliver proportional improvements in door-to-door freight performance. Empirical evidence consistently shows that terminal handling, dwell time, and interface coordination dominate both total transport time and variability in long-distance multimodal chains. Consequently, marginal reductions in travel time achieved through faster vehicles, upgraded tracks, or higher vessel speeds often yield limited benefits when terminal inefficiencies persist.

These findings challenge traditional appraisal frameworks that prioritise corridor speed and capacity expansion. Instead, the evidence supports a node-centric policy perspective, where

investments in port terminals, inland intermodal terminals, air cargo hubs, and border-crossing facilities play a decisive role in improving overall system performance. Policies aimed at reducing dwell time – through terminal automation, extended gate hours, capacity balancing, and streamlined procedures – are likely to generate larger time and cost savings than equivalent investments in line-haul infrastructure alone.

5.6.2 Reliability as a core policy objective

The synthesis of time and cost evidence highlights reliability as a critical but under-prioritised policy objective. Freight users respond not only to average transport cost and time, but also to the risk of extreme delays and missed connections. Policies that improve schedule adherence, reduce variability, and enhance resilience therefore have direct economic value, even if they do not significantly reduce mean travel time.

From a policy perspective, this implies that performance indicators based solely on average speed or throughput are insufficient. Instead, reliability-oriented metrics, such as dwell time distributions, on-time performance at terminals, and connection success rates, should be integrated into monitoring and evaluation frameworks. This shift is particularly relevant for multimodal and intermodal freight corridors, where unreliability at a single interface can propagate through entire supply chains.

5.6.3 Rethinking modal-shift policies and intermodal competitiveness

Many European freight policies explicitly aim to promote modal shift from road to rail or maritime transport. The reviewed evidence suggests that such policies risk underperformance if they assume that lower line-haul costs or environmental advantages alone will drive behavioural change. In practice, additional terminal costs, dwell time, and unreliability often offset the theoretical advantages of intermodal solutions, especially for time-sensitive and high-value goods.

Effective modal-shift policy therefore requires a more nuanced approach. Rather than focusing solely on expanding rail or maritime capacity, policies should address the end-to-end performance of intermodal chains, including terminal coordination, service frequency, and information integration. Without such measures, intermodal transport may remain competitive only for limited market segments, such as bulk or low-value containerised freight over long distances.

5.6.4 Integrating time–cost realism into policy appraisal and DSS

A further implication concerns the analytical tools used to support policy decisions. Many appraisal frameworks and DSS continue to rely on deterministic or average representations of time and cost, which the reviewed literature shows to be systematically biased in multimodal contexts. Such simplifications tend to overestimate the benefits of intermodal infrastructure projects and underestimate the operational challenges faced by freight users.

Policy-oriented DSS should therefore incorporate multi-component and stochastic representations of time and cost, including inventory holding costs, reliability penalties, and non-linear delay costs. While this increases model complexity, the empirical evidence suggests that such realism is essential for credible evaluation of long-distance freight policies. Advances in data availability, digitalisation, and predictive analytics provide new opportunities to operationalise these concepts in practice.

5.6.5 Accounting for heterogeneity by type of load and market segment

The reviewed literature also implies that one-size-fits-all freight policies are unlikely to be effective. Time–cost trade-offs differ substantially across types of load, shipment sizes, and supply-chain strategies. Policies designed around containerised freight may not translate to dry bulk, liquid bulk, or general cargo, where cost structures, handling requirements, and time sensitivity differ markedly.

For policy design, this suggests the need for segmented approaches that recognise heterogeneity in freight markets. Incentives, infrastructure investments, and regulatory measures should be tailored to the specific requirements of different cargo types and logistics chains. Failure to account for such heterogeneity risks reinforcing existing modelling biases and limiting the real-world effectiveness of freight policies.

