Decarbonising Long-Distance Transport: Modal Shift from Short-Haul Aviation to High-Speed Rail for Sustainable Mobility

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Abstract. This paper investigates the sustainable evolution of long-distance transport by examining how rail-oriented strategies can help air travel decarbonization. Focusing on domestic relations in the 300–700 km range, confirmed in the state-of-the-art literature, the study evaluates the potential to shift demand from short and medium-haul aviation to high-speed rail at Romania-wide network scale. The Romanian air and rail transport networks are assessed, quantifications and estimates of traffic are made for airport grid. It analyses connectivity and modal shift potential of high-speed rail line planned from Constanța to the Hungarian border, part of the TEN-T core net, using modal shift scenarios, and estimates CO_2 savings on key routes under optimal rail infrastructure.

Keywords: modal shift · air · high speed rail · connectivity index · decarbonization

1 Introduction

Transport in general, and particularly long-distance transport, are major contributors to polluting emissions. While air transport offers clear advantages, high speed and connectivity, it remains one of the primary sources of pollution. To achieve decarbonization targets across Europe and beyond, air transport faces intense scrutiny, prompting the search for viable alternatives.

Theoretical and practical studies indicate that, for transport distances in the 300–700 km range, short - and medium-haul flights could be partially replaced by rail, especially along shared corridors served efficiently by trains. Statistics points that, on 2024 level, the share of short -haul flights in the distance class of 200–500 km are 2,5% from total passengers, with corresponding CO2 emissions of 1,8% from total emissions and the share of medium -haul flights in the distance class of 500–900 km are 17% from total passengers, with corresponding CO2 emissions of 13% from total emissions [1, 2].

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The present work builds on this literature by extending the rail–air comparison to a system-level, Romania-wide network. This study adopts a comprehensive methodology combining network analysis of air and rail infrastructure with quantitative connectivity metrics. It employs empirical traffic data to simulate scenarios under varying infrastructure and policy assumptions, quantifying environmental benefits like CO_2 reductions.

In conclusion, the analysis reveals that the potential for modal shift from short-haul aviation to high-speed or conventional rail in Romania remains limited at present. Although plans exist for developing a high-speed rail line spanning approximately 780 km, the current state of infrastructure coupled with the ongoing decline in rail traffic (−50% passenger train-km from 2016–2025), which does not justify major investments does not support a sustainable shift in the foreseeable future.

This paper is structured as follows: in Sect. 2 related work on modal shift and decarbonization is reviewed. Section 3 assesses Romania's air and rail networks. Section 4 analyzes ACI metrics and simulates shift scenarios with CO_2 estimates. Last, in Sect. 5 conclusions, with limitations and future directions, are drawn.

2 Related Work

Decarbonising short-haul aviation is critical for reducing the environmental footprint of the aviation sector, which is a significant contributor to global greenhouse gas emissions. According to Allianz Research [1], each year aviation produces one gigaton of carbon dioxide, which is equivalent to 2.5% of total anthropic emissions. The focus of European Union policies is short-haul flights, which are more frequent and contribute substantially to air pollution and climate change. Sustainable aviation fuels (SAFs), hybrid-electric configurations, and improved operational efficiencies are considered possible solutions for mitigating the carbon footprint of the aviation sector [3–5].

However, in recent years, a modal shift from air to rail transport has gained significant attention due to its potential to reduce environmental impacts and improve transportation efficiency [6, 7]. This modal shift is influenced by environmental, economic and political factors. For certain routes, high-speed rail services have become a competitive alternative to air transport [2].

The modal shift from air to rail transport has benefits and challenges, according to some case studies. Rail transport is considered a sustainable option when powered by clean energy sources [7, 8]. The choice between air and rail transport is determined by factors such as distance and comfort, according to studies using multinomial logit models [9, 10]. Investments in high-speed transport infrastructure improve the development of regions by increasing connectivity, according to studies based on economic models [11]. Integrative frameworks for platform-based models promote climate neutrality [12]. Their principles apply to passenger modal shift, accelerating decarbonization through HSR use. Solutions to improve transit through intermodal passenger terminals promote efficient modal transfers [13]. They strengthen the shift to HSR, optimizing flows at airports like OTP.

