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Mapping the substitution potential of air–rail integration across Europe

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ABSTRACT

Air–rail integration agreements are widely regarded as an important strategy to spark and stimulate a modal shift from air to rail. Intermodality has been consistently promoted by European transport policy over the last three decades. At the same time, the literature widely concurs on the potential benefits of air–rail integration for passengers, airports, airlines and rail operators. However, as of 2025, the availability of air–rail integration alternatives on the market is limited, and their potential benefits remain largely unexplored. Thus, this paper investigates the substitution potential of air–rail integration in Europe, compiling an inventory of rail connectivity at European airports and proposing a simple and interpretable indicator to quantify the Air–Rail Integration Substitution Potential (ARISP) at the route and airport levels. Our findings indicate that the substitution potential of air–rail integration in Europe is minimal: even when considering rail travel times within a 100% increase of existing air travel, the potential market represents less than 1% of the 1.2 billion intra-European air journeys. The modest competitiveness of rail travel times and the limited potential passenger flows on most substitutable routes suggest that air–rail integration should not be proposed as an environmental policy but rather as one to enhance connectivity. The ARISP indicator further reveals that the limited substitution potential is highly concentrated across a limited number of routes, airports, and geographical regions. Targeting them by directly connecting cities and airports' railway stations with non-stop high-speed services (where possible) may enhance the effectiveness of air–rail integration on substitution. Our analysis shows that rail infrastructure and service provision at airports, as well as their position within the European railway network, are important determinants of the substitution potential of air–rail integration.

1. Introduction

Since the inception of commercial aviation, global, and European, air travel demand generally maintained a steady annual growth of around 4% (IATA, 2026). Although the 2020 COVID-19 pandemic disrupted this trend, as of 2024, aviation has already recovered and is projected to continue in its growth trajectory (IATA, 2024; Gudmundsson et al., 2021). As a consequence, aircraft traffic congestion has been increasing at major hubs, imposing a vast set of negative impacts on airport-adjacent residents (e.g., noise and local air pollution), air passengers (e.g., delays and limited frequencies), and airlines (e.g., constraints to network planning and delays). Beyond airport congestion, the growing impact of aviation on the climate, affecting society as a whole, has further contributed to stressing the need for sustainable solutions for the future of air travel.

Air–rail integration has long been proposed to address these challenges and mitigate their impacts. The European Commission (EC) has consistently promoted intermodality, including air–rail cooperation and integration, as a cornerstone of the European Union's transport policy. The 1995 Green Paper already identified intermodality as the key to the future of the Union's transport policy (European Commission, 1995). The 2001 White Paper first introduced the concept of intermodal integration, aiming to promote a modal shift from road and air transport towards more environmentally friendly modes, such as rail. The report further stressed the importance of air–rail cooperation, stating that network planning should "seek to take advantage of the ability of high-speed trains to replace air transport and encourage rail companies, airlines and airport managers not just to compete, but also to cooperate" (European Commission, 2001, p. 53). The 2006 mid-term review introduced co-modality, the efficient use of different modes independently and in combination, identifying its importance to enable "an optimal and sustainable utilisation of resources" (European Commission, 2006, p. 4). The 2011 White Paper reaffirmed the centrality of intermodal integration in European policy-making, noting that "better modal choices will result from greater integration of the modal

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networks” (European Commission, 2011, p. 6), and highlighting that railway connectivity at airports is crucial “to deal with future capacity problems” (European Commission, 2011, p. 18). More recently, the European Green Deal has reaffirmed the role of multimodality and transport hubs as core elements of its sustainable and smart mobility strategy, further embedding intermodal integration within the EU’s long-term transport policy (European Commission, 2021). Although the terminology has evolved over the years, the underlying policy objective of promoting intermodal integration has remained a consistent priority of European transport policy.

The policy measures implemented to respond to the objectives outlined in the White Papers have primarily targeted freight intermodality rather than passengers. Despite policy documents outlining a clear role for air–rail integration in passenger transport, these intentions have yet to translate into widely adopted market strategies. Although (Chiambaretto and Decker, 2012) highlights how several air–rail intermodal agreements have been signed since the late 1990s, Givoni (2016) suggests that such agreements are still uncommon and are not regarded as a key strategy by major stakeholders in either the airline or rail industries. In particular, Givoni (2016) concluded that at the time, no signs of progress towards a future where air–rail integration would become standard practice were being made. Admittedly, over the past three decades, despite the exponential growth of the European air market and the boom of low-cost carriers, the landscape of air–rail integration has not kept pace, and not much seems to have changed since 2016. Notably, there have been limited advancements in air–rail agreements, as well as in ticketing conditions, fare structures, and booking systems (Witlox et al., 2022). Furthermore, Vespermann and Wald (2011) add that European airports also lack infrastructural development, as most were planned at a time when intermodality was not a priority and, as a consequence, are directly connected neither to national nor urban rail (i.e., metro, tram) infrastructure. However, Givoni (2016) points out that in China, where the infrastructure has been constructed and adapted to enable air–rail integration, strategic commitment from airlines, the Train Operating Company (TOC), and authorities still appears to prioritise air–rail competition over integration or cooperation.

Although over three decades of research concur that air–rail integration can enhance social welfare, benefitting airlines and TOCs, and European policies have identified its crucial role in the future of transport, air–rail integration remains a relatively underdeveloped strategy in the European transport market as of 2025. Furthermore, while air–rail integration is frequently cited as a key pillar of the sustainable transition, it is unclear to what extent air–rail integration could contribute to reaching the ambitious climate goals set by the European Commission. To this end, this paper aims to explore the substitution potential of air–rail integration across Europe, quantifying its scale and identifying possible directions to facilitate implementation efforts. In light of the above, we define the following research questions:

1. What is the current state of infrastructural and operational rail connectivity across European airports?
2. How can an interpretable indicator be designed to quantify the substitution potential of air–rail integration across a diverse network?
3. On which European routes and airports does air–rail integration hold the greatest substitution potential?

We first make an inventory of rail connectivity (including railway infrastructure and train services) at European airports, assessing whether the minimum infrastructural requirements for the implementation of air–rail intermodal agreements are present and, if not, how they might be lacking (as well as updating in the process the information gathered by Vespermann and Wald (2011)). We further propose a simple and interpretable indicator rooted in competitiveness and market size to quantify the substitution potential of air–rail integration on substitutable routes at the route and airport levels. By systematically quantifying and mapping the substitution potential of air–rail integration across Europe, this study provides a comprehensive overview of the scale and spatial scope of said potential, offering a benchmark for monitoring its progress over time. The results identify high-potential routes and airports, providing an empirical foundation for future economic and environmental evaluations and targeted policy interventions.

The remainder of this paper is structured as follows. A literature review on the potential of air–rail integration is provided in Section 2, and the conceptual framework is described in Section 3. The methodology, including the analysis approach, scope and steps, is described in Section 4. Section 5 discusses the results and Section 6 concludes, presenting policy implications, limitations and future work.

2. The potential for air–rail integration

Over the last three decades, High-speed Rail (HSR) networks have been steadily expanding in Europe, China and Japan and are projected to continue growing in the following years (Xia and Zhang, 2017). Due to the spread of HSR, rail has increasingly emerged as a direct competitor for short-haul flights (Albalate et al., 2015). However, the role of rail in long-distance transport extends beyond mere competition. Givoni (2016) argues that air–rail cooperation and integration hold substantial potential, given that the primary markets for rail and air do not significantly overlap.

The literature has long discussed the potential for intermodal cooperation and integration between air and rail. There is widespread agreement among the empirical literature that air–rail integration and cooperation can reduce airport congestion and contribute to overall social welfare (Givoni and Banister, 2006; Grimme, 2007; Janic, 2010, 2011; Givoni et al., 2012; Zanin et al., 2012; Socorro and Viecens, 2013; Jiang and Zhang, 2014; Xia and Zhang, 2017; Jiang et al., 2017; Avenali et al., 2018; Xia et al., 2019). Givoni and Banister (2006), Grimme (2007), Socorro and Viecens (2013) and Xia and Zhang (2016) concur that air–rail integration is more likely conducive to welfare benefits when airports are capacity-constrained, thereby implying that such integration efforts should be prioritised at highly congested hubs (e.g., Frankfurt Airport, London Heathrow). The findings of Socorro and Viecens (2013) enable distinguishing the impacts of air–rail integration on capacity-constrained and unconstrained airports. Integration at capacity-constrained airports would alleviate congestion, increase accessibility, and reduce emissions per seat/km, albeit the induced trips would impose more emissions overall. In contrast, at airports without binding capacity constraints, modal substitution due to air–rail integration is more likely to yield environmental benefits, despite eliminating intermodal competition, potentially leading to increased rail fares and lower service quality (Socorro and Viecens, 2013). Jiang and Zhang (2014) adds that the welfare impact of air–rail cooperation depends on hub capacity constraints only when modal substitutability in the overlapping markets is high. In that case, cooperation enhances welfare at highly congested hubs but will likely reduce it at uncongested airports. However, if the modal substitutability is low, air–rail cooperation enhances welfare independently of the extent to which capacity limits at the hub are met (Jiang and Zhang, 2014). Furthermore, Takebayashi (2016) and Xia et al. (2019) concur that air–rail cooperation at smaller airports can relieve congestion at larger hubs, diverting passengers to less congested airports and consequently enhancing system-wide societal welfare. Xia and Zhang (2016) and Avenali et al. (2018) also note that air–rail cooperation is more likely to contribute to welfare when significant economies of traffic density are present in either mode. Finally, international air–rail agreements between a foreign airline and a domestic airline are found to enhance social welfare more than domestic air–rail agreements, provided that pre-existing service quality is adequate and investment costs are limited (Jiang et al., 2017).

Research also concurs that air–rail integration can enable service providers (e.g., airlines and TOCs) to generate profits while, at the same time, benefiting passengers. In particular, airlines can benefit from a more efficient slot allocation (especially at capacity-constrained hubs), while TOCs can gain increased market shares. The theoretical model developed by Socorro and Viecens (2013) demonstrates that integration is always profitable for both airlines and TOCs when it enables access to a new market. In particular, Xia et al. (2019) suggest that positive benefits of air–rail cooperation in terms of airline fares and transfer traffic are more likely to be achieved with an air market monopoly, as the initial fares are higher than under competition. The level of integration also matters, as Avenali et al. (2018) find that higher levels of cooperation, such as an airline-TOC merger, exclusively benefit the companies involved while intermodal agreements generally benefit passengers, even at congested hubs. Despite passengers always benefiting from seamless air–rail transfers, profit-oriented airlines and TOCs may lack incentives to integrate and share revenues, especially if investment costs are high, meaning that a welfare-oriented TOC could facilitate air–rail integration agreements (Xia and Zhang, 2017; Xia et al., 2019). The misalignment between private and societal interests implies that governments might have to subsidise air–rail cooperation, for example, through the participation of publicly owned airports in the required infrastructure costs, to ensure that agreements are targeted at enhancing consumer surplus rather than companies' profits (Avenali et al., 2018). In particular, Avenali et al. (2022) find that the misalignment of incentives between transport operators and airport companies can push the latter to deter the formation of air–rail cooperation agreements. Thus, despite the theoretical benefits for service providers, governments may need to actively intervene to enable such agreements, address these misalignments and ensure they enhance societal welfare.

Although the literature widely agrees on the potential of air–rail integration to improve societal welfare and reduce airport congestion, its environmental impacts remain ambiguous. On the one hand, Janic (2010, 2011) suggest that even modest shares of air-to-rail modal substitution (about 2%) may reduce both delays and the related costs, and, to a lesser extent, greenhouse gas emissions and noise exposure, especially at congested hubs. For example, the development of an intermodal railway station at Madrid-Barajas (MAD) would reduce CO_2 emissions by 10% due to the induced modal shifts from air and car to rail (Zanin et al., 2012). On the other hand, Givoni and Banister (2006), Socorro and Viecens (2013) and Givoni (2016) concur that air–rail integration is less likely to yield environmental benefits at capacity-constrained airports, especially due to freed slots. Airlines, despite partly replacing feeder flights with rail alternatives, may employ the released airport slots at congested hubs to launch new flights (Avenali et al., 2018). Induced demand and network expansion could therefore offset the environmental benefits of substitution, questioning whether air–rail integration would contribute to reducing environmental emissions (Socorro and Viecens, 2013; Zhang et al., 2019). Thus, although research generally agrees that air–rail integration is likely to induce demand, the extent to which the resulting increase in emissions offsets potential savings from modal substitution remains unclear.

