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Exploring impacts, capacity requirements and policy implications

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Replacing short-haul flights with train travel: Exploring impacts, capacity requirements and policy implications

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ABSTRACT

Short-haul Flight (SHF) bans aim to stimulate the air-to-rail modal shift, consequently curbing the aviation sector's environmental impact. We investigate the potential implications of various SHF ban policy designs on CO_2-equivalent (CO_2e) emissions, passengers' travel times and rail capacity under the assumption of full air-to-rail modal substitution. Ranging from 0.4 Mt to 7.5 Mt CO_2e, respectively 0.6% to 12.3% of the emissions of commercial intra-European aviation, the environmental impact of SHF ban policies is shown to be largely dependent on the policy design, namely the affected journey types and rail in-vehicle time thresholds. Our findings underscore the significant challenges of implementing such policies for the longer rail in-vehicle time thresholds and wider geographical scopes associated with noticeable environmental benefits. Despite the marginal impact of SHF ban policies on capacity utilisation in the case study, considerable interventions on rail infrastructure would be required to absorb existing air demand completely while ensuring attractive schedules. The results contribute to the ongoing policy debate, providing actionable insights to support Europe's ambitious environmental goals in the transport sector.

1. Introduction

Over the past two decades, environmental concerns have increasingly taken centre stage in the public, planning and political discourses. Seeking to reduce the anthropogenic impact on global climate, the European Commission (2020) aims to cut Greenhouse Gas (GhG) emissions by 55% compared to 1990 levels before 2030, reaching net zero by 2050. In a context where GhG emissions are generally decreasing, the transport sector appears to be going against the trend (Eurostat, 2021a,b), being currently responsible for about a quarter of the EU's total GhG emissions and growing (EEA, 2023b). Thus, to achieve these ambitious targets, a drastic reduction in transport-related GhGs to 90% of 1990 is required by 2050 (European Commission, 2020).

Air transport, in particular, sees the most conspicuous growth in emissions, with an 84% increase between 1990 and 2022 (EASA, 2024), and a 2.7-fold rise projected between 2025 and 2050 (Gelhausen et al., 2025). In 2022, the aviation sector accounted for 13.9% of the total transport GhG emissions, making it the second most polluting mode after road transport (European Commission, 2023). At the same time, the World Tourism Organization (2018) highlights that demand for long-distance travel (i.e., trips longer than 100 km) has soared dramatically, especially in the air and road sectors, with this trend projected to continue climbing (Limtanakool et al., 2006). In 2009, the long-distance market was responsible for 55% of the continent's passenger-km despite only representing 2.5% of all European trips (Petersen et al., 2009). Thus, ambitious measures addressing long-distance transport are required to limit the impact of air and road transport on the environment.

In an effort to reduce the GhG emissions of short-haul flights (SHF) of up to 800 km, the European Commission (2011) outlines the strategy of increasingly shifting passengers to rail, targeting by 2050 to have a majority of medium-distance passengers travelling by rail. Rail is widely viewed as a viable substitute, coupling comparable travel conditions (e.g., travel times, travel costs and level of service) with reduced environmental impact (Grimme and Jung, 2018). The energy requirements per seat/km of high-speed and conventional rail alike are considerably lower compared to aviation (Dalla Chiara et al., 2017). Despite aviation's higher, on average, load factors contributing to reducing this efficiency gap, this does not completely bridge the energy requirements gap. Furthermore, rail is, in many cases, directly powered by electricity,

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imposing lower emissions per energy unit than aviation's fossil fuel-powered combustion engines. These considerations are limited to direct operational emissions, as life cycle assessments (LCA) of air and rail transport are notably underexplored in existing literature (Jiang et al., 2021). In this regard, Westin and Kågeson (2012) find that considerable traffic volumes (i.e., more than 10 million one-way trips per year) are required to offset the emissions due to rail infrastructure construction and that most diverted passengers must come from aviation. Furthermore, Chen et al. (2021) show that the additional CO_2 emissions generated from HSR infrastructure construction and vehicle manufacturing on the Beijing–Shanghai corridor can be compensated only after 26 years of HSR operations. Thus, accounting for the entire life cycle would likely diminish, yet not exhaust, the environmental advantages of rail, as rail operations represent the major source of GhG emissions (Jones et al., 2017). Moreover, Zhang et al. (2019) highlight the importance of accounting for the effects of induced/generated travel demand other than the modal substitution effects when assessing the environmental impact of rail. Givoni and Dobruszkes (2013), through a review of ex-post evidence on HSR demand, estimate that about 20% of the HSR demand a few years after its introduction is induced demand.

Despite the extensive set of initiatives and measures undertaken by the European Union over the last decade, their implementation has proven more challenging than expected, and the air-to-rail modal shift is still not happening at the desired pace (Witlox et al., 2022). Growing environmental concerns have, consequently, pushed different governmental bodies across Europe to take action following three main approaches to aid rail in substituting SHF: introducing additional taxes for flights within specific ranges (i.e., below 500 km in Belgium and 350 km in Austria), banning all those flights where rail alternatives are available within defined time limits (i.e., 2.5 h in France and 3 h in Austria) or increasing competitive pressure on the air sector by opening the rail market to competition and leveraging the substitution dynamics of the free market (Dobruszkes et al., 2022).