5.6.6 Implications for European freight strategy and governance

At the European level, the combined evidence supports a shift in freight strategy from mode-specific targets towards system-level performance optimisation. Initiatives such as the Trans-European Transport Network (TEN-T) and combined transport programmes would benefit from greater emphasis on terminal performance, cross-border coordination, and digital interoperability, alongside traditional infrastructure investments.

More broadly, the findings underline the importance of governance arrangements that facilitate coordination among infrastructure managers, terminal operators, carriers, and public authorities. Improved information sharing, harmonised procedures, and aligned incentives are critical for translating infrastructure capacity into reliable and cost-effective freight services. Without such coordination, the time–cost advantages of multimodal transport are unlikely to be fully realised.

6. Research gaps and future research agenda

This chapter synthesises the outcomes of Chapters 4 and 5 to identify systematic research gaps in the literature on long-distance multimodal and intermodal freight transport. This chapter adopts a critical, structural perspective, highlighting where dominant modelling paradigms, data practices, and policy narratives differ from observed freight system behaviour. Based on these gaps, a comprehensive future research agenda is proposed to advance both scientific understanding and practical decision support.

1. Ambiguity in multimodal freight concepts: Despite of two decades of research, core concepts such as *intermodal*, *multimodal*, *co-modal*, and *synchromodal* freight transport remain inconsistently defined and operationalised. While conceptual distinctions are well articulated in review literature, empirical and modelling studies frequently conflate these terms or apply them selectively based on data availability rather than analytical intent. As a result, findings across studies are often not directly comparable, and policy conclusions drawn from one conceptual framing are transferred uncritically to others. There is a need for operational definitions that explicitly link conceptual categories to measurable system characteristics, such as flexibility of mode choice, degree of contractual integration, and real-time adaptability. Empirical studies should state clearly which concept is being operationalised and why, enabling cumulative knowledge building rather than parallel, fragmented research streams.

2. Overreliance on deterministic and average time measures: A common limitation across freight transport models is the continued reliance on average or scheduled travel times. Chapters 4 and 5 demonstrate that terminal dwell time, waiting time, and delay propagation dominate realised door-to-door performance, yet these components are frequently simplified or omitted in strategic and tactical models. This creates a systematic bias in favour of multimodal solutions by understating their exposure to variability and tail delays. Future models should move beyond mean-based representations and adopt distributional approaches to time, explicitly modelling dwell-time distributions, connection reliability, and extreme-delay risk. This requires closer integration between operational data analysis and higher-level modelling frameworks.

3. Limited empirical validation of time estimates: Many modelling studies rely on assumed or abstract time parameters rather than empirically validated estimates. Even where empirical data are used, validation is often limited to single terminals or corridors, raising questions about generalisability. There is a strong need for multi-site, comparative empirical studies of time components across ports, inland terminals, rail yards, and air cargo hubs. Such studies should aim to establish transferable benchmarks and identify structural determinants of time variability rather than case-specific anomalies.

4. Narrow focus on line-haul transport costs: The literature exhibits a persistent bias towards line-haul transport costs, typically expressed in €/tkm, at the expense of terminal, inventory, and delay-related costs. Chapters 5.3 and 5.4 show that these omitted components often dominate the generalised cost of multimodal freight transport, particularly for containerised and time-sensitive cargo. Therefore, freight cost models should adopt full generalised cost formulations, integrating inventory holding costs, reliability penalties, and non-linear delay costs. Empirical estimation of these components remains limited and should be prioritised, particularly using revealed operational and contractual data.

5. Insufficient treatment of non-linear and threshold effects: Delay-related costs such as demurrage, detention, and contractual penalties exhibit stepwise and non-linear behaviour, yet are often approximated using linear cost functions. This simplification obscures critical tipping points where small increases in delay generate disproportionately large economic impacts.

Future modelling efforts should incorporate piecewise or non-linear cost functions that reflect contractual realities and operational thresholds. This is particularly important for policy appraisal, where linear assumptions may significantly misrepresent project benefits.