In conclusion, few scholars have offered comprehensive insights into the state of air–rail integration implementations. Vespermann and Wald (2011) provides a first global overview of the state of intermodal integration, with a particular focus on the motivations driving airports to connect with surface transport infrastructure. Furthermore, Li et al. (2018) thoroughly mapped worldwide air–rail cooperation cases and classified them by integration level. However, to the best of our knowledge, no detailed overview of the current availability of rail infrastructure and train services at European airports is available in the literature. Additionally, knowledge on the potential impact of air–rail integration on affected passengers and consequent travel time implications remains limited.

3. Conceptual framework

Air–rail integration and cooperation are not sharply defined in the literature, and the terms are often used interchangeably, see Xia and Zhang (2017), for example. The intermodal transport policy literature generally favours the term integration, whereas the economic and game-theoretic literature tends to use cooperation. Givoni and Banister (2006) first conceptualises air–rail integration, distinguishing it from cooperation and competition between the two modes. Within this framework, cooperation denotes a state of complementarity between the two transport modes, where both are required to complete a journey from origin to destination. In contrast, integration entails combining air and rail services through fast, seamless transfers into a single, unified journey (Givoni and Banister, 2006). Chiambaretto and Decker (2012) further distinguishes three degrees of integration (i.e., low, moderate and high) based on the type of agreement between airlines and TOCs. Conversely, Avenali et al. (2018) defines air–rail integration as a specific form of cooperation implemented at full scale, akin to a merger between an airline and a TOC. We build on the former set of definitions, in which the key distinction between integration and cooperation lies in the existence of formal agreements between airlines and TOCs on ticketing, timetable coordination, and passenger guarantees in the event of delays or disruptions. Following this conceptualisation, air–rail integration in this study is broadly defined as the state where airlines and TOCs cooperate through formal agreements to offer seamless intermodal journeys.

We further distinguish between two primary forms of air–rail integration: one targeting substitutable routes and the other targeting generated routes. The former refers to routes served by both modes, where rail constitutes a potential substitute for air. On such routes, airlines may adopt air–rail integration either to complement their supply, thereby widening passengers' travel alternatives, or to substitute existing services, replacing feeder routes with more profitable ones. In contrast, generated routes are complementary rail corridors that connect destinations not served by air networks, thereby extending airports' catchment areas. Airlines can leverage these routes by integrating rail legs with the main air leg(s) to expand their reach. The primary characteristics of these two types of integration are summarised in Table 1. We also review European air–rail agreements in effect as of 2025 and categorise a selection by integration type, as shown in Table 2. The following paragraphs elaborate on the defining features of each form of integration and discuss their relation to airline network structure.

Based on the definition above, the fundamental condition of air–rail integration is formal cooperation between airlines and TOCs. Such cooperation can take the form of interlining agreements, code-share agreements and joint-venture agreements (Chiambaretto and Decker, 2012). In this context, it is therefore useful to distinguish between horizontal and vertical agreements. Horizontal agreements involve suppliers of services perceived by consumers as substitutes, whereas vertical agreements involve a buyer–seller relationship in which one party offers a service to the other. Air–rail integration agreements can fall under either category. Generated routes typically rely on vertical behind-and-beyond intermodal agreements, while substitutable routes require horizontal parallel intermodal agreements. Horizontal parallel agreements may raise competition concerns, as firms could use them strategically to avoid competition and create collusive oligopolies (Chiambaretto and Decker, 2012). Hence, robust intramodal competition in both air and rail markets is crucial for horizontal agreements. In contrast, vertical agreements generally do not pose a threat to competition, as both parties are incentivised to keep prices low. Vertical agreements may restrict market access for competitors when either party holds a monopoly and the agreements are exclusive; a situation that can be avoided through open-access TOCs arrangements (Chiambaretto and Decker, 2012). On a different note, Socorro and Viecens (2013) show that in monopolistic markets and those with limited intramodal air

Table 1
Characteristics of air–rail integration targeting substitutable and generated routes.

Integration type	Substitutable routes	Generated routes
Mode Availability	Air and rail	Rail only
Mode Relationship	Potential Substitution	Complementarity
Inter-operator Agreement Type	Horizontal Primarily (Parallel)	Vertical Primarily (Behind and Beyond)
Target Passenger Segment	Connecting Passengers Only	All Passengers
Suitable Airline Network	Hub & Spoke Only	Hub & Spoke and Point-to-Point
Target Airports	Key Hubs Primarily	Hubs, Spokes and Origin & Destination Airports
Target Airlines	Full-Service Airlines Only	Full-Service Airlines and Low-Cost Carriers
Target Airline Market	Domestic Market Primarily	Domestic and Foreign Markets
Target Rail Services	High-Speed Rail Primarily	All Rail Services

Table 2
Examples of air–rail integration across different European countries as of 2025.

Country	Substitutable routes	Generated routes
Germany	Lufthansa & DB (Lufthansa Express Rail) between Düsseldorf and Frankfurt Airport	EVA Air & DB (Rail&Fly) at Munich Airport and Amsterdam Schiphol Airport (full DB network access)
Italy	ITA & Trenitalia between Florence and Rome Fiumicino Airport	Air Canada & Trenitalia at Rome Fiumicino Airport and Milan Malpensa Airport (full Trenitalia network access)
France	Air France & SNCF (TGV INOUI) between Bruxelles and Paris Charles de Gaulle Airport	Air Tahiti Nui & SNCF at Paris Charles de Gaulle Airport (18 destinations in France and 1 in Belgium)
Switzerland	Swiss & SBB (SWISS Air Rail) between Geneva and Zurich Airport	Emirates & SBB at Zurich Airport (8 destinations in Switzerland) and Geneva Airport (7 destinations in Switzerland)
Spain	Iberia and RENFE (Train & Fly) between Sevilla and Madrid-Barajas Airport	Air Moldova and RENFE at Madrid Airport (28 destinations in Spain) and Barcelona Airport (9 destinations in Spain)
Austria	Austrian & ÖBB (Austrian AIRail) between Graz and Vienna Airport	China Airlines & ÖBB at Vienna Airport (7 destinations in Austria, 3 in Czechia, 2 in Hungary)

competition, vertical air–rail agreements can contribute to introducing and fostering competition by widening passengers' alternatives.

Airline network structures can significantly influence the attractiveness and feasibility of air–rail integration. A potential air–rail integration model for Hub-and-Spoke (H&S) networks is illustrated in Fig. 1. H&S networks generally imply a domestic market (not necessarily confined to a single country) in which several short-haul feeder flights converge at a hub, which connects the domestic market to several foreign markets via long-haul flights. In the domestic markets, airlines may substitute such short-haul feeder flights with rail connections. An example of which is the DB-Lufthansa collaboration on the Frankfurt–Cologne or Frankfurt–Düsseldorf route (see Table 2). Air–rail agreements in this context specifically target connecting passengers, leading to a partial (or complete) modal shift from air to rail alternatives. Conventional rail has limited attractiveness for substitutable routes, as rail must provide comparable travel times to be an attractive substitute for passengers, implying that rail alternatives should preferably but not necessarily consist of HSR. This model is particularly relevant for major hub airports, which are often capacity-constrained. Following the implementation of air–rail integration, airports may experience reduced congestion and delays if airlines reduce flight numbers. While airlines can cut unprofitable SHF services by relying on integration with rail alternatives, they may also reallocate freed airport slots to more profitable long-haul routes to increase network efficiency. Finally, railway undertakings benefit from induced demand and higher ridership, while intermodal competition is likely mitigated.

Air–rail integration in H&S networks can further serve to expand airlines' networks by incorporating additional destinations. This is exemplified by Lufthansa Express Rail services connecting Frankfurt (FRA) to cities that lack direct air connections (e.g., Mannheim or Würzburg). While substitutable routes are generally confined to domestic markets, generated routes often extend into foreign markets, a notable example being Air Canada's access to the Italian rail market through Trenitalia (see Table 2). In foreign markets, airlines typically operate only a limited number of medium- or long-haul flights to their domestic market and do not maintain short-haul feeder services, thereby limiting the number of directly accessible destinations and constraining overall network connectivity. Airlines have traditionally relied on code-share agreements with local airlines to facilitate onward connectivity (Alderighi et al., 2015). By complementing (or replacing) traditional airline-to-airline code-share agreements, air–rail integration grants airlines access to the railway network. Using rail alternatives as feeder services can facilitate network expansion and passenger flow consolidation at non-hub airports in foreign markets, thereby improving load factors on long-haul flights.

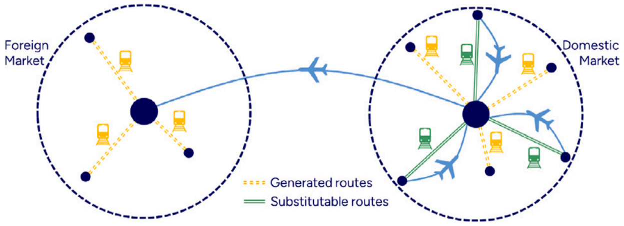


Fig. 1. Air–rail integration model for Hub & Spoke networks.

Point-to-point (PtP) airlines could also benefit from air–rail integration, targeting generated routes to expand the catchment areas of the airports served by their networks. A potential air–rail integration model for PtP networks is illustrated in Fig. 2. While PtP networks have historically focused on short- and medium-haul markets, recent developments, such as the introduction of long-range single-aisle aircraft (e.g., Airbus A321LR/XLR) and the emergence of long-haul low-cost carriers (e.g., Norse Atlantic Airways) operating on high-demand routes (e.g., London Gatwick–New York JFK), have opened new possibilities

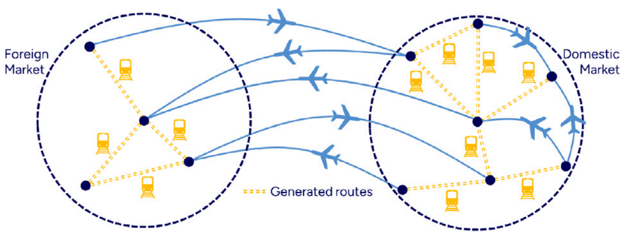


Fig. 2. Air–rail integration model for point-to-point networks.

for long-haul PtP services. Although only full-service airlines presently have standing air–rail integration agreements with TOCs, low-cost airlines could potentially enter this market using the PtP model.

4. Methodological framework

4.1. Conceptualisation of the air–rail integration substitution potential (ARISP) indicator

We develop a stepwise approach grounded in theoretical conceptualisation and literature review to map the substitution potential of air–rail integration across European routes and airports. To do so, we identify three core components determining air–rail integration substitution potential: (1) feasibility, (2) competitiveness, and (3) the market size of the substitution potential. In the following, we elaborate on each component.

Feasibility captures whether air–rail integration is currently possible without additional infrastructural investments. Past studies identify railway station presence within airports, preferably integrated into the main terminal(s), as the key prerequisite for air–rail integration (Givoni and Banister, 2006; Janic, 2011; Givoni, 2016), with Li et al. (2018) showing this to be the most influential enabling factor. Additionally, feasibility implies alternative rail routes should be either served by scheduled train services ("existing routes") or directly connected by rail infrastructure that would enable supplying such services ("potential routes"). Thus, the feasibility of air–rail integration at the airport and route level is operationalised by filtering out airports based on railway station availability and routes based on the current infrastructure and service supply.

Competitiveness is measured using travel times as a proxy for generalised travel costs (GTC). Conceptual studies consistently identify comparable rail travel times as a crucial enabler of air–rail integration (Givoni and Banister, 2006; Janic, 2010; Givoni, 2016), with (Janic, 2011) extending this to GTC more broadly. Empirically, Román and Martín (2014) further demonstrate the importance of travel costs and, especially, travel times, while (Li and Sheng, 2016) find that demand for air–rail integrated services is more elastic to in-vehicle time than to monetary expenditures. While GTC would, in principle, provide a more comprehensive behavioural measure, relying on travel times seems more appropriate considering the scope of the indicator is to provide a first-order indication of the substitution potential of European routes and airports for air–rail integration, rather than modelling modal shift or forecasting behavioural responses. To measure the competitiveness of rail and air feeder legs, their implicit prices as part of wider multi-leg air trips should be compared. However, only stand-alone fares or prices for the entire journey are observable, while comparable integrated fares for rail–air trips are not always available, making monetary comparisons challenging and unreliable. In contrast, travel times can be directly observed and combined across air and rail legs, including for air–rail connections yet to be integrated, enabling consistent comparisons. Moreover, incorporating fares could introduce additional noise due to the high volatility of long-distance ticket prices across booking windows and times of day and year.