Past studies have investigated the impact of such approaches on the transport market to guide future policy development. Clewlow et al. (2014) find that despite the entrance of more competitive high-speed rail (HSR) in the long-distance market contributed to reducing the number of respective air passengers, the growth of low-cost airlines has caused a greater surge in air passenger traffic. This suggests that more stringent interventions might be required, leading researchers to investigate the implications of SHF bans. Concentrating on routes with available rail alternatives (Szymczak, 2021) analyses the impact of a SHF ban on European airports, whilst (Avogadro et al., 2021) broadens the scope to encompass other alternative transport modes, including but not limited to rail. The former concludes that a SHF ban with a threshold below the 4-h travel time of the rail alternative would hardly affect related emissions, suggesting that a 5-h threshold (or above) would be required to reduce aviation emissions effectively. The impact of such thresholds on passengers, however, is only examined by the latter study, which concludes that 63 million (7.2%) intra-European trips could be replaced with an increase of up to 20% in travel time, causing an estimated 4.72% drop in related CO_2e emissions. The authors further argue that, despite the several critical questions and issues raised by its implementation, such policies would bring the EU closer to its ambitious environmental goals. At the national level, Reiter et al. (2022) assess the impact of a potential SHF ban in Germany, focusing specifically on minimum shares of connecting passengers, estimating between 4% and 13% growth in rail demand. In the Finnish context, Baumeister (2019), and Baumeister and Leung (2021) evaluate the emission reduction potential of substituting domestic SHF with land-based alternatives and non-HSR, respectively. At the route level, Cantos-Sánchez et al. (2023) including both cars and rail as alternative modes, model the supply and demand dynamics in the event of a SHF ban, concluding that these policies are detrimental to social welfare due to the increased externalities caused by passengers switching from air to car transport. In particular, the two case studies in Spain suggest that SHF bans always impose losses to society, despite lowering the external environmental costs in some cases. Research also focused more broadly on the potential environmental benefits of an air-to-rail modal shift. Employing a methodology rooted in environmental and behavioural sciences, Morfeldt et al. (2023) estimate the carbon footprint effects (i.e., in terms of CO_2e) related to future mode shifts from flights to night trains for Swedish tourism.

While past studies highlighted the environmental advantages of policy measures banning SHF, the network-wide feasibility of their implementation has not been directly addressed or evaluated insofar. In particular, it is unclear whether the anticipated positive environmental benefits, at the premise of this policy intervention, can be achieved in light of the constraints imposed by rail capacity, and if so, what burden reaching these benefits would impose on passengers' travel times. Consequently, this study explores the potential implications of a set of SHF bans on the environment, travel times and rail capacity under the limit case of a complete air-to-rail modal shift, where air demand is assumed to be entirely substituted by rail alternatives in response to the policies. Thus, this study does not aim to forecast the impacts of SHF ban but rather serves as a stress test of such policy measures. The results provide conservative insights into the best-case scenario policy outcomes, thereby offering a plausible upper bound of the associated environmental and travel time impacts and illustrating potential capacity constraints. To the best of our knowledge, this is the first study to consider the influence of different policy design features (i.e., affected journey types and rail in-vehicle time thresholds) on the impact of SHF bans and to evaluate their implications on network-wide rail capacity utilisation. This study evaluates the impact of a set of policy designs on the trade-offs between CO_2e emissions and passengers' travel times imposed by SHF bans. Understanding the range of such trade-offs can aid policymakers in fine-tuning existing policies and designing future policies that properly align with their social, economic and environmental goals.

To bridge this gap, we address the following research questions:

1. What is the best-case scenario contribution of various SHF ban policies to curbing the GhG emissions of the European aviation sector?
2. How would different policy designs affect passengers' travel times, and what are the trade-offs between reducing travel time losses and curbing emissions?
3. To what extent is rail infrastructure currently capable of absorbing the air-to-rail modal shift in demand?

We first provide an overview of the potential impact of a set of policy designs by identifying the intra-European air routes with viable rail alternatives. We then estimate the number of additional train services required to supply the air demand affected by the SHF ban in its entirety. In light of our research questions, we assess the social and environmental impacts of SHF ban policies in terms of generalised travel time savings (GTTS) and CO_2e savings resulting from the imposed modal shift. The former represents the level of service and accessibility for passengers, while the latter captures the externalities generated by transport activities. Finally, we exemplify the analysis of limitations posed by current infrastructural constraints for the Swedish case (including international connections to Oslo and Copenhagen), accounting for the consequences of the additional train services on railway infrastructure capacity utilisation. The results provide valuable insights for refining existing SHF bans and shaping future policy measures targeting the air-to-rail modal shift in Europe to meet the ambitious environmental goals set by the European Commission.

The remainder of this paper is structured as follows. The methodology, including the analysis' approach, scope and steps, is described in Section 2. The results are illustrated in Section 3 and discussed in light of assumptions and limitations in Section 4. Finally, Section 5 presents the conclusion of this paper.

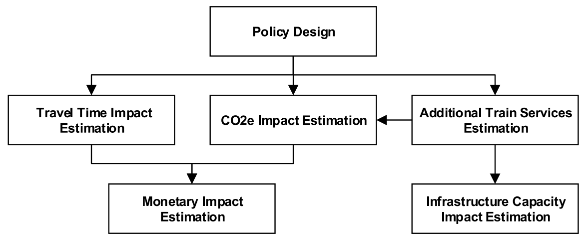


Fig. 1. Overview of the research steps.

2. Analysis approach, scope and steps

The European Union aims to shift continental long-distance passengers from air to rail alternatives. To stimulate the air-to-rail modal shift, in May 2023, the French government implemented a SHF ban targeting passengers on domestic (as opposed to international) routes where rail alternatives below two-and-a-half hours are available (Le Monde, 2023). Later that year, the proposal for a similar policy was also approved in Spain (El País, 2023; Climática, 2024). Following the footprints of France, a Union-wide SHF ban could be proposed to curb CO_2e emissions from long-distance transport. This exploratory study employs a stepwise approach to investigate the impact of a series of SHF ban policy designs on the environment and passengers' travel times at the broader European level. A narrower Swedish case study (including international lines to Copenhagen and Oslo) is employed to identify the constraints imposed by rail infrastructure capacity. The decision to target a more limited geographical scope for the latter is driven by the fragmented practices and applications of capacity utilisation computation methods across different European countries. Assessing the infrastructure capacity at the European level would have required considerable additional data and efforts to harmonise the procedures employed by each country. The proposed stepwise approach is illustrated in Fig. 1. The following subsections discuss the policy design and describe the data and the methods employed.

