



INTEGRATION OF ROAD AND RAIL FREIGHT TRANSPORT IN THE DEVELOPMENT OF REGIONAL MULTIMODALITY

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Abstract

Regional rail lines represent an important yet still underused component of the freight transport system, particularly in their potential to support multimodal connections with road infrastructure and local logistics nodes. Although European transport strategies encourage a greater shift of freight to rail, many regions continue to rely primarily on road transport due to limited rail capacity, insufficiently developed terminals, weak coordination among actors and fragmented operational procedures. Analyses carried out across several regional case studies indicate that infrastructural constraints, inadequate handling equipment, organisational inefficiencies and a complex regulatory environment remain among the key obstacles to wider use of rail in freight transport. At the same time, the assessment of external costs highlights the clear advantages of shifting part of the freight volume from road to rail, especially in terms of reduced emissions, lower energy consumption and decreased pressure on the road network. Quantitative comparisons show that rail transport delivers the greatest benefits on medium and long-haul routes, particularly for heavier cargo flows, and that its effectiveness increases when combined with road transport for the first and last mile. This paper presents the main insights that can support the development of more effective regional multimodality, focusing on the infrastructural, operational and regulatory challenges that influence freight transport performance. The analysis is based on a case study of Northern Croatia, with a particular focus on the Varaždin logistics node as a representative regional freight hub. Particular attention is given to opportunities for building a more sustainable and better connected system, including improved planning of logistics hubs, the digitalisation of operational processes, the reduction of administrative barriers and more coherent alignment of transport and spatial planning policies. The findings underline the potential of regional rail to play a stronger role in freight distribution and provide guidance for strengthening multimodal solutions in regional logistics networks.

Keywords: multimodal freight transport, rail-road integration, regional logistics, modal shift, CO₂ emission reduction

1 Introduction

Freight transport is central to EU economic competitiveness but remains a major source of greenhouse gas emissions, with road freight accounting for a dominant share [1]. In response, the European Green Deal and the Sustainable and Smart Mobility Strategy promote a substantial modal shift towards rail and inland waterways [2]. Although rail offers lower CO₂ emissions per tonne-kilometre and reduced external costs [3], it remains underutilised outside core TEN-T corridors. At the regional level, infrastructural deficiencies, limited terminal capacity and organisational and governance bottlenecks constrain wider rail uptake [4].

Effective multimodality therefore requires not only corridor investments but also systematic integration of road and rail systems through revitalised loading points, improved terminal infrastructure and better alignment between transport and spatial planning. The analysis presented in this paper builds upon the methodological framework and empirical findings developed within the Rail4Regions project, which focuses on strengthening regional rail freight systems in Central Europe. Northern Croatia represents a relevant case. Despite a dense railway network and strong links to Adriatic ports and Central Europe, more than 90% of freight tonne-kilometres are transported by road, indicating significant untapped rail potential [5]. This paper assesses the potential for integrating road and rail freight transport at the regional scale, addressing two research questions:

- What infrastructural and organisational barriers limit regional multimodal freight development?
- What CO₂-equivalent emission reductions could be achieved through selected multimodal measures?

The paper contributes by operationalising regional multimodality through route-specific emission modelling applied to key freight relations connecting the Varaždin logistics node with major regional and international destinations, thereby linking infrastructure planning with quantitative environmental assessment. The research is conducted as a case study of Northern Croatia, with a focus on the Varaždin logistics node, enabling a context-specific assessment of multimodal freight integration and emission reduction potential.