6. Lack of cohesion of reliability into freight models: Although the importance of reliability is widely acknowledged, it is rarely integrated consistently into freight demand and network models. Where reliability is included, it is often represented through ad hoc penalty terms rather than grounded in empirically observed delay distributions. There is a need for integrated reliability modelling frameworks that connect stochastic operational processes at terminals and interfaces with strategic freight demand and mode choice models. This requires methodological bridges between simulation, stochastic optimisation, and econometric analysis.

7. Dominance of container-centric modelling: Containerised freight dominates the empirical and modelling literature on multimodal transport, driven by data availability and standardisation. While analytically convenient, this focus obscures the distinct time–cost structures of dry bulk, liquid bulk, and general cargo. Dedicated modelling and empirical studies are needed for non-containerised cargo, explicitly capturing handling intensity, safety requirements, and commodity-specific constraints. Without such work, conclusions regarding multimodal competitiveness will remain biased and incomplete.

8. Fragmented and proprietary data environments: A fundamental constraint across the literature is limited access to high-resolution, end-to-end freight data. Operational data at terminals, ports, and logistics hubs are often proprietary, fragmented, or incompatible across systems, constraining empirical validation and comparative analysis. Progress in freight research depends on data-sharing frameworks, standardised data models, and collaboration between public authorities and private operators. The expansion of digital freight platforms and real-time tracking technologies offers significant opportunities, but governance and interoperability challenges remain.

9. Methodological silos and lack of integration: Freight research remains divided into methodological silos, with limited interaction between econometric demand modelling, optimisation, simulation, and data-driven prediction. This fragmentation hinders the development of coherent decision support tools. Future work should prioritise hybrid modelling approaches that integrate behavioural models, operational simulation, and optimisation within unified frameworks. Such integration is essential for analysing long-distance multimodal freight systems realistically.

The identified gaps have direct implications for the credibility and usefulness of policy-oriented freight research. Simplified representations of time, cost, and reliability risk producing optimistic assessments of multimodal transport initiatives that fail to materialise in practice. Conversely, more realistic models, while complex, offer the potential for more robust and actionable insights. Policy-facing research should prioritise decision relevance over analytical convenience, explicitly addressing uncertainty, heterogeneity, and operational constraints. This shift is necessary to align academic freight research with the realities faced by shippers, logistics providers, and public authorities.

Taken together, the reviewed research gaps provide directions to a next-generation research agenda for long-distance goods mobility that is empirically grounded, methodologically integrated, and policy-relevant. Key priorities include:

- Developing empirically validated, multi-component representations of time and cost.
- Integrating reliability and disruption into freight demand and network models.
- Expanding research beyond containerised freight to encompass diverse load types.
- Bridging methodological silos through hybrid and data-driven modelling approaches.
- Aligning freight research more closely with decision support and governance needs.

Addressing these priorities require interdisciplinary collaboration, improved data access, and closer engagement between multiple stakeholders including researchers, industry stakeholders, and policymakers. Only through such efforts can the literature move beyond stylised representations and contribute meaningfully to the design of resilient and efficient long-distance freight transport systems.

7. Conclusions

7.1 Review summary

This review set out to systematically synthesise the current state of knowledge on long-distance goods mobility, with a specific focus on how time and cost components are conceptualised, measured, and modelled across road, rail, maritime, air, and multimodal freight transport chains. Motivated by persistent policy interest in multimodality and modal shift, the review aimed to move beyond mode-specific or method-specific perspectives and instead provide an integrated, extensive understanding of freight transport performance, grounded in both empirical evidence and modelling practice.

By combining a detailed analysis of transport mechanics (Chapter 4), a comprehensive review of modelling methodologies with focus on various time and cost components (Chapter 5), and a critical assessment of research gaps (Chapter 6), the study offers a consolidated synthesis that clarifies why long-distance multimodal freight transport continues to underperform relative to theoretical expectations, despite decades of policy support and analytical advancement.