2.1. Policy design

There are many possible approaches for the design of SHF ban policies. Recent proposals include the weighted increase of travel time (Avogadro et al., 2021) or the minimum shares of connecting passengers (Reiter et al., 2022). However, to keep this study as close to reality and practice as possible, we focus on analysing variations of the sole SHF ban policy implemented to date: the French SHF ban (Le Monde, 2023). The French SHF ban affects all domestic routes where the corresponding rail in-vehicle time is below 2:30 h. However, French authorities decided to restrict the ban to three routes (i.e., between Paris-Orly and Bordeaux/Nantes/Lyon) only, excluding five other routes that do meet in principle the conditions defined in the policy (European Commission, 2022). The routes between Paris-Charles de Gaulle and Bordeaux/Nantes are excluded as more than 2:30 h are required to reach the Paris-Charles de Gaulle airport station via rail (European Commission, 2022). On the other hand, the routes between Paris-Charles de Gaulle and Rennes/Lyon and Lyon-Marseille are excluded due to existing rail services not allowing passengers to connect in Paris-Charles De Gaulle Airport, arriving early enough in the morning or departing from there late enough in the evening (European Commission, 2022). Thus, the policy specifically targets direct (as opposed to connecting) passengers, excluding feeder routes. Following the definition of the French SHF ban, three key design variables directly influencing its scope and impact can be identified: affected journey type (i.e., direct non-connecting passengers), jurisdictional scope (i.e., domestic flights) and maximum in-vehicle time of rail alternatives (i.e., 2:30 h threshold). In light of this, we consider two sets of policies based on the example of the French SHF ban. "Partial SHF ban" or "partial substitution", whereby the ticket types airlines are allowed to sell on the flight routes affected by the ban are restricted to connecting passengers only. This is a twist in the practical application of the French policy that aims to preserve its main drive of targeting direct passengers while effectively preventing connecting passengers from being negatively affected. "Full SHF ban" or "full substitution", on the other hand, extends the scope of the French SHF ban, indiscriminately affecting all passengers and flights on impacted routes". Unlike the French policy, we assume that all policies have international jurisdiction, meaning that domestic and international flights are equally subject to the SHF ban. Furthermore, in comparing and estimating the impact of each policy design, we distinguish between 4 incremental thresholds affecting the magnitude of the SHF ban scope. The lower and upper boundaries are set at 2:30 and 6:30 h, respectively. The former reflects the threshold used in the French ban, whereas the latter is defined based on the possibility for rail to guarantee comparable perceived door-to-door travel time and level of service. The remaining two thresholds are defined based on the point at which cumulative GTTS-related benefits from the full SHF ban begin to stagnate near zero and the point at which its total cumulative benefits transition from positive to negative. These points are derived from the cumulative benefit per rail alternative in-vehicle time, illustrated by Fig. 5, and are set at 4 and 5:30 h, respectively.

2.2. Data

The required data pertains to four main categories: air service characteristics (i.e., air travel supply), passenger flows (i.e., air travel demand), travel times, and current capacity utilisations on rail networks. Data covering all scheduled flights for the year ranging from the 15th of November 2023 to the 14th of November 2024 between the selected airports was collected through the Official Airline Guide (OAG) Schedules database. The available data includes flight number, carrier, scheduled flight times, departure/arrival time, aircraft type and offered seats. Routes and frequencies were, thus, derived per unique origin–destination airport pair. Passenger flow data covering the realised traffic for the year 2023 was retrieved through OAG Traffic Analyser. Traffic Analyser is a data analysis tool that provides the segmented number of passengers per passenger journey type (i.e., local, behind, beyond and bridge). As a reference, across the European case study, the shares of passenger journey types vary from just below 1% for bridge passengers to around 13.5% for behind and beyond passengers, and just above 72% of the passenger journey types being local. Travel times were collected through multiple sources. Rail in-vehicle times are retrieved from the planned travel time provided by the journey planner Rome2Rio (2024). In the case of multiple train services with different travel times on the same OD pair, the one yielding the shortest time is selected. Travel times between centroids/urban areas and airports were collected through Google Distance Matrix API (Google, 2024), using car as the transport mode. All these data sources have been widely used by previous studies in the field and throughout academia in general (Avogadro et al., 2021; Reiter et al., 2022; Avogadro and Redondi, 2023; Szymczak, 2021; Dobruszkes et al., 2022; Seymour et al., 2020). Finally, the characteristics of the rail infrastructure (i.e., stations, line sections) and services (i.e., type of service and daily frequency) on the Swedish (including Copenhagen) and Norwegian rail networks have been provided respectively by the Swedish Transport Administration (Trafikverket) and the Norwegian Railway Directorate (Jernbanedirektoratet). It is interesting to note that the two governmental authorities employ different thresholds to categorise capacity utilisation. Given the scope of the research, the Swedish thresholds and data structure are used as the standard, and the Norwegian data is harmonised to be comparable.

2.3. Analysis scope

This study examines a set of 343 European airports, connecting 328 unique urban areas in 29 European countries. This includes 25 of the 27 EU member states (i.e., Cyprus and Malta are excluded due to the absence of rail alternatives) plus Norway, Serbia, Switzerland and the United Kingdom. Only airports with regular commercial traffic are included in the analysis. To analyse the alternative rail routes available to passengers, airports are mapped to urban areas using distance, urban area population and airport naming as the main criteria. Urban areas are represented as centroids centred in their geographical coordinates, which were collected using the GeoPy library with the geocoding software Nominatim in Python. A centroid-based approach is employed under the assumption that passengers' preferred origins and destinations are evenly distributed in their surroundings. These are geographic centroids and, as such, do not account for the population distribution within the urban area. The geographic and population-weighted centres may vary in reality for polycentric (e.g., London, Paris), coastal (e.g., Barcelona, Genova) or mountainous (e.g., Bilbao, Innsbruck) urban areas. Furthermore, we assume that the relevant train stations are located in proximity to the geographical centroids. Conversely, airports are treated individually, considering the specific access/egress travel times to their respective centroids. While introducing some imprecision, both assumptions are considered reasonable for the purpose of this analysis. Urban areas and airports exhibit a one-to-many relationship, meaning that urban areas can be connected to more than one airport. In contrast, airports are connected to only one urban area. Although we consider this assumption to have a limited impact in most cases, it becomes more problematic in demographically dense regions where multiple urban areas and airports are clustered. Some exceptions where this assumption especially constrains accuracy are regional airports (e.g., Weeze Airport, Bergamo Orio al Serio Airport, Charleroi Airport) and multi-city airports (e.g., Rotterdam-Den Haag Airport, Maastricht Aachen Airport, Karlsruhe/Baden-Baden Airport and Schiphol Airport). This assumption is employed to limit the modelling complexity and data requirements imposed by identifying the actual origins and destinations of the passengers. Airport catchment areas are particularly complex to model because they depend on many variables, including frequency, distance, airline type (e.g., low-cost versus full-service carriers) of the specific air route and mode, travel time and cost available for the access/egress trips (Lieshout, 2012).