1.1 Theoretical background

Multimodal and intermodal freight transport systems are recognised as key mechanisms for improving efficiency and sustainability in transport logistics. While multimodal transport refers to the use of different modes under separate contracts, intermodal transport involves the movement of goods in a single loading unit across successive modes without handling the cargo during transshipment [6]. In both cases, effective road-rail integration is fundamental. Rail freight offers high capacity, energy efficiency and lower greenhouse gas emissions per tonne-kilometre compared to road transport [7]. However, its competitiveness depends on flow concentration and the availability of adequate fixed infrastructure, aspects that are emphasised in the operational research literature as key determinants of service performance and logistics costs in intermodal systems [8]. Building on the intermodal transport literature [9], multimodal freight performance may be examined through three interrelated dimensions: infrastructure, operations and governance. The decline of single wagonload services and local sidings has reduced rail accessibility for smaller shippers, contributing to increased reliance on road transport and constraining modal shift potential [10]. Consequently, revitalisation of loading points and industrial sidings is increasingly recognised as a strategic measure for improving first- and last-mile integration. From an environmental perspective, modal shift to rail remains one of the most effective medium-term strategies for reducing freight emissions [11]. Emission reduction potential depends on transport distance, traction type and operational efficiency, with electrified rail systems offering particular advantages over diesel road vehicles [7]. However, modal shift is also influenced by logistics cost, reliability and administrative simplicity, while digital coordination and transparent information systems enhance the attractiveness of rail-based solutions [12]. Regional multimodality should therefore be understood as a systemic process integrating infrastructure investment, operational optimisation and governance alignment.

1.2 Case study framework

This section introduces the case study framework used to operationalise the analysis and link the methodological approach with a specific regional context. Northern Croatia was selected as the broader regional context for the case study due to its substantial modal shift potential and the presence of underutilised rail infrastructure. Within this regional context, the Varaždin area represents a relevant logistics node characterised by strong industrial activity and strategic connections to Adriatic ports and Central European logistics centres. The identification of the case study area and the assessment of rail accessibility follow the analytical and methodological framework developed within the Rail4Regions project [13]. The qualitative assessment of regional constraints is based on structured stakeholder consultations and systematic classification of bottlenecks into five macro-categories: infrastructure, technological equipment, organisational structure, service and economic structure, and governance [4]. Within this framework, particular emphasis is placed on infrastructure-related limitations (loading points, industrial sidings, terminal capacity) and organisational fragmentation, as these were consistently identified as primary barriers to modal shift implementation.

1.2.1 Identification of multimodal measures

Based on the identified regional constraints and the applied analytical framework, the following section defines the key multimodal measures considered in the analysis. In accordance with the Regional Action Plan for Northern Croatia [5], the analysis focuses on two priority intervention areas:

- development and revitalisation of loading points and intermodal terminals,
- construction and modernisation of industrial sidings.

These measures correspond to the infrastructure dimension of multimodal performance identified in the intermodal transport literature [9]. In the context of this study, particular attention is given to the Varaždin logistics node, where the planned development of the Varaždin Gateway terminal and associated rail connections represent key interventions supporting regional multimodal integration.

1.2.2 Methodological framework for emission modelling

The quantitative assessment estimates potential CO₂ emission reductions resulting from a modal shift of freight flows from road to rail following the implementation of the identified multimodal infrastructure measures. The applied approach follows a scenario-based modelling framework commonly used in transport emission assessment studies, enabling a transparent and replicable estimation of environmental impacts at the regional level. The calculation follows the emission reduction assessment framework developed within the Rail4Regions project [13]. Route-specific railway and road distances for characteristic freight relations connecting the Varaždin logistics node with major regional and international destinations are applied, ensuring geographically grounded estimation of tonne-kilometres (TKM). For each analysed route, tonne-kilometres are calculated as:

$$\text{TKM} = \text{freight volume (tonnes)} \times \text{transport distance (km)} \quad (1)$$

Rail and road tonne-kilometres are derived separately using the respective railway and road distances. Total emission savings (ΔCO_2) are calculated as:

$$\Delta\text{CO}_2 = (\text{EF}_{\text{road}} \times \text{TKM}_{\text{road}}) - (\text{EF}_{\text{rail}} \times \text{TKM}_{\text{rail}}) \quad (2)$$

where EF represents the emission factor expressed in grams of CO₂-equivalent per tonne-kilometre (g CO₂-eq/tkm).

In accordance with the Rail4Regions methodology, articulated heavy goods vehicles are assumed for road freight transport (EF_{road} = 101 g CO₂-eq/tkm). For rail transport, three traction scenarios are considered:

- diesel rail traction: 28 g CO₂-eq/tkm
- electrified rail traction: 14 g CO₂-eq/tkm
- hybrid scenario (50% diesel / 50% electric): 21 g CO₂-eq/tkm.