It is observed that time and cost in long-distance freight transport are dominated by interfaces instead of links. While line-haul transport often attracts primary analytical and policy attention, empirical evidence consistently demonstrates that terminal handling, dwell time, waiting, and coordination failures account for a disproportionate share of door-to-door transit time, variability, and generalised cost.

Across modes, the reviewed studies reveal a common structural pattern. Road transport remains competitive not because it minimises line-haul cost, but because it minimises interfaces. Rail

and maritime transport offer lower unit transport costs over long distances, yet these advantages are frequently offset by additional terminal operations, schedule constraints, and unreliability in intermodal chains. Air freight occupies an extreme position, where very high transport and handling costs are justified only by exceptional time sensitivity and reliability requirements. The synthesis of time and cost evidence further shows that small changes in terminal performance can generate larger reductions in generalised cost than substantial investments in line-haul infrastructure. These findings challenge traditional corridor-centric planning paradigms and underscore the central role of nodes, ports, inland terminals, air cargo hubs, and border crossings, in shaping long-distance goods mobility.

The review further highlights that time and cost cannot be treated as separable attributes in freight transport analysis. Inventory holding costs, delay penalties, and reliability risks directly translate time into monetary terms, producing non-linear and context-dependent trade-offs. Models that rely on average travel time and linear cost functions systematically underestimate the true generalised cost of multimodal freight transport, particularly for time-sensitive and high-value goods. Empirical evidence demonstrates that shippers and logistics providers respond more strongly to variability and tail risks than to marginal changes in mean transport time. Reliability therefore emerges as the missing link between time and cost, mediating mode choice, routing decisions, and supply-chain design. This behavioural realism remains insufficiently reflected in many strategic and tactical freight models, contributing to persistent discrepancies between model predictions and observed freight behaviour.

A further synthesis outcome concerns the systematic bias towards containerised freight in the literature. While containerisation has enabled standardised handling and facilitated intermodal analysis, the dominance of container-centric models obscures the distinct time–cost structures of dry bulk, liquid bulk, and general cargo. These cargo types differ markedly in handling intensity, time sensitivity, regulatory constraints, and risk exposure. By failing to account adequately for cargo heterogeneity, existing models risk overgeneralising the competitiveness of multimodal solutions and underestimating the operational and economic challenges faced by non-containerised freight. This bias has implications not only for academic modelling but also for policy design, where container-focused evidence is often extrapolated to broader freight markets without sufficient justification.

7.2 Policy summary

The combined evidence reviewed in this study suggests that policy strategies centred narrowly on modal shift or line-haul cost reduction are unlikely to achieve their intended outcomes. Instead, improving long-distance goods mobility requires a shift towards system-level performance optimisation, with particular emphasis on terminal efficiency, coordination, and reliability. Policies that reduce dwell time, improve schedule adherence, and enhance information integration across modes can simultaneously lower transport time, reduce costs, and increase resilience. Conversely, infrastructure investments that neglect operational and institutional bottlenecks risk delivering limited real-world benefits, even when they appear economically justified in appraisal models.

At the European level, this implies rebalancing freight policy frameworks to complement corridor development with sustained attention to nodes, interfaces, and governance arrangements. Such a shift aligns with emerging evidence from recent disruptions and underscores the importance of resilience and adaptability in long-distance freight systems.

All in all, this review demonstrates that the challenges of long-distance goods mobility are not primarily technological, but systemic and organisational. Time and cost inefficiencies persist not because faster vehicles or cheaper transport modes are unavailable, but because the coordination of complex, multimodal systems remain imperfect. By consolidating empirical evidence and modelling insights across modes, cargo types, and methodological traditions, the review provides a coherent foundation for advancing both freight transport research and policy. Addressing the identified gaps will require closer integration between data, models, and decision-making processes, as well as sustained collaboration between researchers, industry stakeholders, and public authorities. Only through such integrated efforts can long-distance freight transport systems become not only more efficient, but also more reliable and resilient.

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