2.4. Estimation of travel time impact

Let us consider two urban areas, origin i and destination j, each with a train station, r and s respectively and a set of airports, O and D respectively, where $O = \{o_1, o_2, \ldots, o_n\}$ and $D = \{d_1, d_2, \ldots, d_n\}$, as illustrated by Fig. 2. To estimate the GTTS of cancelling a certain flight route od where an alternative rail route rs connecting the same OD pair ij is available, door-to-door travel times are considered. Door-to-door travel time is composed of in-vehicle and out-of-vehicle travel times, where the former represents the elapsed time of the main leg whilst the latter's definition depends on the passenger journey type. We consider four types of passenger journeys flying between o and d: (1) point-to-point passengers, originating at o with final destination d, (2) behind passengers, connecting (transferring) in o with their final destination being d, (3) beyond passengers, originating at o and connecting in d on their way towards their final destination or a second transfer location, and (4) bridge passengers, who connect in both o and d with trip origin and destination located behind and beyond, respectively. Out-of-vehicle travel time for point-to-point passengers is calculated as the sum of access a, egress e and wait w, where waiting at the origin airport w_o includes check-in and security procedures, and wait at the destination airport w_d includes baggage collection. Fig. 3 illustrates the segmentation of the considered trips per passenger type and transport mode. The literature widely agrees that subjectivity

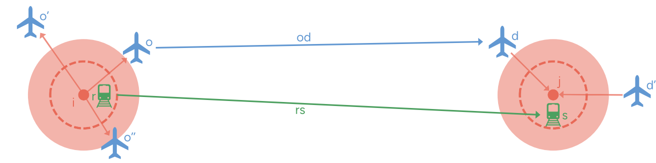


Fig. 2. Illustration of air and rail connections for a city pair.

plays a crucial role in shaping passengers' experience of travel time savings (Banister et al., 2019; Ory and Mokhtarian, 2005; Brands et al., 2022). To capture passengers' different sensitivity/perception to in-vehicle and out-of-vehicle time components, travel time multipliers μ and ν are employed for wait and access/egress time, respectively. Despite the large consensus that perception of in-vehicle time varies across modes, mode-specific travel time sensitivities, such as the ones proposed by Malichová et al. (2022) and Cornet et al. (2022) – which would have further penalised air travel times – are not considered, in line with the general effort of keeping results conservative.

Given a set of origin airports O and a set of destination airports D associated with the origin i and destination j respectively, the total perceived door-to-door travel time for point-to-point passengers $t^{\cdot\cdot}_{ij,m}$ is, thus, calculated per travel mode m as follows:

$$t^{\cdot\cdot}_{ij,air} = \sum_{o\in O}\sum_{d\in D}[(\nu \cdot a_{io} + \mu \cdot w_o + ivt_{od} + \mu \cdot w_d + \nu \cdot e_{dj}) \cdot q^{\cdot\cdot}_{od}] \tag{1}$$

$$t^{\cdot\cdot}_{ij,rail} = (\nu \cdot a_{ir} + \mu \cdot w_r + ivt_{rs} + \mu \cdot w_s + \nu \cdot e_{sj}) \cdot \sum_{o\in O}\sum_{d\in D} q^{\cdot\cdot}_{od} \tag{2}$$

where ivt_{od} represents the in-vehicle time by air between airports o and d, ivt_{rs} represents the in-vehicle time using rail alternatives and $q^{\cdot\cdot}_{od}$ are the point-to-point passengers flying between airports o and d. Perceived door-to-door travel time for behind passengers t^{-}_{ijm} is calculated by adding for air a connection time at the origin airport c_o to allow for feasible connections, and for rail a buffer time b_o to allow for feasible intermodal connections and a terminal transfer time t from origin airport o to the respective rail station r:

$$t^{-}_{ij,air} = \sum_{o\in O}\sum_{d\in D}[(\mu \cdot c_o + ivt_{od} + \mu \cdot w_d + \nu \cdot e_{dj}) \cdot q^{-}_{od}] \tag{3}$$

$$t^{-}_{ij,rail} = \sum_{o\in O}[(\mu \cdot b_o + \nu \cdot t_{or} + \mu \cdot w_r + ivt_{rs} + \mu \cdot w_s + \nu \cdot e_{sj}) \cdot \sum_{d\in D} q^{-}_{od}] \tag{4}$$

Similarly, perceived door-to-door travel time for beyond passengers t^{+}_{ijm} is calculated by adding for air a connection time at the destination airport c_d, and for rail a buffer time at destination station b_s and a terminal transfer time t_{sd}:

$$t^{+}_{ij,air} = \sum_{o\in O}\sum_{d\in D}[(\nu \cdot a_{io} + \mu \cdot w_o + ivt_{od} + \mu \cdot c_d) \cdot q^{+}_{od}] \tag{5}$$

$$t^{+}_{ij,rail} = \sum_{d\in D}[(\nu \cdot a_{ir} + \mu \cdot w_r + ivt_{rs} + \mu \cdot b_s + \nu \cdot t_{sd} + \mu \cdot w_d) \cdot \sum_{o\in O} q^{+}_{od}] \tag{6}$$