Optimizing transport connectivity and efficiency involves network allocation and design. Passenger and freight mobility is improved by integrating transport modes,

thereby reducing congestion, capacity constraints and environmental impacts. Strategies for integrating multimodal transport at different scales and regions, however, have a gap [14]. Some European research projects, such as MODUS [15], have developed macro scenarios for 2040, demonstrating that a short-haul modal shift implies a seamless travel experience. For freight, the transition to rail for high-value goods involves overcoming logistical bottlenecks at intermodal terminals and expediting deliveries [16, 17]. The results of the MODUS project show that an incomplete integration of the fare offer and rail connections at airport terminals prevents the replacement of connecting flights with rail. Good structuring of intermodal networks reduces costs and increases reliability according to some research [18, 19]. Studies focused on Romania are extremely few, making it necessary to study the modernization of conventional railways as an alternative to the missing high-speed transport infrastructure [20]. applies transport forecasting, a key stage in transport management, validating modal shift estimates, projecting realistic HSR demand on regional routes.

The transition from air to rail transport requires the development of policies that facilitate this process. The potential of air-rail intermodality for reducing congestion and decarbonization is evident at transport mode junctions, enabling seamless integration in multimodal hubs [21]. The modal shift to HSR strengthens these interfaces, cutting emissions and boosting accessibility. Increase in the market share of rail transport is encouraged through subsidies and the integration of rail networks with airports [22, 23]. According to the Transport & Environment report [24], this modal shift would reduce intra-European aviation emissions by 4–seven million tons of CO2 per year, a projection modelled on the basis of 3 development scenarios: modernization and increase in speed on rail corridors, 10% reduction in average train travel times, 50% increase in the supply of night trains to carry passengers on long distances. Furthermore, the same report supports the adoption of fiscal policies such as additional taxation on kerosene to encourage the choice of rail transport on distances between 300 and 1000 km. The modal shift from short-haul flights to rail reduces not only CO_2 but also local pollutants like PM2.5. This is especially true in adverse urban atmospheric conditions that amplify traffic-related concentrations. Plus, electrified rail minimizes these non-CO_2 impacts near airports and stations [25]. The shift to HSR boosts positive health effects by promoting clean mobility. Health impact assessments for active travel models in large urban areas show benefits from limiting pollutant emissions [26]

3 Study Area. Assessment of Air and Rail Transport Network

Romania's airport infrastructure constitutes a network of 17 operational facilities, presented in fig. 1, positioned to serve both domestic connectivity and international integration. The system is dominated by Bucharest Henri Coandă International Airport (OTP), which handles over 60% of national passenger traffic, functioning as the primary gateway. Data for the top 10 airports, in total traffic terms, is presented in Table 1.

Regional airports Cluj-Napoca (CLJ), Timișoara (TSR), and Iași (IAS) serve as secondary hubs, while smaller airports serve the niche tourism, cargo, and regional mobility needs.

Romanian airports have undergone substantial modernization, but capacity constraints, despite infrastructure gains, still exist. Service quality in passenger terminals is

key for hub efficiency [27]. The inland connectivity lags, and rail-air intramodality is below EU averages.