Finally, the substitution potential market size is measured as the number of passengers potentially able to substitute their trip. Passengers segmented by journey types (i.e., local, behind, beyond and bridge, further described by Bruno et al. (2025)) are assigned to the relevant alternative route. Building on this conceptual foundation, this paper explores the substitution potential of air–rail integration across Europe by mapping substitutable air routes, identifying existing and potential rail alternatives, and quantifying their travel time competitiveness relative to the number of exposed passengers. Fig. 3 summarises the stepwise approach and data sources used, including air and rail network supply, and air traffic data.

4.2. Data inputs and sources

Three main data sources are employed in our investigation: air service supply characteristics (i.e., scheduled air services and their in-vehicle time), travel times of rail alternatives (i.e., both scheduled and minimum running times), and air travel demand (i.e., passenger flows). Military airbases, civil aviation airfields, airports on islands not served by rail (e.g., Majorca, Malta, and Cyprus), and heliports are filtered out to compile an exhaustive list of 343 input commercial airports encompassing all EU countries, as well as the UK, Switzerland, Norway and Serbia. Data for all flights between the selected airports, scheduled for the year between November 15, 2023, and November 14, 2024, is collected through the Official Airline Guide (OAG) Schedules database. The data is cleaned to exclude civil aviation and cargo, ensuring only commercial flights are accounted for, and is aggregated per unique origin–destination airport pair.

Travel times of rail alternatives are compiled from two main sources, based on the railway station coordinates at airports and urban areas. Commercial running times of scheduled rail services are retrieved from the journey planner (Rome2Rio, 2025), including both direct and transfer options. The travel times provided by Rome2Rio offer representative journey time estimates based on scheduled service data, incorporating scheduled in-vehicle time and typical transfer time between scheduled services. When multiple train options with different transfer numbers, transfer locations or travel times are provided on the same OD pair, the one yielding the shortest journey time is selected. Technical running times and distances, determined solely by infrastructure availability, are retrieved from Signal.eu.org, assuming non-stop services between origin and destination. The Open Source Routing Machine (OSRM) is used to compute the fastest and shortest rail routes between two points along the rail network, based on OpenStreetMap data (e.g., rail infrastructure speed profiles, network characteristics, station names). When multiple paths connect the same origin–destination pair, the fastest route is selected, regardless of distance.

Finally, passenger flow data for 2023 are retrieved individually for each input airport from OAG Traffic Analyser, a data analytics tool providing detailed figures on passenger volumes by journey type, segmented into local, behind, beyond, and bridge traffic. The total "generated" traffic is obtained by summing all direct and indirect (i.e., those connecting at another airport) passengers originating and terminating at the airport. The "hub" traffic is measured by querying flights originating from all world regions and terminating at all world regions connecting at the airport. The total passenger flows are finally calculated as the sum of generated and hub traffic. It is important to note that aggregated figures based on OAG traffic data are lower than official airport-reported figures, due to differences in passenger counting methods (e.g., airports typically count hub passengers twice by summing incoming and outgoing passengers). Despite some minor gaps affecting its accuracy, OAG traffic data is considered a reliable source for capturing the underlying passenger flow patterns and has been previously used in the literature (Gelhausen et al., 2013; Fageda

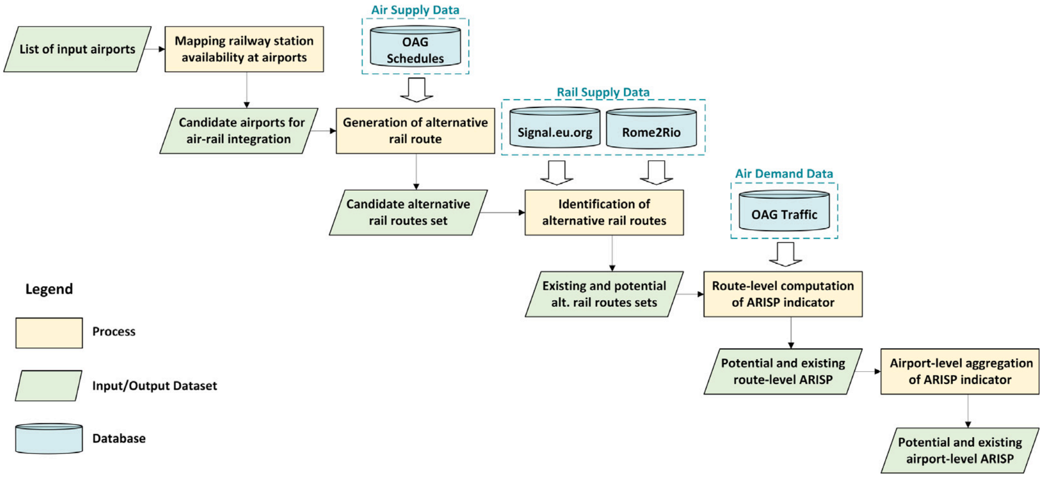


Fig. 3. Overview of the stepwise approach and data sources used to explore the substitution potential of air–rail integration.

et al., 2019; Zuidberg and de Wit, 2020; Cheung et al., 2022; Kuo et al., 2022; Avogadro et al., 2024).

To reflect current travel patterns, the most recent data available at the time of the analysis was chosen. Passenger flow data for 2023 captures a growing market that had nearly fully recovered to pre-Covid levels, whereas the scheduled data between November 2023 and November 2024 reflects a stabilised post-Covid market with continuous growth. Passenger flows at European airports in 2023 had reached 95% of 2019 levels (ACI Europe, 2024), with monthly traffic attaining 99% of pre-pandemic volumes by November 2023 (IATA, 2024), and subsequently surpassing pre-pandemic levels throughout 2024 (ACI Europe, 2025).

4.3. Mapping railway station availability at airports

Givoni and Banister (2006, p. 389) highlight the importance of airport railway stations offering “direct links to a large number of destinations with services at a relatively high frequency”, arguing that this typically requires them to be “through stations on a main line”. Accordingly, an inventory of airport railway station availability in Europe is compiled, classifying the infrastructure and services they provide access to. European airports without OAG Traffic data for 2023 are filtered out to retain only commercially operating facilities. Railway station availability is then screened through the official airport websites, supported by Google Maps and OpenRailwayMap.

An airport is classified as connected to the rail network if (1) a railway station within a 15-minute walk of the terminal (e.g., BHD–Sydenham station), or (2) a free connecting service requiring 15 min or less total transfer time (e.g., BHX–Birmingham International and DUS–Düsseldorf International are considered connected, whereas PSA–Pisa Centrale and MRS–Vitrolles Aéroport Marseille Provence are excluded due to fare-based transfers) is available. For connected airports, rail infrastructure is categorised as through, detour, or branch line, as illustrated in Fig. 4, and available services as regional, long-distance, and high-speed (meaning more than one can be the case at the same time). “Unconnected” airports linked to railway via urban rail systems (e.g., metro, tram, light rail) are labelled as “Linked to Line” (see Fig. 4).

4.4. Identification of alternative rail routes

Considering airport railway station availability as a prerequisite for air–rail integration, “unconnected” airports are excluded as a first step. A complete air route set between all “connected” airports is generated, retaining only scheduled air connections with commercial passenger flights. For each air route, candidate rail alternatives are constructed and classified based on railway station availability at the respective endpoint airports. When both endpoint airports on a certain bidirectional substitutable air route (ABC and XYZ in case of Fig. 5) are “connected”, three bidirectional (six unidirectional) alternative rail routes are identified, each matched to the air passenger segment who could potentially use it as a substitute. Passengers aiming to reach city A served by airport ABC from airport XYZ or vice-versa are beyond passengers on the ABC–XYZ air route and behind passengers on the XYZ–ABC air route. The relevant alternative rail route is illustrated in green in Fig. 5(a). Conversely, passengers aiming to reach city X served by airport XYZ from airport ABC or vice-versa are beyond passengers on the XYZ–ABC air route and behind passengers on the ABC–XYZ air route. The relevant alternative rail route is illustrated in yellow in Fig. 5(a). Finally, passengers aiming to reach airport XYZ from airport ABC or vice versa are bridge passengers on the ABC–XYZ and XYZ–ABC air routes. The relevant alternative rail route is illustrated in red in Fig. 5(a). If only one airport on a certain bidirectional substitutable air route (e.g., ABC–XYZ in Fig. 5) is served by a railway station, only one bidirectional (or two unidirectional) alternative rail route is relevant for air–rail integration, as shown in Fig. 5(b). Finally, Rome2Rio and Signal.eu.org are iteratively queried to identify existing and potential routes, respectively.

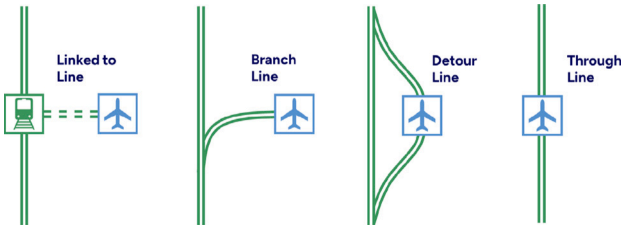
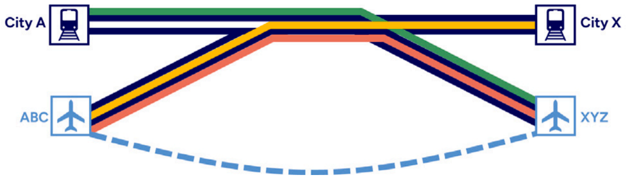


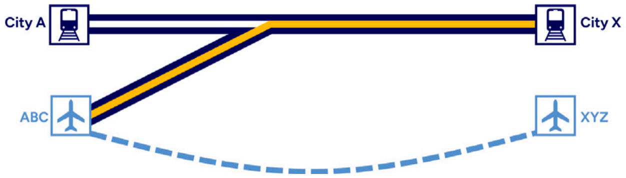
Fig. 4. Illustration of the four types of rail infrastructure.

4.5. Route-level computation of ARISP indicator

The ARISP is computed as the ratio of perceived air-to-rail in-vehicle times to approximate rail alternatives’ relative competitiveness. We focus on in-vehicle time because, without considering disaggregated spatial demand patterns within origin/destination regions, out-of-vehicle components (access, waiting, transfer, egress) are comparable across feeder modes. The ratio emphasises the rare cases where rail travel times are competitive or superior, while compressing the large majority of routes where air outperforms rail toward 0. To capture the size of the potential market for substitution, the ratio is then weighted



(a) Air routes where a railway station is available at both endpoint airports



(b) Air routes where a railway station is available only at one endpoint airport

Fig. 5. Relevant bidirectional alternative rail routes per air route type (blue lines represent rail infrastructure). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by the number of potentially exposed air passengers. Thus, the indicator will assume non-negative values with a lower bound at zero and no natural upper bound.

Let o be the origin airport serving city i, and d the destination airport serving city j. The indicator is computed separately for each route type identified in Fig. 5 using Eqs. (1)–(3), respectively.

$$\mathrm{ARISP}_{id} = \left(\frac{t^{\mathrm{air}}_{od} \cdot \theta^{\mathrm{air}}}{t^{\mathrm{rail}}_{id}} \right) \cdot \left(q^{+}_{od} + q^{-}_{do} \right) \tag{1}$$

$$\mathrm{ARISP}_{oj} = \left(\frac{t^{\mathrm{air}}_{od} \cdot \theta^{\mathrm{air}}}{t^{\mathrm{rail}}_{oj}} \right) \cdot \left(q^{-}_{od} + q^{+}_{do} \right) \tag{2}$$

$$\mathrm{ARISP}_{od} = \left(\frac{t^{\mathrm{air}}_{od} \cdot \theta^{\mathrm{air}}}{t^{\mathrm{rail}}_{od}} \right) \cdot \left(q^{\cap}_{od} + q^{\cap}_{do} \right) \tag{3}$$

Where, t^{air} is scheduled flight time, t^{rail} corresponds to scheduled in-vehicle time for existing routes and the minimum running time for potential routes, and q^{-}, q^{+} and $q^{\cap}$ represent behind, beyond and bridge passengers, respectively. θ^{air} is a mode-specific travel time multiplier capturing the higher perceived disutility of air travel relative to rail. Considering the scope of this analysis, θ^{air} is set to 1.62, the mean air-valued/train-valued value of time from the within-study variation analysis of 27 European studies reported in Wardman et al. (2016). We further examine the sensitivity of the ARISP, travel time increase and travel time difference distributions to the 0.21 standard error associated with this estimate.