Subsequently, perceived door-to-door travel time for bridge passengers $t^{\cap}_{ijm}$ is calculated by merging behind components at the origin and beyond components at the destination for each mode:

$$t^{\cap}_{ij,air} = \sum_{o\in O}\sum_{d\in D}[(\mu \cdot c_o + ivt_{od} + \mu \cdot c_o) \cdot q^{\cap}_{od}] \tag{7}$$

$$t^{\cap}_{ij,rail} = \sum_{o\in O}\sum_{d\in D}[(\mu \cdot b_o + \nu \cdot t_{or} + \mu \cdot w_r + ivt_{rs} + \mu \cdot b_s + \nu \cdot t_{sd} + \mu \cdot w_d) \cdot q^{\cap}_{od}] \tag{8}$$

Finally, the total perceived door-to-door travel time t^{tot}_{ijm} is obtained by summing the total travel time t_{ijm} per passenger-journey category:

$$t^{tot}_{ijm} = t^{\cdot\cdot}_{ijm} + t^{-}_{ijm} + t^{+}_{ijm} + t^{\cap}_{ijm} \tag{9}$$

In-vehicle times for air and rail are based on the scheduled flight times from OAG Schedules and the planned travel time from Rome2Rio, respectively. Access a_{io} and egress e_{dj} times, on the other hand, are set

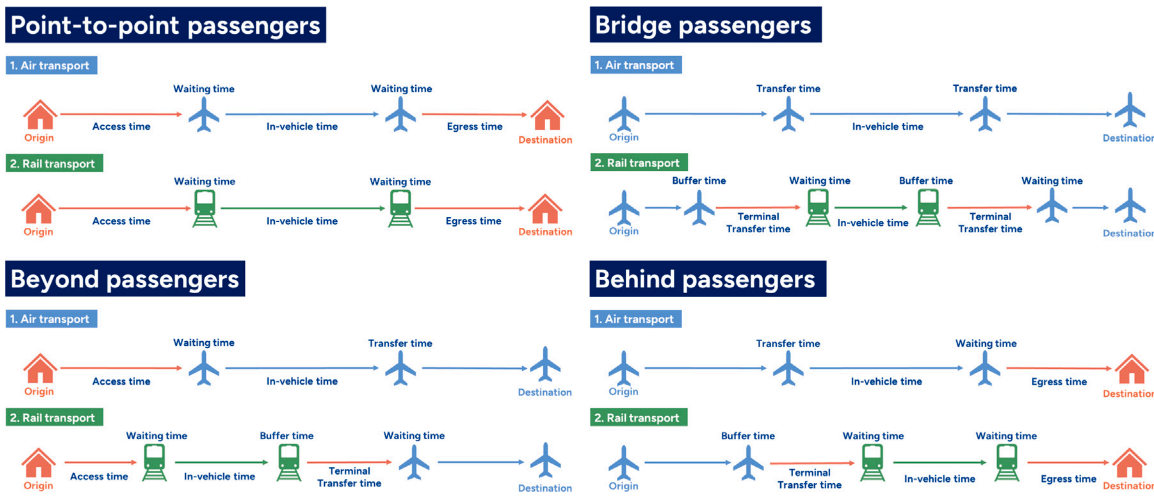


Fig. 3. Door-to-door travel time composition per passenger type per mode.

to the minimum travel time required to connect each centroid with the respective airport(s) by car. Not accounting for congestion (and for the share of passengers using PT), these are to be considered conservative estimates. Due to rail stations being often located in close proximity to the centroids, to avoid unrealistically low access a_{ir} and egress e_{sj} times, these are fixed to 15 min for all urban areas. For the same reason, we assimilate terminal transfer time from airport to rail station t_{or} to egress time for air and terminal transfer time from rail station to airport t_{sd} to access time for air.

In similar studies, such as Avogadro and Redondi (2023), departure waiting times are defined as minimum waiting times and set to the check-in desks' closing time (i.e., generally between 30 and 60 min). We take a different approach, employing waiting time values that could more realistically represent the average passenger behaviour. Thus, waiting times (w_o) at the origin airport are fixed to 120 min for large hubs and 90 min for medium and small airports, whilst waiting times at the destination airport w_d are set to 15 and 30 min, respectively. Conversely, waiting times at the origin (w_r) and destination (w_s) terminals for rail are fixed at 25 and 5 min, respectively. The air–rail ratios for waiting times appear to be in line with previous literature (Baumeister and Leung, 2021; Reiter et al., 2022; Avogadro and Redondi, 2023), despite the slightly larger magnitude of the parameters considered in this study. Minimum connecting time, the minimum time required to guarantee the connectivity of passengers and their baggage between consecutive flights, ranging between 45 and 90 min, is conventionally considered in the literature (Santos et al., 2017; Paleari et al., 2010; Redondi et al., 2011). Even in this case, we account for a more realistic situation rather than the limit case, assigning connecting times c_o, which represent the average transfer time scheduled between consecutive flights, to 120 min for large hubs and 90 min for medium and small airports. Airport buffer times b_o, capturing the buffer between a flight and the subsequent train service, are assimilated to connecting times due to their similarity. Buffer times at rail stations b_s, corresponding to the buffer required to ensure the connection between a train service and the following flight, are set to 50 min to account for possible train delays and the greater disutility of transfer time.

The values of the travel time multipliers μ and ν, employed in Eqs. (1) to (8), are set to 1.76 and 1.87 deriving from the estimates for inter-urban wait time and access time, respectively, of the meta-model developed by Wardman et al. (2016). Buffer times b and connecting times c are assimilated to wait time and thus also multiplied by μ whilst egress times e and terminal transfer times t are assimilated to access time and consequently multiplied by ν.