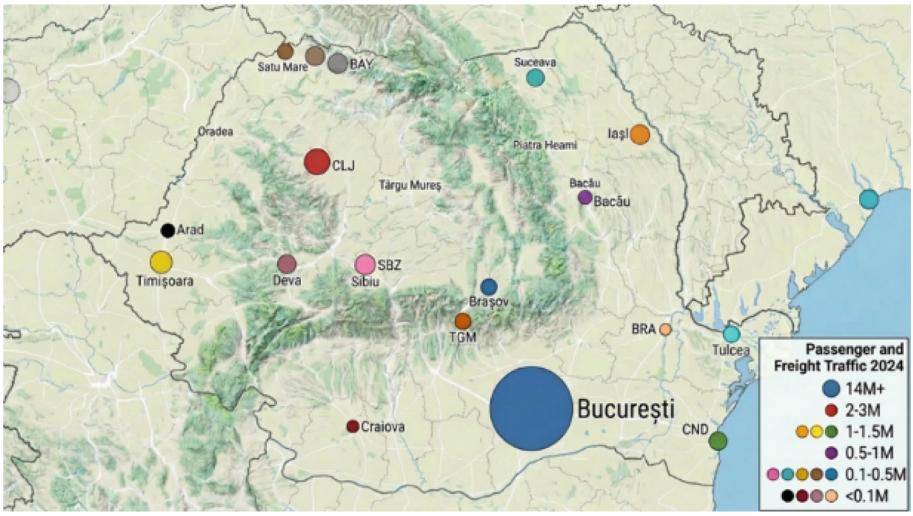

Fig. 1. Romanian top airports in terms of 2024 Passenger and Freight Traffic (*Source: Author's concept)*)

Table 1. Romanian Airports data (2024)

Code	City	Full Name	Traffic [million pax]
OTP	Bucharest	Henri Coandă International Airport	15.9
CLJ	Cluj	Avram Iancu International Airport	2.8
TSR	Timișoara	Traian Vuia International Airport	2.2
IAS	Iași	Iași International Airport	1.5
SBZ	Sibiu	Sibiu International Airport	0.4
BCM	Bacău	George Enescu International Airport	0.6
CRA	Craiova	Craiova International Airport	0.5
OMR	Oradea	Oradea International Airport	0.7
CND	Constanța	Mihail Kogălniceanu Airport	0.8
SUJ	Satu Mare	Satu Mare International Airport	0.2

Romania's rail infrastructure. Analysis of the synthetic characteristics of the Romanian railway infrastructure highlights several limitations that are interesting for the analysis. The share of network length equipped with double track is relatively low, under 30% of

the total network length, representing a limiting factor for the commercial speed of trains. Moreover, the share of network length equipped with electrified track is relatively low, under 40% of the total network length, posing a limiting factor from a decarbonization perspective.

Figure 2 shows rail traffic intensity (trains/day) on Romania's primary network in 2025, with total, passenger, and freight values [28]. For 2025, granulated data per route is unavailable, data from the National Institute of Statistics - INSSE provides national aggregates, Romanian Railways - CFR reports average daily ~1100 passenger trains and, in purple line, the proposed high-speed rail corridor (HSR).

Options for expanding long-distance passenger rail infrastructure fit into strategic sustainable development measures for land transport networks [29]. They validate HSR as a key solution for decarbonizing regional mobility. Romania is preparing a 781.9 km HSR corridor from Constanța to the Hungarian border (see Fig. 2), the opportunity study was completed in December 2025. The alignment runs Constanța – Bucharest – Brașov – Sighișoara (Vânători) – Târgu Mureș – Cluj-Napoca – Zalău – Oradea – border with Hungary, linking to the planned Hungarian high-speed network and forming part of the TEN-T core network.