4.6. Airport-level aggregation of ARISP indicator

To capture the overall market potential of substitutable routes at airports, the route-level ARISP is aggregated as the summation of all the alternative rail routes originating from and terminating at a given airport, as shown in Eq. (4).

$$\mathrm{ARISP}_{o} = \sum_{d,j} \left(\mathrm{ARISP}_{oj} + \mathrm{ARISP}_{od} \right) \tag{4}$$

Only two of the three rail route alternatives are relevant for any given airport. Therefore, airport-level ARISP is ultimately independent of generated passengers (i.e., point-to-point and spoke passengers connecting at a third airport), depending solely on hub passengers connecting at the airport.

5. Results

5.1. Mapping railway infrastructure and train services availability at European airports

The classification of railway infrastructure and train service availability across 343 commercial airports in Europe is presented in Fig. 6, highlighting the number of airports in each class. A direct link refers to a fixed connection via urban rail systems, meaning that some of these 234 offer scheduled bus services enabling connections to the railway system. Consistent with prior literature, such services are not deemed sufficient to provide the seamless intermodal journeys required for air–rail integration. All mapped airports exhibit a clear hierarchical structure in train service provision, independent of the type of railway infrastructure (i.e., branch, detour, or through lines). Every airport railway station served by high-speed trains also accommodates long-distance and regional services, while all those with long-distance operations are concurrently served by regional services.

Regional train services are available at the railway stations of all 62 airports, while 41 offer exclusively regional or suburban connections, mostly on branch lines. Long-distance train services are available at 22 airports, with the 14 lacking HSR connections rather evenly distributed across line types. Considering all connected airports, detour lines are the least common (10 occurrences), whereas branch lines are the most common (31 occurrences). Conversely, the overwhelming majority (6 out of 8) of HSR stations are located on a through line. The limited HSR connectivity at Rome Fiumicino (FCO) and Cologne/Bonn (CGN), the only HSR airports lacking through-line infrastructure, supports the argument that mainline through-stations are a critical prerequisite for air–rail integration (Givoni and Banister, 2006).

Next, we analyse the distribution of rail infrastructure availability across airports and investigate its relationship with airports' total and hub passenger flows (Fig. 7). The geographical distribution reflects both the maturity of national rail networks and the strategic centrality of regions within the broader European railway system. Airports' railway connectivity is concentrated in central Europe, with through-lines particularly common in eastern France, Germany, southern England, the Netherlands and Denmark. By contrast, airports in peripheral regions, including Ireland, more remote areas of the UK, western France and the Iberian Peninsula, generally lack direct railway access. Similar patterns exist in northern and eastern Europe, with the notable exception of Poland.

Railway infrastructure availability appears poor overall, albeit significantly better for larger airports. Despite the large majority of the airports lacking a direct link to railways, most of those with over 15 million total passengers/year are served by railways, with Paris-Orly (ORY), Lisbon Portela (LIS), London Luton (LTN), and Dublin (DUB) being the only exceptions. All major hubs (i.e., over 5 million hub passengers/year) host a railway station, mostly on through or branch lines.[1] This suggests that major European hubs already possess the railway infrastructure required for air–rail integration. Notably, the few well-connected airports located on through lines with low traffic (e.g., LEJ) could be further expanded through intermodal agreements.

Finally, Fig. 8 illustrates the distribution of train service type availability across airports (Fig. 8(a)) and its relationship with airports' total (Fig. 8(b)) and hub passenger flows (Fig. 8(c)). Similar to rail infrastructure, the geographical distribution of rail service types at airports appears uneven across Europe, with well-connected airports clustered along a few key corridors. Several countries (e.g., the Nordics, Belgium, the Netherlands, France and Spain) feature a centralised system, where only major airports are connected by rail. Notably, Spain prioritises city-to-city HSR connectivity over airport integration into the network.[2]

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[1] Only Zurich airport (ZRH) station lies on a detour line.

[2] The only Spanish airport on a through line is Jerez de la Frontera (XRY), on a conventional (Iberian gauge) line.

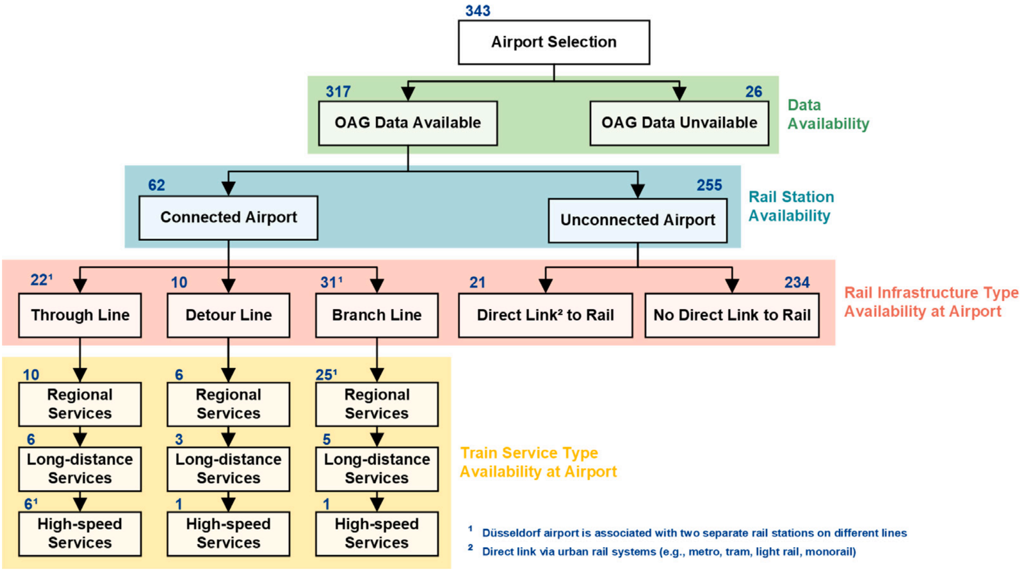


Fig. 6. Diagram of the airport classification steps (number of airports pertaining to each class shown in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Most connected airports are served only by regional or suburban train services, suggesting that railway access at European airports primarily supports local, regional and city-to-airport connectivity, rather than proper intermodality. The UK and Scandinavia are notable exceptions, indicating stronger integration of airports into the national long-distance railway system. Generally, train service provision at airports depends on geographical location, rail infrastructure provision, and traffic: regional or suburban services are more common in peripheral areas, on branch lines, and at smaller airports, whereas high-speed and long-distance services are concentrated in central regions, on through or detour lines, and at larger airports. FRA, Amsterdam Schiphol (AMS), and CDG exemplify this pattern, combining centrality within the rail network, significant passenger flows, and access to HSR through-lines. However, significant exceptions exist. Major hubs (i.e., over 25 million total and 8 million hub passengers/year) like London Heathrow (LHR), MAD and Munich (MUC) still lack HSR and long-distance connectivity, relying solely on regional or suburban services. Conversely, some mid-sized non-hub airports (i.e., under 20 million total and 550.000 hub passengers/year), such as DUS, Lyon Saint-Exupéry (LYS) and CGN, offer HSR connections, highlighting (unexplored) potential for air–rail integration on generated routes. Strengthening air–rail integration at these well-connected mid-sized airports could help redistribute air traffic, thereby relieving congestion at major hubs.

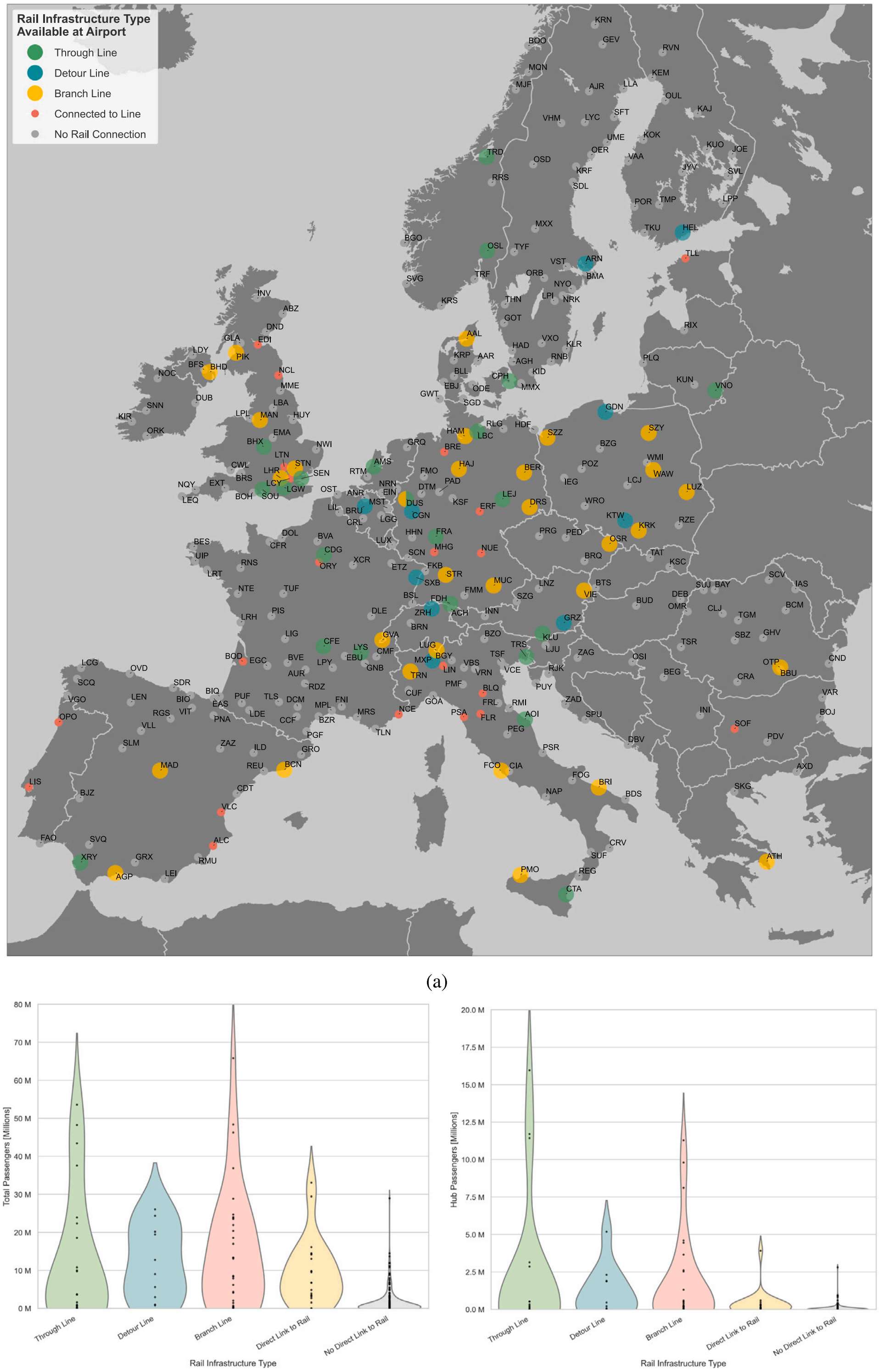
5.2. Route-level analysis

After excluding airports without direct railway access, candidate alternative rail routes are generated based on flight schedules and passenger flows. After applying infrastructure or service availability filters, 7.758 rail routes are identified as alternatives to 5.720 air routes, which are further aggregated into 7.425 unidirectional routes (3.814 bidirectional) for unique city-airport pairs. These include 4.966 unidirectional (2.672 bidirectional) “existing” routes with scheduled services, and 7.183 unidirectional (3.669 bidirectional) “potential” routes where continuous railway infrastructure enables direct train supply. The filtering steps are summarised in Fig. 9.

Fig. 10 illustrates the ARISP distribution for both existing and potential unidirectional rail routes, where scheduled rail travel times are employed for the former and rail minimum running times for the latter. The KDE of the route-level ARISP, see Fig. 10(a), suggest that the distribution exhibits heavy-tailed characteristics. No theoretical distribution (including power-law, log-normal, Pareto, and Weibull) that was fitted to the data provided a statistically significant fit across the entire range of values. The heavy-tailed distribution implies that a few routes have extremely large ARISP whilst the majority of routes have limited potential, stressing the importance of targeting routes with extreme ARISP values to maximise the impact of air–rail integration. This skewed distribution is unsurprising given the concentration of passenger flows on a few routes and substantially longer rail travel times on most routes. Targeting 363 existing routes alone could enable offering rail alternatives to 50% of the 93 million potential passengers (i.e., all air passengers where either an existing or a potential alternative rail route is available). At the same time, targeting the top 20% routes (slightly less than 1.000 routes) by passenger demand would affect up to 76.5 million passengers. It is worth considering that a substantial modal shift on busy routes might not necessarily be possible or plausible in the case of rail capacity constraints. To assess the substitution potential on such routes further, rail capacity on the top-performing routes should be analysed.