The impact of the SHF ban on travel time is measured in terms of GTTS in percentage and absolute terms. The former represents the percentage decrease in perceived door-to-door travel time and is calculated as:

$$GTTS^{\%}_{ij} = \frac{t^{tot}_{ij,air} - t^{tot}_{ij,rail}}{t^{tot}_{ij,air}} \cdot 100 \tag{10}$$

where $t^{tot}_{ij,air}$ and $t^{tot}_{ij,rail}$ are the perceived door-to-door travel times on route ij for rail and air respectively. The data is then aggregated by weighting the generalised travel time savings per route by the total number of passengers travelling by air q^{tot}_{ij} on route ij subject to the SHF ban:

$$GTTS^{\%} = \frac{\sum_{ij} q^{tot}_{ij} \cdot GTTS^{\%}_{ij}}{\sum_{ij} q^{tot}_{ij}} \tag{11}$$

Finally, $GTTS_{ij}$ represents the total number of passenger hours saved/lost on route ij by imposing the SHF ban:

$$GTTS_{ij} = t^{tot}_{ij,air} - t^{tot}_{ij,rail} \tag{12}$$

2.5. Estimation of additional train services

The number of additional trains v_{ij} required to serve all the passengers flying on each route affected by the SHF ban is calculated as follows:

$$v^{p}_{ij} = \lceil \left(\frac{q^{tot}_{ij}}{s^{p}} \right) \rceil \tag{13}$$

where s^p corresponds to the seat capacity of a train unit of type p. It is assumed that each train unit runs on a fixed wagon configuration with a specific number of seats, which cannot be decomposed. Consequently, the number of additional trains is always rounded up to the next integer value. Furthermore, the residual seat availability of the current rail supply and the possibility of coupling trains are not accounted for.

For the European case, we assume that the additional train services (v^{p}_{ij}) computed using Eq. (13) are to be consistently operated by intercity train unit type due to the lack of HSR services on many routes. The capacity of an average European Intercity train is set to 300 seats (Iraklis, 2018). On the other hand, for the Swedish case study, a specific train type p is assigned to each route ij based on the current usage from the Swedish railway undertaking SJ and on the business of the route. The rolling stock types included in this research are the X2000 (362 seats) and the X55 (245 seats) electric multiple units, the former being employed on all the routes using the two Swedish main lines connecting Stockholm to Gothenburg and Malmö/Copenhagen and the latter being employed on the remaining routes.

2.6. Estimation of infrastructure capacity impact

In this study, capacity utilisation is employed as a relevant measure to estimate the impact of the SHF ban on railway capacity. A wide range of methods and models is employed to estimate capacity utilisation, and their use tends to vary across countries. Weik et al. (2020) highlight that the International Union of Railways (UIC) guidelines are the reference standard for capacity assessments in international contexts. Considering this study's strategic and international scope, capacity utilisation is computed through the national adoptions of such UIC guidelines. In particular, Trafikverket in Sweden uses an adaptation of the UIC 406 method, while Jernbanedirektoratet employs a method rooted in the older UIC 405 method (UIC, 2004). The Swedish adaptation of the UIC 406 method and its approximations are described in more detail in Wahlborg (2004). Infrastructure capacity is computed by calculating the total utilised time per line section (i.e., "Linjedel" as per Trafikverket's definition) per day and dividing it by the daily time period for operations. In line with the operating times of short-haul flights and long-distance rail services, and with the parameters employed by Trafikverket (2024), we consider the operative time for train traffic to be 18 h/day, leaving 6 h/day for trackwork and maintenance. The additional rail services per day required on each route affected by the SHF ban are then added to the daily passenger traffic (consisting of commuter train services, freight trains and long-distance traffic) on all the line sections traversed by the route. For the top-two-hour analysis, the number of additional daily trains is divided by 9, assuming trains are operating and consequently occupying capacity evenly during the 18 h between 06:00 and 24:00.

Threshold-specific capacity utilisation rates are then estimated, accounting for the number of trains and the train types, without considering detailed timetables. In other words, the train mix is considered, whereas traffic heterogeneity is not. Hence, the estimated increase in capacity utilisation is not exact but is rather intended to provide an approximate indication in line with the strategic level of the analysis. Based on the percentage capacity utilisation, the most congested line sections are identified and categorised as either highly saturated (i.e., capacity utilisation between 60% and 80%), critical (i.e., between 80% and 100%), very critical (i.e., between 100% and 120%) or extreme (i.e., over 120%). In practice, capacity utilisations from critical or higher require timetable measures (e.g. reducing heterogeneity in terms of stops, top speed and time additions) to be operational and high values reflect a significant risk of delays (Abril et al., 2008).

It is worth noting that capacity utilisation is only measured for lines, excluding stations, as the additional trains are expected to affect mostly the former. This is due to the impact of SHF bans on Swedish infrastructure capacity being assessed assuming additional trains to run non-stop between origin and destination and pass through intermediate stations without dwelling, imitating and directly replacing the banned scheduled flights.

2.7. Estimation of CO_2e impact

Next to the impact on passengers' travel times and volumes and their consequences for rail capacity utilisation, we are interested in estimating the CO_2e emissions associated with passenger journeys for their main trip leg (i.e., either rail or air connection), which is the prime motivation for the SHF ban policy. The CO_2e impact of the SHF ban is calculated by subtracting the CO_2e of the additional trains from the CO_2e emitted by the banned flights. Two distinct methodologies are employed for estimating the CO_2e emissions associated with the two modes. The reference metric employed for air is the Fuel burnt F, and the one used for rail pertains to the Energy consumption E. The former metric is obtained using the Fuel Estimation in Air Transportation (FEAT) method developed by Seymour et al. (2020). This approach was chosen due to its accuracy, simplicity and repeatability, as corroborated by Sobieralski (2021), Sobieralski and Mumbower (2022), and Dobruszkes et al. (2022). A review of alternative methods for assessing fuel consumption against distance flown can be found in Dobruszkes et al. (2022). F_{ij} depends on two factors, the flight distance d_{ij} and the aircraft type y used for each flight f:

$$F_{ij} = \sum_f \alpha_y \cdot d_{ij}^2 + \beta_y \cdot d_{ij} + \gamma_y \tag{14}$$