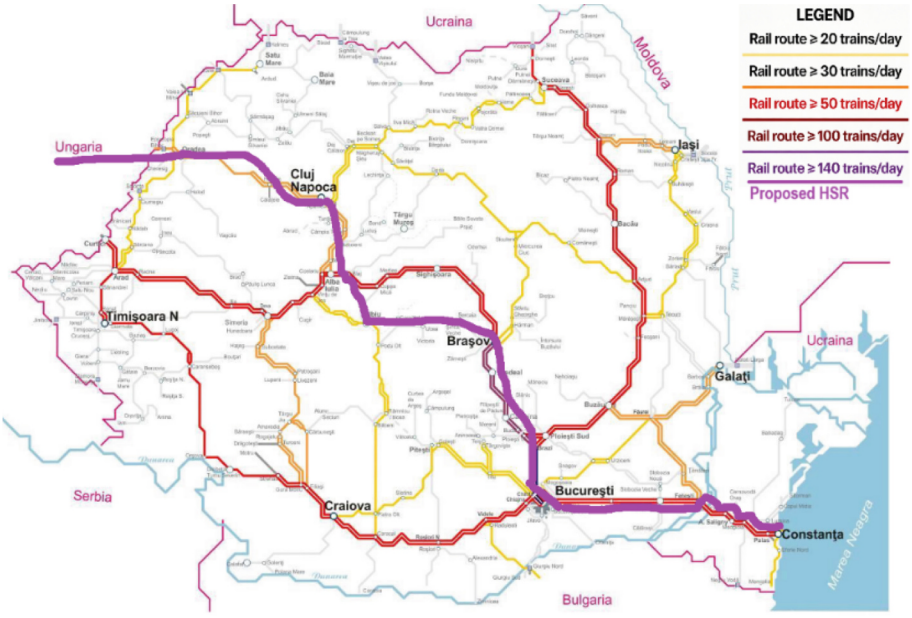

Fig. 2. Romania's existing primary rail network with traffic intensity and proposed HSR (*Source: Author's concept))*

4 Analysis of Potential Air to High-Speed Rail Modal Shift

4.1 Evaluating Air Connectivity

Air connectivity at national level reflects a mix of factors, including economic performance, trade links and openness, diasporas, inbound and outbound leisure demand, and of course geographical position. But air connectivity is also increasingly shaped by national and regional policies, regulation, taxation – and the overall support (or lack of it) for the aviation sector. Romania has now achieved the 2019 level of air connectivity, only −1% for 2025 compared to 2019 level, ranking 12 out of 31 EU+ countries.

In this study, air connectivity is used as a measure of network concentration enabling passenger movement from origin to destination. The direct connectivity denotes the level of connections offered from the assessed airport and indirect connectivity, the level of reasonable connections offered from the assessed airport indirectly through other airports.

From the perspective of measurement metrics, Equation 1, there can be identified key metrics like passenger volumes, fares, direct/indirect destinations, travel times, and hub linkages, all of them network scope and efficiency quantifications.

$$ACI_j = \frac{1}{10000} \sum_{i=1}^{k} f_{ji} \cdot s_{ji} \cdot w_i \tag{1}$$

where:

ACI_j represents air connectivity index for origin airport j,
f_{ji} - flight frequency from j to destination i,
s_{ji} - average seats per flight on route ji,
w_i - weight of destination i,
k - number of destinations,

and the scalar 10000 normalizes units, levelling the index to integer-like values for readability (common in connectivity metrics, yielding ACI ~1000 for EU airports). The weights *wi* were considered 1 for all destinations i prioritizing frequency/seat volume; the distance/population adjustments were initially tested but excluded for ease in this aggregate analysis.

Direct and indirect year-over-year variations of *ACI* from *t* and *t-1* year, in Equation 2, are calculated separately by comparing absolute values calculated annually then computing the percentage change. The traffic values used for calculation are the ones from June peak week.

$$YOY = (ACI_t - ACI_{t-1})/ACI_{t-1} \times 100\% \tag{2}$$

Existing theoretical frameworks and mechanisms underpin the potential modal shift. First, the time-competitive threshold posits that high ACI on routes under 700 km favors HSR when rail travel time approximates air door-to-door duration. Second, price signals amplified by kerosene taxes and low direct ACI encourage shifts if rail offers equivalent frequency of 20 trains/day or more.

Romanian air connectivity metrics. A merged comparison of Romanian airports connectivity, combining historical 2018/2017 data with estimated 2024/2023 from ACI Europe 2024 (Romania total + 3% YoY, direct −0.9%) and 2025/2024 from ACI Europe 2025 (Romania total + 11% YoY, direct −1%) national aggregates, distributed by airport using historical patterns, is presented in Table 2.