The selected emission factors represent average operational values derived from established emission databases and are widely used in comparative assessments of freight transport modes. While such values do not capture all operational variations, they provide a consistent and methodologically robust basis for evaluating relative differences between transport scenarios. The results are presented as annual emission reduction potential under the defined operational assumptions regarding train frequency, transported volumes and characteristic routes. This approach ensures consistency with the regional action planning framework while providing a transparent and replicable estimation of environmental benefits. It should be noted that the analysis is based on a defined modal shift scenario and represents an illustrative assessment of potential emission reductions rather than a predictive model of future freight system behaviour.

2 Case study: Varaždin logistics node in Northern Croatia

Northern Croatia represents a territorially compact but economically dynamic freight region characterised by strong industrial activity, export-oriented production and a strategic position between Adriatic ports and Central European markets. Within this regional context, the Varaždin area represents an important industrial and logistics node with growing relevance for multimodal freight transport.

2.1 Regional freight context and infrastructure

Freight flows in Northern Croatia are predominantly directed towards the Adriatic ports of Rijeka (Croatia) and Koper (Slovenia), as well as towards logistics centres in Austria and Germany. Despite the existence of a relatively dense railway network, more than 90% of freight tonne-kilometres in the region are currently transported by road [5], indicating substantial untapped rail potential. The quantitative analysis focuses on characteristic freight relations connecting the Varaždin logistics node with key maritime and inland logistics destinations, including the Adriatic ports of Rijeka and Koper and the inland logistics centre of Graz. Route-specific railway and road distances are applied for each relation to reflect realistic transport conditions and network geometry. The corresponding transport performance is expressed in tonne-kilometres, calculated by multiplying the transported freight volume by the respective transport distance for each relation. This approach enables a consistent comparison between road and rail transport performance and provides the basis for estimating potential emission reductions resulting from modal shift scenarios. The planned development of intermodal infrastructure, particularly the Varaždin Gateway terminal within the Brezje industrial zone, represents a central intervention within the Regional Action Plan [5]. The project includes container loading facilities and industrial sidings connected to railway line R201, thereby enabling direct rail-based freight services to Adriatic ports and international markets. In addition to the Brezje initiative, several industrial zones located along railway lines R201 and R202 demonstrate potential for the construction or modernisation of industrial sidings.

Stakeholder consultations conducted within the Rail4Regions framework identified infrastructural constraints and organisational fragmentation as the dominant barriers to rail freight development in the region [4]. These include underutilised sidings, limited terminal handling capacity, insufficient coordination between rail operators and industrial users, and incomplete integration of freight infrastructure into regional spatial planning frameworks. These characteristics make Northern Croatia an appropriate case for assessing how targeted regional infrastructure measures may enhance rail accessibility and generate measurable environmental benefits.

2.2 Quantitative assessment of emission reduction potential

The quantitative assessment estimates potential CO₂ emission reductions resulting from a modal shift of freight flows from road to rail across the analysed freight relations connecting the Varaždin logistics node with major regional and international destinations. Containerised freight represents the dominant form of cargo transport within the analysed logistics system. Therefore, container units and their mass are used as the basis for estimating freight volumes and corresponding emission impacts. The maximum payload of a standard 20-foot container amounts to approximately 28.2 tonnes, with a total gross weight of 30.48 tonnes [6]. In practical operations, containers are rarely loaded to their maximum capacity; therefore, the average payload is assumed to correspond to approximately two-thirds of the maximum payload. This results in an estimated average payload of 18.8 tonnes and an average gross weight of approximately 21 tonnes per container. Each 20-foot container is treated as one TEU (Twenty-foot Equivalent Unit). A typical freight train composition can transport up to approximately 68 TEUs, for example when using six-axle Sdggmrs wagons capable of carrying four TEUs each. Under these assumptions, a single train composition can replace approximately 50 articulated heavy goods vehicles transporting semi-trailers. These operational assumptions provide the basis for estimating the annual freight volumes used in the emission modelling framework.

The assessment applies route-specific railway and road distances for freight relations connecting the Varaždin logistics node with the Adriatic ports of Rijeka and Koper and the inland logistics centre of Graz. These relations represent important freight corridors identified within the regional action planning framework [13]. The annual freight volume considered in the analysed scenario amounts to 428, 400 tonnes and is distributed across the analysed routes in accordance with the Rail4Regions dataset. The key operational parameters used in the calculation, including transport distances, freight volumes and corresponding transport performance indicators, are presented in table 1.