Flight distance is defined as the great-circle distance between the origin and destination airport (computed using the GeoPy library in Python), as the FEAT method already accounts for average detours of flight routing (Seymour et al., 2020). Variations in fuel-burning patterns are introduced using the aircraft type-specific fuel-burning parameters $\alpha_y, \beta_y, \gamma_y$ defined by Seymour et al. (2020). Where these are unavailable (e.g., for newer aircraft types like the Airbus A320NEO Family), the parameters of the older version of the same aircraft type are used instead. In those cases, a multiplier (i.e., the ratio between the older and newer aircraft versions) is estimated from the Eurocontrol Smart Emitter Tool (SET) to adapt and fine-tune the parameters to the newer aircraft models. CO_2 emissions are calculated by multiplying the fuel burnt by the 3.16 kg CO_2 / kg fuel CO_2 CO_2 Emission Index EI recommended by Fleming and de Lépinay (2019). Finally, CO_2e emissions are derived through a 1.7 Emission Weighting Factor EWF, considering a Global Warming Potential with a 100-year time horizon (GWP100) as defined by Lee et al. (2021), in line with Åkerman et al. (2021). This factor captures all the effects of aviation on climate that are not CO_2-related, including Nitrogen Oxides (NOx), water vapour, sulphate and soot aerosols, linear contrails and aviation-induced cirrus cloudiness (Lee et al., 2010). The longer time frame (i.e., GWP100 as opposed to GWP50 or GWP20) is chosen to yield more conservative estimates, as higher EWFs are associated with shorter time perspectives (i.e., 2.3 for GWP50 and 4.0 for GWP20).

$$CO_2e_{ij}^{air} = F_{ij} \cdot EI \cdot EWF \tag{15}$$

Conversely, CO_2e Emissions for rail $CO_2e_{ij}^{rail}$ are calculated as a function of the energy consumption per route E_{ij} using a GhG Emission Factor EF:

$$CO_2e_{ij}^{rail} = E_{ij} \cdot \ EF \tag{16}$$

where the energy required to run the additional train services is estimated based on railway distance d_{ij}^{rail} and an Energy Usage factor EU^p:

$$E_{ij} = d_{ij}^{rail} \cdot s^p \cdot v_{ij}^p \cdot EU^p \tag{17}$$

Railway distance at the European level is measured using a railway detour factor defined by Kim and Wee (2011). For the Swedish case study, railway distance is computed considering the railway length of all the sections crossed by each route, based on the information provided by järnväg.net (2024). Following Morfeldt et al. (2023), the energy use factors per train type EU^p are defined according to the estimates of the energy simulation tool developed in the FINE1 EU project (Iraklis, 2018), considering a timetable with coasting and averaging the winter/summer and autumn/spring cases. The X2000 is assimilated to high-speed trains with a 250 km/h top speed, whereas intercity energy consumption values are considered for the X55. Finally, to translate the energy consumption into CO_2e emissions a GhG Emission Factor EF is defined. We consider a value of 251 g CO_2e / kWh for Europe, the Greenhouse gas emission intensity of electricity generation in 2022 according to EEA (2023a). For Sweden, the EF is set to 90.4 g CO_2e/kWh, the average GhG emission factor derived by Sandgren and Nilsson (2021) considering the used energy mix of the Nordic countries (i.e., Sweden, Norway, Finland and Denmark) for the years 2016–2018. Albeit Trafikverket, the Infrastructure Manager of Swedish rail, states that the energy supplied to trains in Sweden is "entirely produced by hydro-power" (Trafikverket, 2016), it is preferred to take into account the entire energy mix to provide more conservative estimates on the possible CO_2e savings. This follows the consideration that the energy used by the rail sector, as clean as it might be, is not available to other sectors that consequently have to rely on more GhG-intensive energy sources. In our analysis of CO_2e impacts, passenger journeys' access and egress legs are disregarded. In the absence of data on the modal split of access/egress trips per airport, any estimation is considered too assumption-heavy. To validate this choice, we examined the share of the CO_2e emissions associated with the access/egress parts of the journey CO_2e relative to the total journey emissions for a few case studies. Assuming an extreme case where all passengers access and egress airports using private vehicles or taxis (without sharing) for a few sample routes, access/egress-related CO_2e emissions consistently amount to less than 5% of the total journey emissions. Therefore, we conclude that, in contrast to the out-of-vehicle time component, the impact of the access/egress on the CO_2e of trips is marginal. Finally, this study only accounts for CO_2e emissions related to operations, whereas the entire life cycle emissions are beyond the scope of this study.

2.8. Conversion of travel time and CO_2e impact in monetary terms

Finally, to compare the impact of the SHF ban policy on the environment and passengers' travel times, GTTS and CO_2e savings are translated into monetary terms. Mode and purpose-specific VoTs for air travel estimated by Trafikverket (2023) for 2017 are deployed as GTTS multipliers and scaled to all other European countries using country-specific price level index (PLI) for transport services (Eurostat, 2023b). The currency is converted from SEK into EUR at 2017 exchange rates and adjusted for inflation to 2022 levels, using the country-specific harmonised index of consumer prices for transport services (Eurostat, 2023a; Office for National Statistics, 2023). The trip purpose is accounted for through leisure-specific VoTs for economy class passengers and business-specific VoTs for business class passengers. For international routes, the leisure and business VoTs are obtained by averaging the values of the origin and destination countries. On the other hand, the monetary value attached to CO_2e savings is based on the emissions allowances' price established by the EU Emission Trading System (ETS). Given the volatility of the emissions allowances' price established by the ETS, CO_2e savings are multiplied by an estimate of 90 €/t CO_2e, as between 2022 and 2023 the carbon emission price has generally been floating between 80 €/t CO_2e and 100 €/t CO_2e with a few exceptions only, mostly due to the breakout of the Russia–Ukraine war (Statista, 2023).