Table 2. Romanian Airports Connectivity for direct and indirect traffic

Code	YOY 2018/2017(%)		YOY 2024/2023 (%)		YOY 2025/2024 (%)	
	Direct	Indirect	Direct	Indirect	Direct	Indirect
OTP	2.5	11.7	−0.9	5.2	4.6	7.3
CLJ	−0.5	33.8	5.0	10.0	8.6	12.1
TSR	−6.7	8.8	−2.0	6.0	3.9	11.0
IAS	−6.9	−0.3	3.0	8.0	11.6	4.3
SBZ	12.3	20.5	8.0	4.0	11.3	1.1
BCM	9.0	0.0	12.0	2.0	15.3	3.8
CRA	0.1	0.0	1.0	1.0	9.7	0.9
CND	−5.2	−2.3	−1.0	3.0	1.6	3.4
OMR	27.2	−59.1	15.0	−5.0	21.3	- 0.3
SUJ	49.4	−66.1	20.0	−10.0	25.6	−11.6

The high indirect YOY ACI values for OTP (7.3%) and CLJ (12.1%), estimated for 2025, indicate a pattern of multi-leg travel via hubs for regional access, which HSR can successfully compete with directly door-to-door services under 3 h, on 300–700 km routes. This connectivity configuration justifies the modal shift, as improved rail options reduce the need for indirect air links, attracting traffic according to air-rail intermodality thresholds established in the literature. Most of the airports analysed show signs of indirect recovery, positive indirect trends, in 2024 and 2025, can be observed for most airports. Airports SUJ, OMR show regional operators' volatility, with high fluctuations and instability in operations, networks, routes, and market shares of carriers operating regional short-haul flights. Indirect ACI growth at OTP also reflects feeder-type congestion in airport terminals. Some authors [30] model passenger flows in airport terminals via discrete simulation. This justifies how the HSR shift eases it by diverting regional passengers, reducing terminal bottlenecks. Moreover, air traffic management automation enhances indirect connectivity efficiency at hubs like OTP [31], boosting modal shift potential via competitive HSR

4.2 Air to Rail Modal Shift Scenarios

Post-HSR completion, the connectivity data evaluated in Table 2 enables air-rail shift potential at key airports. Current rail infrastructure constrains this, but the presented scenarios below assume corridor operationalization. Under proper competition conditions, HSR can capture 10–30% share, as simulated in Table 3 scenarios.

The logical link between rising indirect ACI and modal shift tendency has two components. First, indirect connectivity reveals latent demand for seamless regional trips. HSR unlocks this by matching air's total cost, mainly time and fare, via logit-based elasticities. Second, for the 450 km OTP-CLJ route, indirect ACI growth signals substitutability. Although Romania's YOY ACI in 2025 is +11% compared to 2024, the indirect YOY ACI is high for the hubs OTP and CLJ, an indicator that can justify the shift from air to rail.

The hypotheses under which the analysis is conducted are as follows: the high-speed rail corridor from Constanța to the Hungarian border (purple line in Fig. 2) is finalized, the HSR speed is 250 km/h, a level of 10–30% modal split versus air is assumed. The optimistic 30% upper modal split draws from top EU cases like Paris-Lyon (25–35%) and Madrid-Barcelona (20–40%) [3, 4]. These feature high population density and 300 km/h HSR. The sensitivity analysis was adjusted down conservatively for Romania's lower density and 250 km/h HSR.

In those hypotheses, the necessary conditions for considering modal shift are met. They include:

- comparable travel time (door to door),
- the existence of balanced frequency (more than 4 trains/day on peak hours in some studies, or more than 20 trains/day in other studies),
- competitive rail pricing, and
- intermodal facilities for access to the rail infrastructure, with durations of maximum 30 min.