Comparing the $\text{ARISP}_{\text{existing}}$ and $\text{ARISP}_{\text{potential}}$ histograms (Fig. 10(a)) indicates that most routes that could theoretically be (but are currently not) served by rail alternatives have low ARISP values, suggesting limited attractiveness for substitution potential. The pool of candidate routes with substitution potential appears rather limited in size. The CDFs, illustrated in Fig. 10(b), show that about 80% of both potential and existing unidirectional routes have ARISP below 6.000, compared to maximum values of 307.468 for unidirectional (541.544 for bidirectional) existing routes on the Barcelona–MAD and 275.711 for unidirectional (484.800 for bidirectional) potential routes on the Lyon-CDG.

As the numerical definition of the indicator prioritises passenger demand over travel time, we further analyse the percentage travel time increase and the travel time difference across existing and potential routes. Their cumulative distribution functions, illustrated by Figs. 11(a) and 11(b), respectively, show that the advantage of air in terms of travel times is significant and widespread across most existing and potential routes. Thus, the ARISP does not employ filtering constraints for rail in-vehicle times, meaning that competitiveness is not guaranteed upfront. However, doing so would considerably reduce the feasible route set and hamper mapping the full spectrum in relation to potential service integration. For example, examining routes with travel time increases below 20% reveals only three existing bidirectional routes (FRA–Stuttgart, LYS–Paris, LYS–Marseille), accounting for



(a)

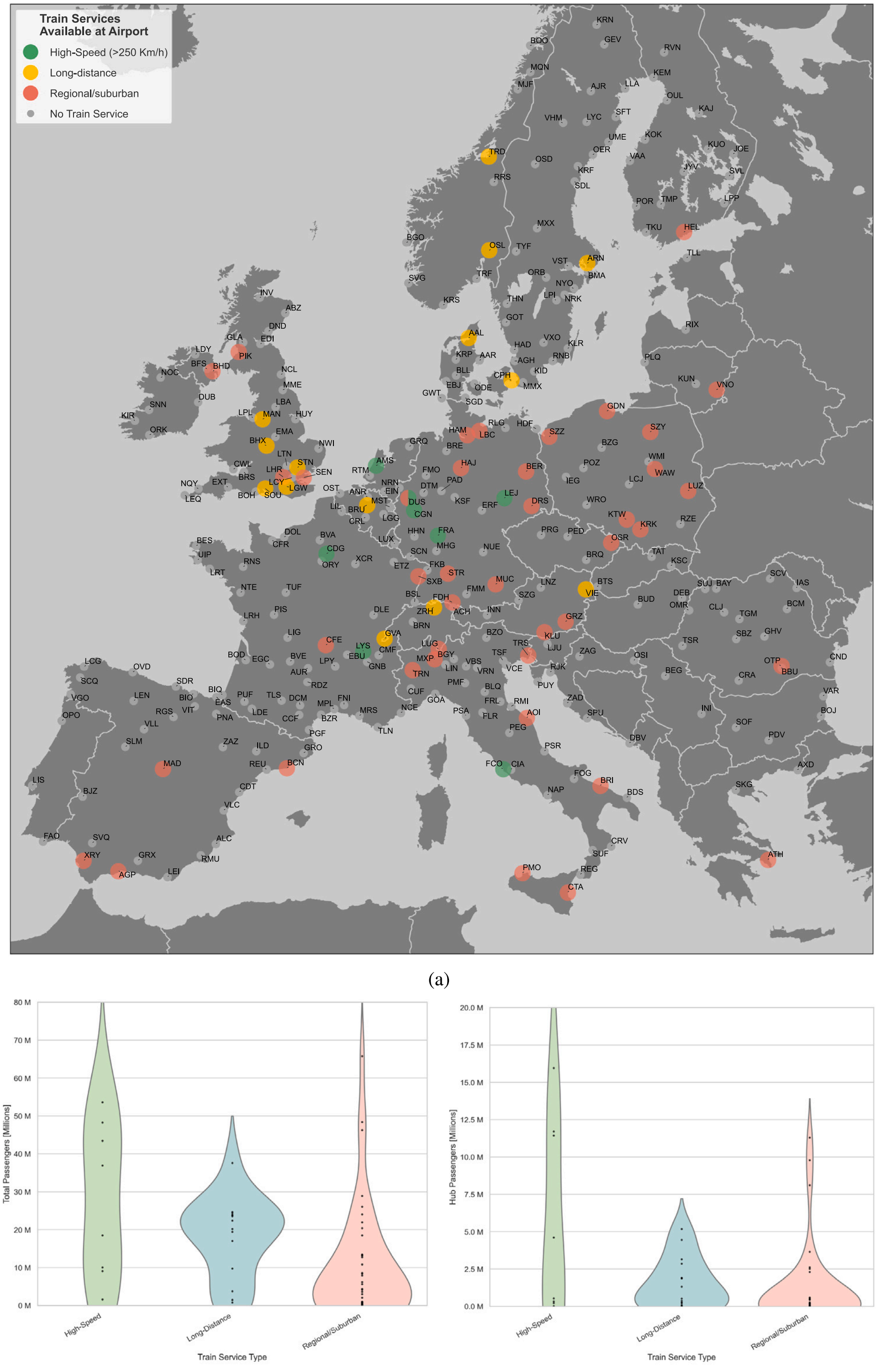
(b)

(c)

Fig. 7. Rail infrastructure type availability at European airports: (a) geographical distribution, (b) distribution by total passengers per airport in 2023, (c) distribution by hub passengers per airport in 2023.

around 330.000 passengers. Although relatively time-competitive rail alternatives are offered on a few routes only, targeting them could yield a disproportionately high impact. Rail alternatives within 100% travel time increase are already available for up to 9 million passengers on 122 unidirectional routes, rising to 29 million passengers on 811 routes considering minimum running times. Similarly, alternative rail services within 100 min of additional travel time are available for up to 8 million passengers on 116 routes, reaching up to 20.5 million passengers on 500 routes, considering the minimum running times.

Despite the comparable shapes of CDFs for existing and potential routes and passengers (see Fig. 10(b)), the more pronounced steepness of potential curves highlights untapped potential offered by existing rail infrastructure. Fig. 11 further shows a substantial gap between routes and passengers, for ARISP$_{\text{existing}}$ and ARISP$_{\text{potential}}$ alike, at moderate



(a)

(b)

(c)

Fig. 8. Train service type availability at European airports: (a) geographical distribution, (b) distribution by total passengers per airport in 2023, (c) distribution by hub passengers per airport in 2023.

travel time differences and increases, especially considering the more than 2.000 additional potential routes. This gap suggests that existing rail services connecting airports currently lag behind the theoretical capability of rail infrastructure in many instances, indicating opportunities for their improvement through planning changes (e.g., more direct connections to airports, reduced running time supplements and fewer stops). However, minimum running times assume exclusive use of the infrastructure (meaning no dependencies and conflicts) and do not account for running time supplements, required to ensure safe and efficient operations, increase reliability and avoid delays and knock-on delays. Thus, travel times of potential routes represent only a lower bound and reaching them imposes a trade-off between lowering travel times and enhancing service reliability and timetable robustness. Although potential travel times should consistently outperform existing

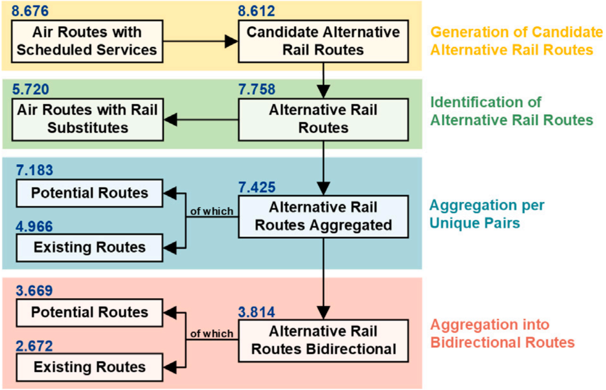


Fig. 9. Diagram of the route filtering steps (number of routes shown in blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ones, a few exceptions are found in the data, often caused by gaps in infrastructure connectivity. Notable examples include the infrastructure gap between Sicily and the mainland and the gap between the Iberian gauge of conventional lines and the standard gauge of high-speed lines in Spain.

The geographical distribution of the top 100 existing and potential bidirectional routes by ARISP is illustrated in Figs. 12 and 13, respectively. Line width represents potential passenger flows, while the colour indicates the percentage of travel time increase relative to air travel. The combination of competitive travel times (i.e., below 150% increase) and high demand (i.e., above 225.000 passengers/year) for the top 25 existing routes suggests that frequent high-speed city-to-airport rail services may be justifiable under air–rail integration agreements. However, the significant rail travel times on many high-ARISP routes suggest rail alternatives are unlikely to substitute feeder flights. The average rail service travel time on these routes is 3,5 h, ranging from 72 min on the FRA–Stuttgart to 354 min on the FRA–London, compared to the average flight times of just 73 min (119 when considering valued air travel time). Rail services outperform air travel times only between Stuttgart and FRA, allowing marginal travel time savings of around 2 min, almost 3% of the valued flight time. Expanding to the top 100 ARISP routes, travel time differences below 60 min are offered by existing services only on 11 routes.[3] Air–rail integrated services could be offered on these routes to complement or substitute existing short-haul flights, affecting a significant number of passengers, ranging from 134.066 passengers/year (around 367 daily passengers) travelling between AMS–Brussels to 768.916 passengers/year (around 2.107 daily passengers) travelling between MAD–Barcelona.

Fig. 13 suggests that increasing average operating speeds within infrastructural limits could considerably widen the set of competitive rail routes, as minimum running times outperform air on seven routes.[4] On 10 routes with considerable $\text{ARISP}_{\text{potential}}$, minimum running times push travel time differences below 10 min, making them particularly attractive for substitution.[5] Most of these routes concurrently feature service travel time differences below 60 min, except for the LHR–Brussels (231.906 annual or ca. 635 daily passengers) and the CDG–Bordeaux (321.018 annual or ca. 880 daily passengers). Both require interchange to the urban or regional rail network due to the lack of a cross-city connection for long-distance services in London and Paris, respectively.

Most of the top 100 routes are consistent across $\text{ARISP}_{\text{existing}}$ and $\text{ARISP}_{\text{potential}}$. Investigating the 24 exceptions indicates that on nine routes, existing outperform potential alternatives due to infrastructural gaps (i.e., Spain and Sicily). On four routes, scheduled travel times approach minimum running times, suggesting optimal average speeds with minimal running time supplements. The limited demand and large distances on the remaining 11 routes[6] are likely causes for the subpar existing travel times compared to potential.

Routes with substitution potential are concentrated in Western Europe, with a few notable exceptions. In Poland, existing rail services between Warsaw Chopin (WAW) and Krakow (231.876 annual or ca. 635 daily passengers) and the WAW–Gdansk (186.369 annual or ca. 511 daily passengers) are the only ones with some degree of substitution potential, requiring around 78 min and 100 additional minutes, respectively. The 500 additional minutes required between FRA and Budapest (286.278 annual or ca. 784 daily passengers) highlight the poor state of rail infrastructure in parts of Central Europe. The ARISP indicator also highlights a few routes in Scandinavia, such as the Oslo (OSL)-Trondheim/Bergen and the CPH–Oslo. Despite the high demand for these routes, rail services impose excessive travel times compared to air, with service time increases ranging from 304% on the OSL–Trondheim to 448% on the OSL–Bergen. Consequently, it is unrealistic to consider any of these Scandinavian routes as potential candidates for air–rail integration. In Sweden, air–rail integrated services connecting Stockholm Arlanda (ARN) and Gothenburg (224.110 annual or ca. 614 daily passengers) or between Stockholm and CPH (283.567 annual or ca. 777 daily passengers), respectively, requiring 140 and 250 additional minutes, respectively, may be worth exploring. Finally, no routes connecting two airports are in the top 100 routes by ARISP indicator, most likely due to the lower share of bridge passengers as opposed to behind and beyond passengers. This suggests that the supply of direct rail connections between airports and cities should be prioritised over airport-to-airport connections.