Table 1 Freight transport volumes and transport performance (Source: Authors based on [14])

Relation	Railway distance [km]	Road distance [km]	Annual freight [t]	Rail [tkm]	Road [tkm]
Varaždin – Rijeka	359	244	142,800	51,265,200	34,843,200
Varaždin – Koper	356	326	142,800	50,836,800	46,552,800
Varaždin – Graz	138	124	142,800	19,706,400	17,707,200
Total	–	–	428,400	121,808,400	99,103,200

The values presented in table 1 provide the basis for calculating route-specific tonne-kilometres for both rail and road transport using equation (1). Application of the calculation framework results in total annual transport performance of 121, 808, 400 tkm for rail transport and 99, 103, 200 tkm for road transport.

The emission reduction estimates are calculated using the emission factors defined previously (EF_{road} = 101 g CO₂-eq/tkm; EF_{rail} = 14, 21 and 28 g CO₂-eq/tkm depending on traction type). The emission factors applied in the analysis are derived from the TREMOD/TREMOD-MM database developed by the German Environment Agency (UBA) [15]. According to this dataset, the average emission factor for road freight transport is 119 g CO₂-eq/tkm, while the emission factor for articulated trucks (101 g CO₂-eq/tkm) is applied in the present analysis due to the containerised nature of the analysed freight flows. The total CO₂ emission savings are calculated using equation (2), and the resulting emission reductions for the analysed rail traction scenarios are presented in table 2.

Table 2 Estimated annual CO₂ emission reductions under the analysed scenario (Source: Authors)

Scenario	Annual emission reduction (tonnes CO ₂)
Rail - Diesel traction	6,598.79 t
Rail - Hybrid (50/50)	7,451.45 t
Rail - Electric traction	8,304.11 t

The applied emission factors represent average values for freight transport operations and therefore provide a conservative estimate of potential emission savings. The results in table 2 should be interpreted as a baseline estimate; actual emission reductions may be higher with further improvements in rail energy efficiency, increasing electrification, and a growing share of renewable electricity for rail traction.

3 Discussion

The results obtained through the applied emission modelling framework demonstrate that coordinated multimodal development in Northern Croatia can generate measurable environmental benefits at the regional system level. The estimated annual emission reduction of approximately 8,300 tonnes of CO₂ under the electrified rail scenario reflects the cumulative effect of shifting freight flows across several strategic transport relations rather than the impact of a single infrastructure intervention. The findings highlight the structural relevance of regional multimodality. While individual infrastructure projects may appear moderate in scale, their combined impact across interconnected freight corridors can generate significantly greater environmental benefits. These findings are consistent with previous studies highlighting the environmental advantages of rail-based freight transport on medium and long-distance routes, particularly under electrified traction conditions.

The magnitude of emission reduction depends strongly on rail traction type, with electrified rail providing the highest environmental benefit. The results must also be interpreted within the broader context of regional freight governance. Stakeholder consultations identified infrastructural limitations, coordination challenges and fragmented planning frameworks as key barriers to modal shift implementation. Consequently, the identified emission reduction potential depends not only on infrastructure investment but also on effective institutional coordination and regional planning. Several methodological limitations should be acknowledged. The analysis is based on defined freight volumes and stable operational assumptions and does not include economic feasibility or cost-benefit evaluation. Nevertheless, the results demonstrate that regional multimodal integration can represent a meaningful contribution to freight transport decarbonisation strategies.

4 Conclusion

This paper examined the potential for strengthening regional multimodal freight integration in Northern Croatia through coordinated development of loading points, industrial sidings and improved rail accessibility. By applying a route-specific emission modelling framework to three characteristic freight relations connecting the Varaždin logistics node with Rijeka, Koper and Graz, the analysis quantified the environmental benefits of shifting freight flows from road to rail. The results indicate that coordinated regional multimodal measures can achieve significant emission reductions, reaching approximately 8, 300 tonnes of CO₂ annually under electrified rail operation scenarios. These findings demonstrate that regional freight systems, even outside core TEN-T corridors, possess considerable potential to contribute to freight transport decarbonisation. Despite defined operational assumptions, the study provides a transparent framework for evaluating regional modal shift potential and highlights the importance of coordinated planning and infrastructure investment for sustainable freight transport.

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