The values used for evaluating items in Table 3 are based on 2024 Romanian air traffic, logit models elasticities, and HSR times from 2025 feasibility study. The estimates of ±30% sensitivity were supposed to be dependent of low traffic/volatility; the maximum 28kt CO_2 saving are conservative vs. EU benchmarks. Emissions of 0.2 kg CO_2/pax-km for air and 0.02 kg CO_2/pax-km for electrified rail were considered for evaluation of decarbonization, data confirmed by ICAO 2025 Environmental Report. Commonly, levels of ~0.15–0.25 kg CO_2/pax-km for short-haul air and 0.01–0.04 kg CO_2/pax-km for electrified rail are used for computations.

Table 3. CO2 saving from HSR modal shift on key relations

Key Relation	Distance (km)	Domestic [M pax/year]	Shifted [M pax/year]	Pax-km [kt]	CO_2 Savings (kt)	Shifted [M pax/year]	Pax-km (kt)	CO_2 Savings (kt)	Shifted [M pax/year]	Pax-km (kt)	CO_2 Savings (kt)
			Scenario 1–10% shift			Scenario 2–20% shift			Scenario 3–30% shift		
OTP-CLJ	450	0.30	0.03	14	2	0.06	27	5	0.09	40	7
OTP-TSR	500	0.20	0.02	10	2	0.04	20	4	0.06	30	5

(*continued*)

Table 3. (*continued*)

Key Relation	Distance (km)	Domestic [M pax/year]	Shifted [M pax/year]	Pax-km [kt]	CO_2 Savings (kt)	Shifted [M pax/year]	Pax-km (kt)	CO_2 Savings (kt)	Shifted [M pax/year]	Pax-km (kt)	CO_2 Savings (kt)
OTP-CND	225	0.10	0.01	2	0.4	0.02	5	1	0.03	7	1
CLJ OTP	450	0.30	0.03	14	3	0.06	27	5	0.09	40	7
TSR OTP	500	0.20	0.02	10	2	0.04	20	4	0.06	30	5
CND OTP	225	0.10	0.01	2	0.4	0.02	4	1	0.03	7	1
Total	–	1.2	0.12	52	**9.8**	0.24	104	**19**	0.36	156	**28**

5 Conclusions

The connectivity analysis performed in Table 2 directly feeds the modal shift scenarios. It uses indirect ACI as a shift potential indicator. Air hubs like OTP/CLJ show growth (7–12% YOY) from feeder traffic.

The estimates are, according to different sensitivity analysis, 0.12–0.36 M shifted passengers/year equivalent to 9.8–28 kt CO_2 savings. CO_2 savings were computed as shifted passenger traffic multiplied with 0.18 kg/pax-km across bidirectional OTP-CLJ, OTP-TSR, and OTP-CND relations. Domestic traffic, (1.2 M pax/year total domestic traffic, aligns with short-haul share) was estimated for each of the key relations as 5–15% of airport totals (e.g., statistics for CLJ report ~9% domestic per 2024 data), focused on OTP links.

OTP-CND traffic is lower than on other key relations due to shorter distance and competition from road/rail, but contributes in some extent to modal shifts

The proposed scenarios, 10% shift, 20% shift and 30% shift apply calculations post-estimation and the results show that savings concentrate on CLJ/OTP (50% of total).

Present study relies on aggregated 2024–2025 traffic data from INSSE/CFR without granular route-level details, for domestic estimates (e.g., 1.2 M pax/year total, 5–15% per route), as considerable data limitations were encountered. The CO2 emission values are consistent with ICAO, but calculations can be refined by considering variability in short-haul operations or rail electrification inconsistencies.

As further development, real life delays and/or costs, validation of scenarios choice for Romanias' case, taking into consideration Romanian road competition, fare integration gaps, and behavioural factors like comfort will allow generalizability beyond selected airports. More empirical surveys and sensitivity tests are needed for robustness as the study innovates Romania-wide network view but underplays economic barriers (e.g., aviation subsidies) and equity risks (e.g., rural access loss).

This contribution informs funding TEN-T policymakers, concerning the much-needed CFR SA upgrades, airport operators (multimodal hubs), and EU (Fit55 targets), advancing sustainable mobility.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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