To investigate the relationship between the two main variables included in the indicator, i.e. passenger demand and travel time, the number of annual potential passengers against the percentage travel time increase for both existing and potential bidirectional routes is plotted in Fig. 14. The two plots display similar patterns, despite the higher point density of the potential (right), due to the larger number of routes included. The distribution of potential routes is considerably shifted to the left compared to existing ones, highlighting the margin for reduced scheduled service times. For example, while travel time increases for existing services are comparable across Berlin–FRA and FRA–London, the wider minimum travel time gap suggests that FRA–London has wider improvement margins, possibly due to cross-border barriers. Fig. 14(a) shows that the highest-demand routes with feasible rail alternatives are Barcelona–MAD and Berlin–FRA, with travel time increases of around one hour and two-and-a-half hours, respectively. Other high-demand routes (i.e., more than 425.000 annual or 1.164 daily passengers) with moderate scheduled travel time increases (under 200 min) include FRA–London, LHR–Edinburgh, LHR–Glasgow, FRA–Hamburg and CDG–Lyon. Fig. 14(b) highlights that all have margins to increase competitiveness, subject to rail capacity constraints.

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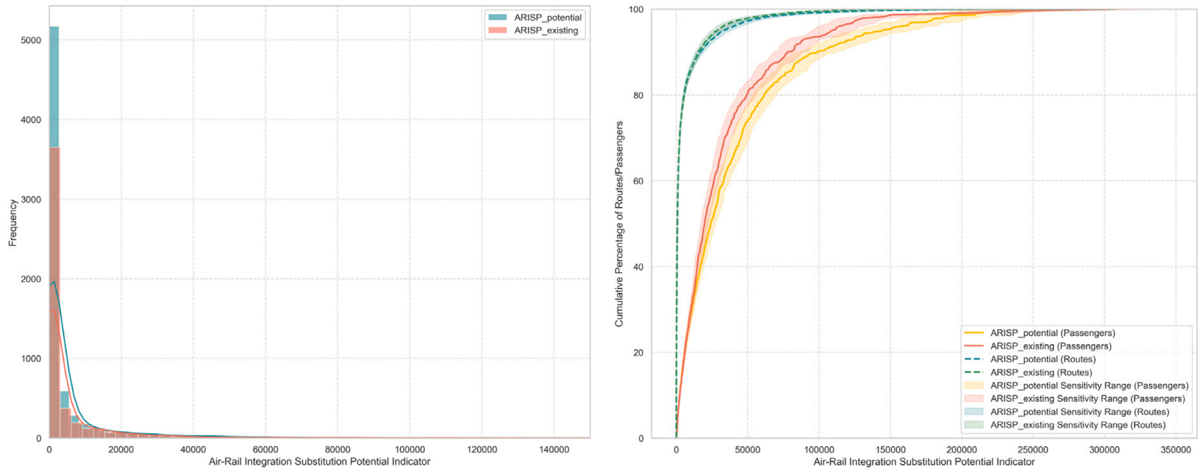
[3] Those between FRA and Stuttgart/Düsseldorf, AMS and Brussels/Paris/Düsseldorf, between BRU and Paris, FCO and Naples/Florence, CDG and Lyon, and between MAD and Valencia/Barcelona.

[4] Those between FRA and Düsseldorf/Stuttgart, CGD and London/Lyon, Brussels Zaventem (BRU) and Paris/London, and between AMS and Brussels.

[5] Those between FRA and Düsseldorf/Stuttgart, CDG and London/Lyon/Bordeaux, FCO and Florence, BRU and Paris/London, AMS and Brussels, and between LHR and Brussels.

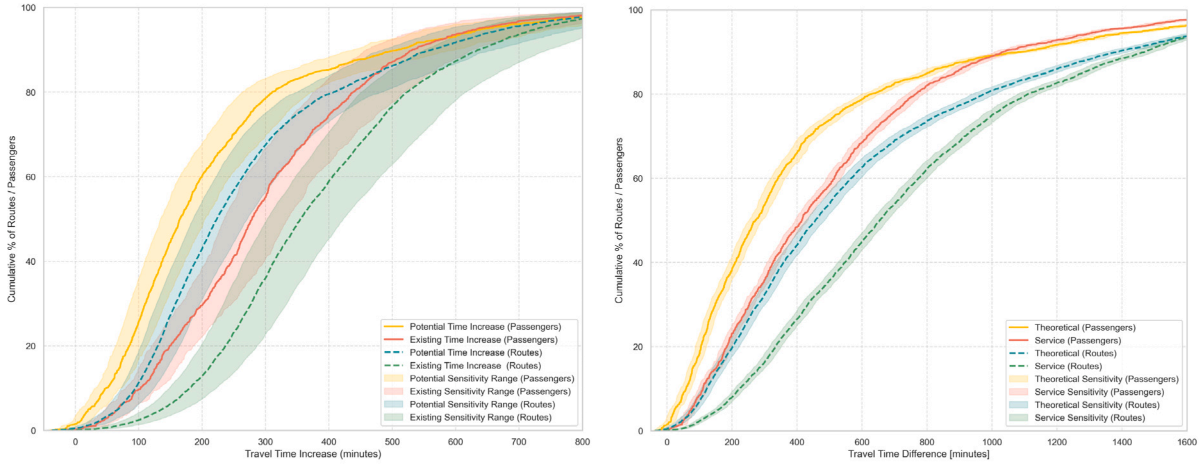
[6] Those between CDG and Düsseldorf/Venice/Florence/Berlin/Brest, between FRA and Basel/Copenhagen, between LHR and Frankfurt/Milan/Zurich and between AMS and Lyon.



(a) Kernel Density Estimation (KDE)

(b) Cumulative Distribution Function (CDF)

Fig. 10. Distribution of the ARISP$_{\text{existing}}$ and ARISP$_{\text{potential}}$.



(a) Travel Time Increase CDFs

(b) Travel Time Difference CDFs

Fig. 11. Distribution of the travel time increase and travel time difference across unidirectional existing and potential rail routes.

5.3. Airport-level analysis

The ARISP indicator is aggregated at the airport level to identify airports with considerable substitution potential and, consequently, direct strategic efforts and investments. Both ARISP$_{\text{existing}}$ and ARISP$_{\text{potential}}$ are available for each connected airport, with a few exceptions only.[7] High airport-level ARISP values reflect a combination of high-demand connecting air routes and time-competitive rail alternatives. To isolate the contribution of the three main variables (i.e., number of substitutable routes, potential passenger flows and time-competitiveness of rail alternatives), we investigate the relationship between the airport level ARISP and three passenger metrics: total, connecting (i.e., hub and spoke passengers), and potential passengers, as presented in Fig. 15.

FRA exhibits the highest ARISP, followed by CDG, AMS, MAD, LHR and MUC. The top-three airports all feature through-line HSR stations, highlighting the importance of service and infrastructure availability for air–rail integration, as proposed by Givoni and Banister (2006). The main contributing factor for FRA's superior ARISP indicator compared to CDG is the sizeable number of potential passengers 15(c), suggesting that rail alternatives at CDG offer, on average, more competitive travel times. At the same time, FRA and CDG have rather comparable connecting passenger volumes (Fig. 15(b)), suggesting that a larger share of connecting passengers have rail alternatives available at FRA. Consequently, FRA's attractiveness reflects its centrality within the European rail network and the broad availability of alternative rail routes, while CDG benefits from more competitive travel times of rail alternatives across a smaller route set. Two other airports with high-speed stations on through lines, DUS and LYS, also emerge as positive outliers (Fig. 15(f)), implying better-than-average rail performances and suggesting some potential for air–rail integration, especially on generated routes.

While the ARISP is to some degree positively related to connecting and potential passengers, it shows a weaker relationship with total passengers (Fig. 15(a), 15(b), 15(c)). This divergence highlights the critical influence of airline hubs: airports dominated by point-to-point or spoke flows, such as BCN, LGW, and MXP, offer limited scope for air–rail integration on substitutable (but not generated) routes compared to hubs with comparable total passengers, such as FRA, FCO, and

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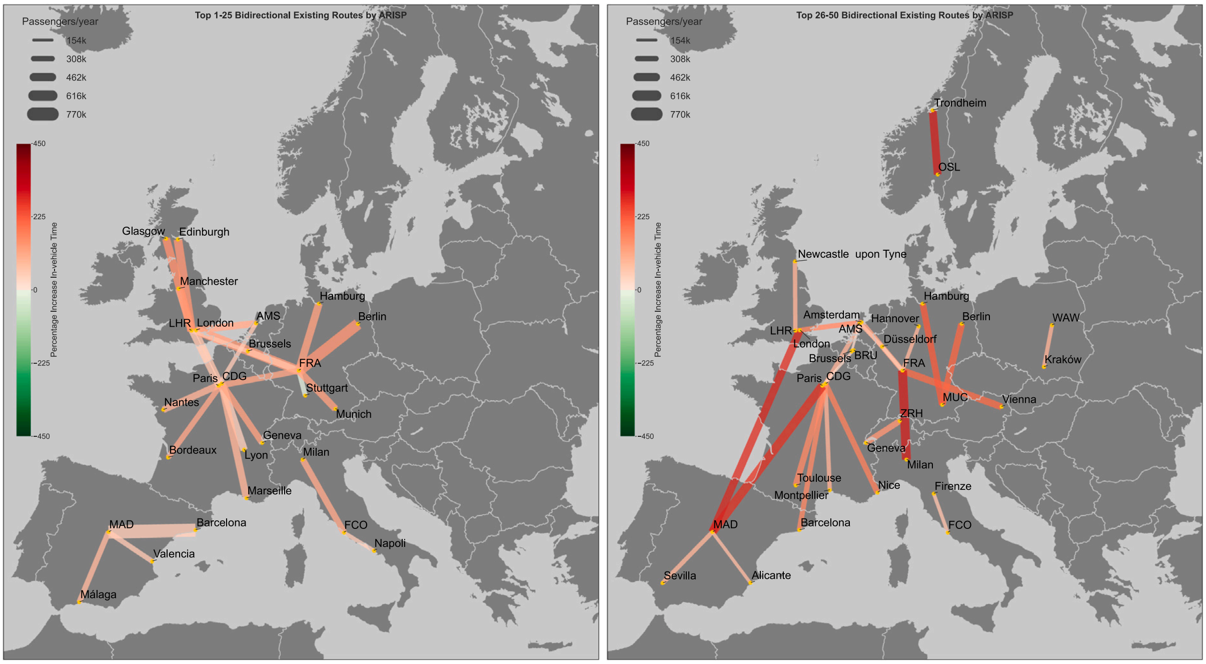
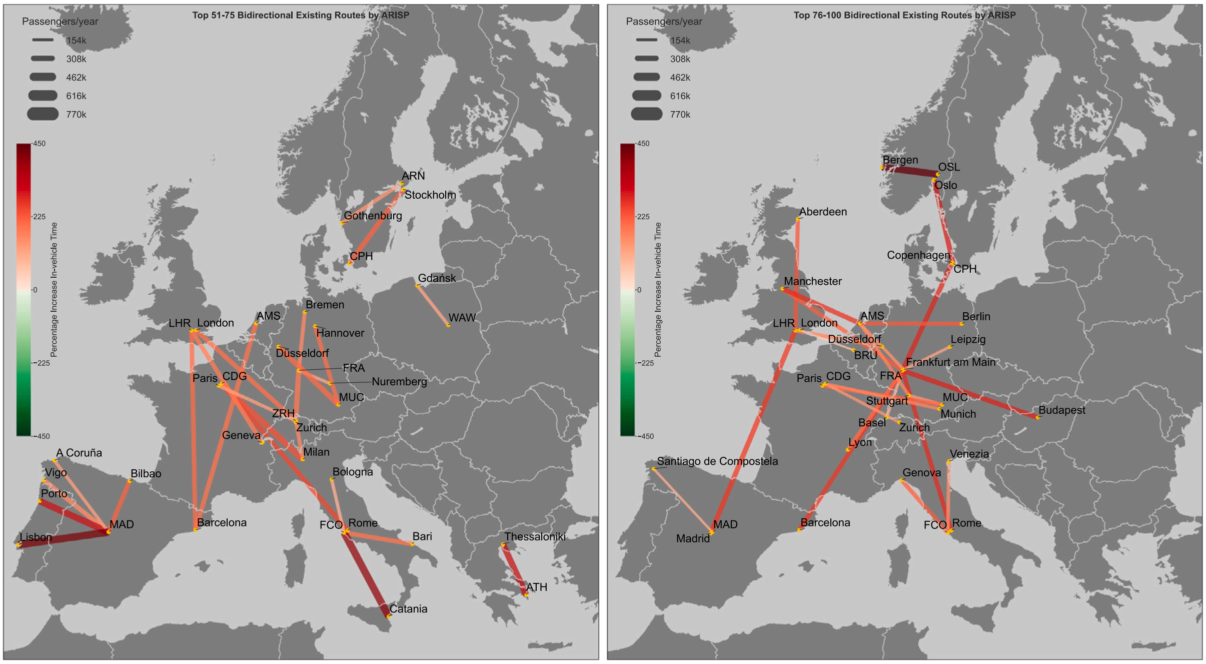
[7] George Best Belfast City (BHD) completely lacks alternative rail routes, Marche (AOI) and the Gdańsk Lech Wałęsa (GDN) lack alternatives with existing services, while Catania–Fontanarossa (CTA) and Palermo Falcone–Borsellino (PMO) lack alternatives connected by continuous rail infrastructure.



(a) Top 1-25 routes

(b) Top 26-50 routes



(c) Top 51-75 routes

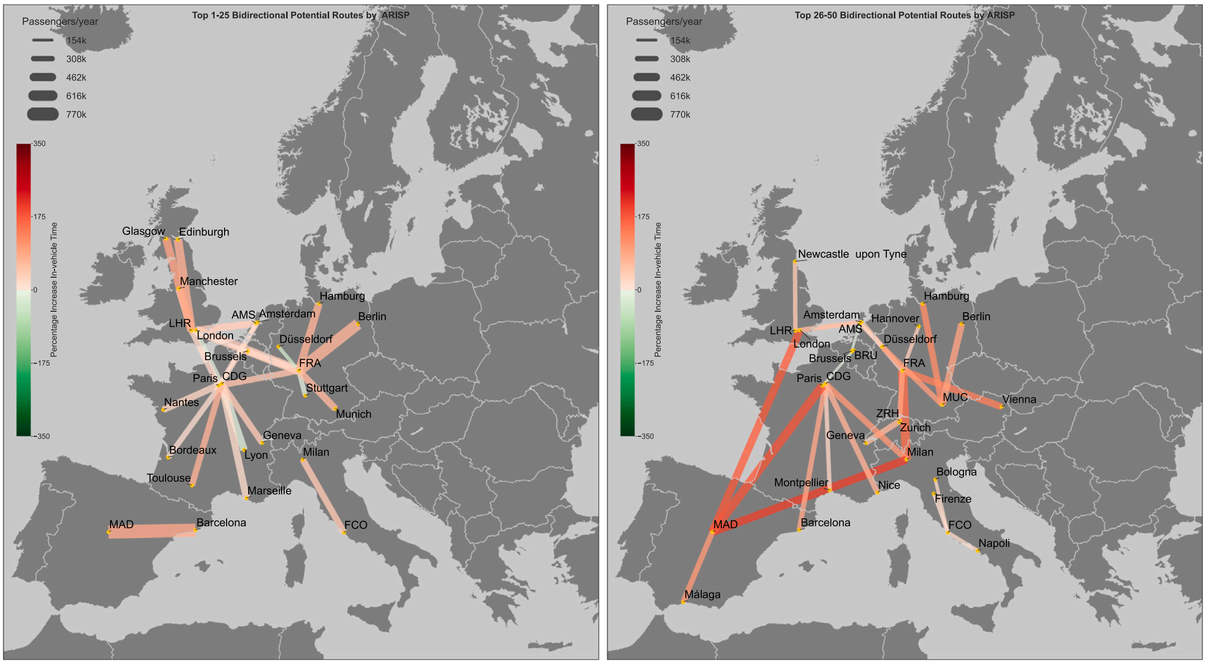
(d) Top 76-100 routes

Fig. 12. Geographical distribution of the top 100 existing bidirectional routes ranked by ARISP.

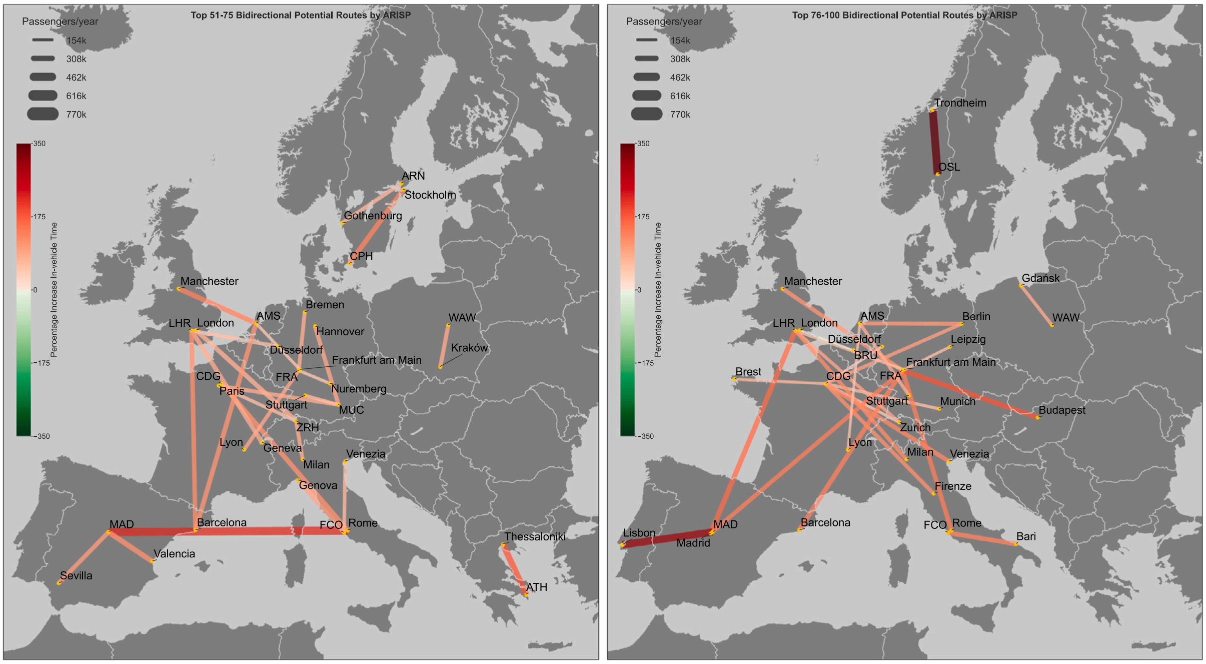
ZRH. Consequently, substitution potential for air–rail integration often remains highly concentrated in primary national hubs, such as FCO for Italy and LHR for the UK. Notably, in the UK, even STN outperforms LGW. Despite STN's lower connecting passengers overall, its higher volume of potential passengers, and consequently ARISP, are likely due to the stronger focus on the European market as opposed to the point-to-point intercontinental connections common at LGW.

However, airline hubs and high connecting flows are not a guarantee of high ARISP if rail alternatives are uncompetitive or absent, due to a lack of rail infrastructure and service provision at the airport. The large gap between potential and connecting passengers at hubs like LHR and Athens (ATH) is largely responsible for their underperforming ARISP compared to airports with similar connecting flows, such as FRA and CPH (Figs. 15(b) and 15(e)). For ATH, this gap is likely a byproduct of its geographical location at the edges of the European rail network, while infrastructural gaps penalise LHR's ARISP performance. Similarly, MUC's lower ARISP compared to CDG, despite comparable potential passenger volumes, reflects the burden imposed by its branch-line regional-services-only station on the travel times competitiveness of rail alternatives.

Finally, our findings demonstrate that even when high potential passenger volumes exist, an airport's ARISP performance depends on its location and functional role within the wider railway network. Despite boasting a high-speed station on a through line, AMS offers relatively poorer rail alternatives compared to MAD, which relies on a branch-line suburban station (see Fig. 15(c)). AMS' suboptimal rail performances



(a) Top 1-25 routes (b) Top 26-50 routes

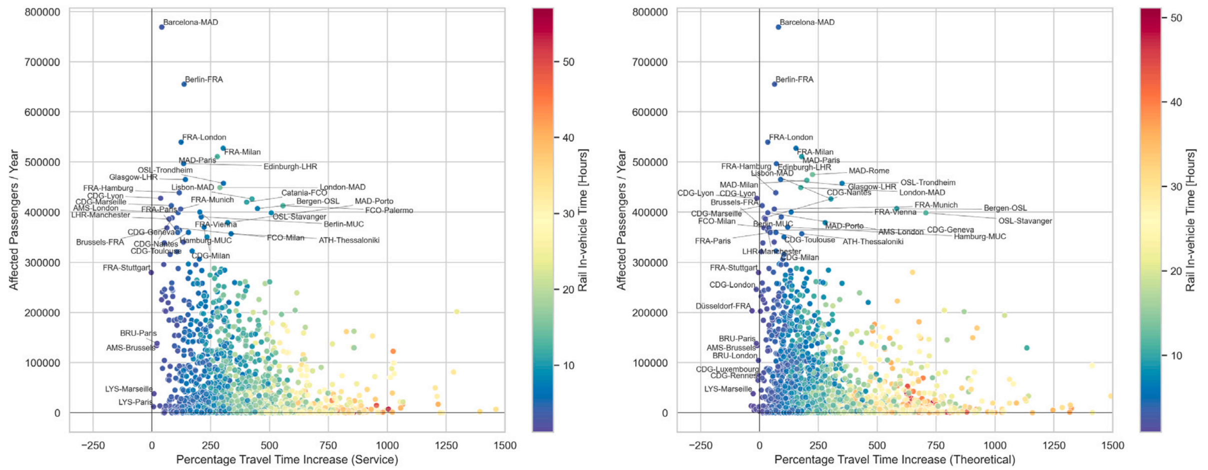


(c) Top 51-75 routes (d) Top 76-100 routes

Fig. 13. Geographical distribution of the top 100 potential bidirectional routes ranked by ARISP.

reflect the Dutch rail market orientation towards high-frequency regional traffic rather than long-distance connectivity, combined with its relatively peripheral location within the European HSR network. Similarly, the comparison between FCO and ZRH highlights the impact of network centrality. Despite the comparable ARISP and potential passengers, FCO's considerably higher connecting passengers suggest that the share of connecting passengers with viable rail alternatives is lower. By contrast, ZRH's greater share of hub passengers and more central location in the European rail network make it a slightly more attractive air–rail integration hub for substitution potential.

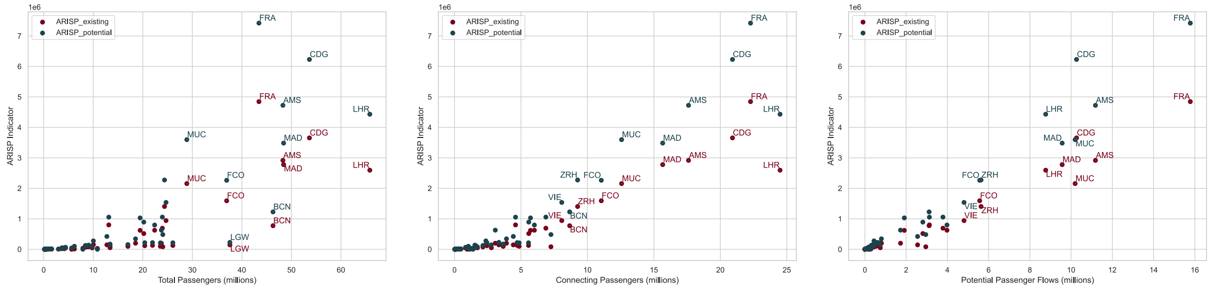
Fig. 16 maps the airports with the widest gap between existing and potential ARISP, revealing the airports most penalised by service travel times in relation to minimum running times enabled by existing infrastructure. The ARISP$_{existing}$-ARISP$_{potential}$ delta highlights the most strategic targets for enhancing direct rail service frequency. For instance, the relatively larger gaps at airports with similar passenger flows and function (e.g., ARN, as opposed to CPH and OSL, CDG, as opposed to AMS and MUC, and ZRH, as opposed to FCO and VIE) suggest wider improvement margins of existing rail supply through optimised scheduling or more direct services. Notably, while CPH benefits from its position on a major through-line to densely populated southern Sweden, ARN's location north of Stockholm imposes transfers for passengers arriving from the more densely populated south, resulting in a higher improvement margin. In line with the route distribution shown in Figs. 12 and 13, substitution potential remains concentrated



(a) Existing bidirectional routes

(b) Potential bidirectional routes

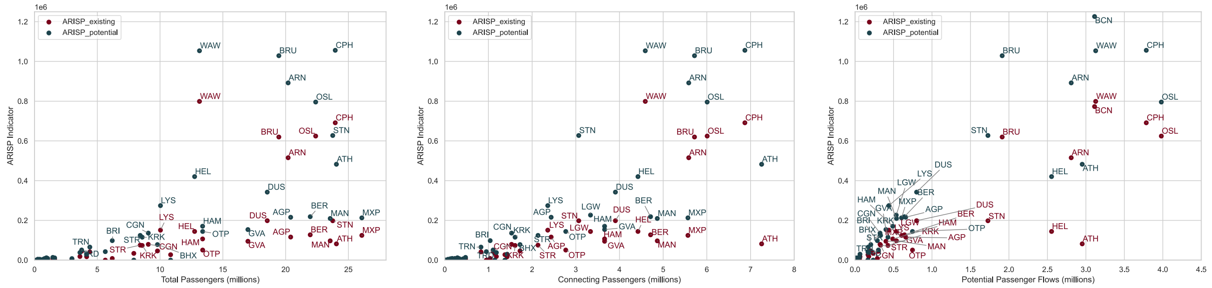
Fig. 14. Percentage increase in in-vehicle time and affected passengers in 2023 for bidirectional routes.



(a) Total Passengers in 2023

(b) Connecting Passengers in 2023

(c) Potential Passengers in 2023



(d) Total Passengers in 2023 (Zoomed)

(e) Connecting Passengers in 2023 (Zoomed)

(f) Potential Passengers in 2023 (Zoomed)

Fig. 15. Relationship between airports' $\text{ARISP}_{\text{existing}}$ and $\text{ARISP}_{\text{potential}}$, and yearly passenger flows.

at Western-Central European airports due to geographical centrality and the more limited rail infrastructure and services availability at Eastern European airports, with WAW standing as the sole exception.

6. Conclusion

In the last decades, European long-distance transport policies have increasingly targeted a modal shift from air to more environmentally friendly rail alternatives. One commonly discussed strategy involves promoting air–rail integration agreements to substitute short-haul flights. Despite prior research agreeing on its theoretical benefits (Givoni and Banister, 2006; Janic, 2011; Vespermann and Wald, 2011; Givoni, 2016), evidence on the scope for this remains limited. To address this gap, this paper proposes an Air–Rail Integration Substitution Potential (ARISP) indicator to explore the substitution potential of air–rail integration combining (i) the availability of alternative rail routes, (ii) their in-vehicle travel time competitiveness relative to air, and (iii) the size of the passenger markets on affected routes, based on empirically observed travel patterns.

Our findings suggest that the substitution potential of air–rail integration in Europe is severely constrained as of 2023. Competitive rail alternatives within double the travel time of existing air travel could realistically be offered to serve less than 1% of the 1.2 billion intra-European air journeys made through the 343 analysed airports across the EU, UK, Switzerland, Norway and Serbia in 2023. When considering minimum running times for rail, the passenger volume potentially affected would only rise from 9 to 29 million, still accounting for less than 2.5% of total intra-European demand. This indicates that while existing infrastructure theoretically provides some room to improve the attractiveness of air–rail integration, the overall scope remains fundamentally limited.

Rail infrastructure and train service availability are generally scarce across European airports, albeit consistently more prevalent at major hubs. Building on this, the extreme concentration of potential passenger demand on a limited number of core routes (and consequently

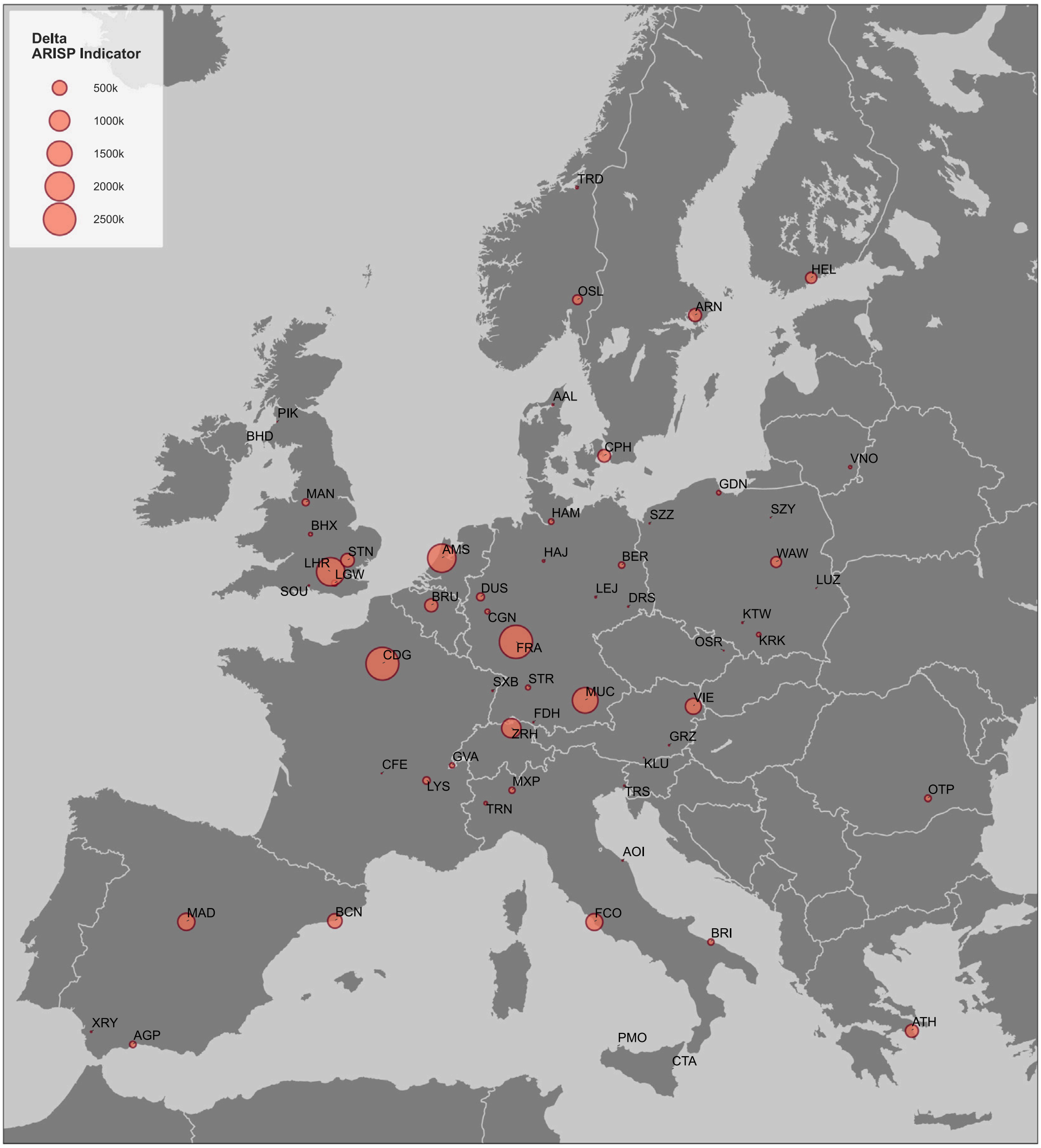


Fig. 16. Geographical distribution of the delta between airport-aggregated $\text{ARISP}_{\text{existing}}$ and $\text{ARISP}_{\text{potential}}$.

airports) means that the substitution potential of air–rail integration is highly localised. The ARISP indicator captures routes where considerable demand is accompanied by somewhat time-competitive rail alternatives, including the two routes with the largest potential passenger volumes (i.e., MAD–Barcelona and FRA–Berlin). Offering non-stop high-speed services between cities and airport railway stations on such high-demand routes could disproportionately increase the substitution potential, highlighting the potential for route-specific targeted approaches.

The ARISP indicator underscores the significance of rail infrastructure and service provision at airports, and highlights the crucial role of an airport's location within the European rail network, supporting the findings of Li et al. (2018). Airports located on through-lines of HSR networks (e.g., FRA, AMS and CDG) exhibit significantly higher potential than those on branch lines (e.g., FCO and MUC), as air demand alone would hardly justify the provision of high/frequency long-distance rail services. Furthermore, the geographical distribution of the substitution potential is strongly skewed towards Central and Western Europe, with concentrations around major hubs, such as FRA, CDG and AMS. Eastern Europe, except for WAW, remains hampered by the absence of major hubs and substandard rail connectivity. In specific cases, infrastructural barriers, such as the gap between the Iberian-gauge rail at MAD and the standard-gauge Spanish high-speed lines, represent a considerable constraint that service improvements alone cannot overcome.

The predominance of extremely uncompetitive in-vehicle times suggests that, at least in Europe, it is unrealistic to expect air–rail integration alone to reshape the long-distance transport landscape and enable the European Commission's ambitious environmental targets to be met. The results suggest that air–rail integration should not be framed or promoted as a decarbonisation strategy, but rather as a means to enhance connectivity and accessibility. Considering its relatively low implementation costs and the broader benefits for airports, airlines, and passengers, it may still be worth pursuing related policies. However, if limiting aviation's environmental impact is the policy priority, air–rail integration at capacity-constrained airports can only be justified as a strategic enabler for no-expansion policies when complemented by the environmental measures (e.g., airport capacity or long-haul flight caps) required to prevent the redistribution of freed slots.

7. Limitations and future research

This study proposes a systematic, data-driven framework for assessing the substitution potential of air–rail integration. To maximise interpretability and comparability, the ARISP indicator deliberately prioritises simplicity and transparency by focusing on in-vehicle time ratios and passenger demand alone. Future research could enhance the indicator's realism by incorporating other determinants of substitution potential, such as market concentration and other GTC components (e.g., prices). Furthermore, the comprehensiveness of the analysis could be improved by accounting for heterogeneity in mode preferences across trip purposes (i.e., leisure and business) and expanding the spatial scope to include airports connected to railway via urban rail or bus.

A key assumption of the indicator formulation is that out-of-vehicle time components (i.e., access time, waiting time, transfer time, and egress time) are comparable for the air and air–rail integrated travel alternatives when the railway station is located at the transfer airport. Although this assumption is justified by the strategic research objectives of this study, mode substitution ultimately depends on the GTC of door-to-door alternatives. Consequently, future research aiming to quantify air-to-rail modal shift may explicitly model demand distribution across airport catchment areas to disaggregate the spatial distribution of origins and destinations within metropolitan regions (Kinene and Birolini, 2024).

Furthermore, the existence of a few high-demand air routes where rail alternatives are reasonably competitive and air–rail integration agreements are already in place raises questions about the factors hindering the modal shift. These cases warrant further investigation into rail capacity constraints, operators' willingness to cooperate, fare differences and passenger preferences, including baggage handling and personal attitude towards flying, and how they affect supply and demand dynamics on such routes. The ARISP indicator also highlights margins offered by existing rail infrastructure to reduce travel times. Future research may investigate existing barriers to operating non-stop services to airports and the extent to which running time supplements can be safely reduced to ensure the competitiveness of rail alternatives against flights.

The systemic impacts of air–rail integration also warrant further exploration. On high-ARISP routes connecting congested hubs, modal substitution may inadvertently increase GHG emissions if freed slots are reallocated to long-haul flights. Future research should model the potential slot release and the subsequent reallocation of air supply under various supply–demand contexts (e.g., capacity-constrained or -unconstrained airports) and regulatory frameworks (e.g., complementary environmental measures and policies). Incorporating the resulting environmental, economic and accessibility impacts into comprehensive cost–benefit analyses would allow for a robust evaluation of the attractiveness of air–rail integration in different scenarios, as well as the long-term impact and economic feasibility of specific investments.

Finally, future research should delve beyond substitutable routes to measure the potential for air–rail integration on generated routes, perhaps integrating both into a single, comprehensive indicator. Generated routes raise fewer competitive concerns and avoid slot-reallocation concerns at capacity-constrained airports, although their feasibility may require additional investments, particularly for PtP networks. Our results indicate that while the infrastructure and services needed to support air–rail integration are generally in place at major hubs, they remain limited or absent at many smaller airports, with a few notable exceptions.

CRediT authorship contribution statement

Francesco Bruno: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Oded Cats:** Writing – review & editing, Supervision, Methodology, Investigation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The dataset supporting the findings of this study is publicly available in the 4TU.ResearchData repository at https://doi.org/10.4121/f045231a-a153-43cb-a5b2-9b37f4528ccf.

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