3. Results

3.1. Threshold-level analysis

First, the marginal impact of rail travel time thresholds is presented and analysed so as to highlight the influence of each incremental step individually. Table 1 provides an overview of the intra-European routes, flights, seats and passengers affected by the SHF ban for each marginal policy setting. The percentage values are calculated for flights which have both their origin and destination within the study area. The routes on average feature above-average frequencies and below-average aircraft seating capacity, suggesting that several feeder flights are affected by SHF-ban policies. Interestingly, the shares of feeder flights and connecting passengers are higher on shorter routes where rail offers more competitive travel times. A full SHF ban within 2:30 h would affect over 2.7 times as many flights and passengers as a partial ban. This share decreases to less than 2.3 between 2:30 and 4 h and further drops to around 1.4 for policy settings over 4 h. Thus, implementing policies aimed at substituting feeder flights (e.g., air–rail integration) could considerably impact the number of short-haul flights, especially on routes with up to 4 h of rail in-vehicle times. Within this threshold, almost 59% are, in fact, connecting passengers (i.e., over 16 million passengers a year). The number of connecting passengers more than doubles when considering a 6:30-h threshold, affecting nearly 38 million passengers a year (i.e., about 39% of the 97 million passengers flying amongst the selected routes in 2023).

These patterns are also reflected in the CO_2e savings illustrated by Table 2, along with the number of additional trains and GTTS. Depending on the threshold, CO_2e emissions would drop between 96% and 97% as a consequence of a full SHF ban. These shares include the increasing emissions caused by the additional rail supply required to serve the banned air passengers. The slight decline with increasing thresholds stems from longer flights' marginally higher fuel efficiency. Conversely, the percentage weighted reduction of CO_2e savings for a partial SHF ban would be limited to less than 50% below the 4-h threshold and amount to around 70% between 4 and 6:30 h. This implies that over half and one-third of the potential environmental benefits of the policy are lost with partial (as opposed to a full) substitution within a 4-h and 6:30-h rail in-vehicle time threshold, respectively.

Considerable differences between the two policies are also observed in terms of GTTS. The GTTS are positive only for the 2:30-h full substitution threshold, whilst extending up to 5:30 h for partial substitution. This is due to the larger additional costs in terms of travel time for connecting (as opposed to point-to-point) passengers switching to rail. The percentage GTTS indicates that travel times on average drop when switching from air to rail alternatives within the 2:30 h threshold. Travel time losses for full substitution are limited until up to 5:30 h, ranging roughly between 4% and 7%, while sharply rising beyond that point. This suggests that full SHF ban policies with rail in-vehicle time thresholds longer than 5:30 h would be hardly justifiable. On the other hand, partial SHF bans could be defended up to 5:30 h, preventing losses in generalised travel times for passengers.

Fig. 4 summarises the CO_2e-related, GTTS-related and Total (i.e., sum of CO_2e-related and GTTS-related) Benefits per rail in-vehicle time thresholds and policy design. Above the 2:30-h threshold, the considerable travel time losses make full SHF bans increasingly less appealing. In particular, considering the marginal impact induced by each threshold setting, the policy does not translate into enough environmental benefits to offset the additional travel time losses over the 4-h threshold. However, between 2:30 and 4 h, the monetary savings related to CO_2e emissions can compensate for most of the additional costs related to travel time losses. This allows us to conclude that policymakers may push the threshold up to around 4 h while attaining a break-even between the additional costs related to longer travel times and the benefits related to CO_2e savings when considering both in monetary terms. Despite the substantially lower environmental impact, partial substitution has a decidedly better outlook in terms of monetary benefits due to the greater order of magnitude of GTTS-related monetary benefits (as opposed to CO_2e-related). A partial SHF ban could be implemented for thresholds of up to 6:30 h with environmental benefits compensating for the GTTS costs.

When considering the cumulative impact of full substitution, shown in Fig. 5, higher thresholds (i.e., up to slightly below 5:30 h) for full SHF bans could be defended, as the benefits below that level almost completely compensate for the additional costs between 4 and 5:30 h. However, this requires accepting a degree of generalised travel time losses on certain routes. To investigate the uncertainty driven by the multipliers μ (Wait Time) and ν (Access Time), used to capture travel time sensitivity of out-of-vehicle time in Eqs. (1)–(8), we consider the standard error of the mean of the actual multipliers for inter-urban access time (0.10) and wait time (0.20) provided by Wardman et al. (2016). The areas between the upper and lower bounds of the GTTS-related benefits are illustrated as a light blue area in Fig. 5 with the baselines at their centre. The uncertainty of partial benefits is expected to be greater than that of full benefits when testing the sensitivity of the multipliers for out-of-vehicle time (including waiting, access, and egress). This is due to the differences in out-of-vehicle time components between rail and air being more significant in point-to-point passenger journeys (the only ones considered for partial substitution) as opposed

Table 1
Overview of the Routes, Flights, Seats and passengers affected per marginal policy setting at the European level.

Rail In-vehicle time threshold	Routes [#]	Flights Full [K/year][a]	Flights partial [K/year][b]	Seats full [M/year]	Pax full [M/year][a]	Pax partial [M/year][b]
≤2:30 h	34 (1.31%)	104.09 (3.06%)	33.75 (0.99%)	15.57 (2.85%)	11.09 (2.69%)	4.08 (0.99%)
2:30 < x ≤ 4:00 h	71 (2.74%)	181.35 (5.32%)	75.41 (2.21%)	24.45 (4.48%)	16.77 (4.07%)	7.32 (1.78%)
4:00 < x ≤ 5:30 h	138 (5.33%)	422.59 (12.41%)	277.59 (8.15%)	62.87 (11.52%)	46.25 (11.24%)	31.64 (7.69%)
5:30 < x ≤ 6:30 h	100 (3.86%)	216.86 (6.37%)	143.81 (4.22%)	31.18 (5.71%)	23.18 (5.63%)	16.29 (3.96%)

[a] Full refers to a SHF ban affecting all flights and passengers.
[b] Partial refers to a restriction affecting only point-to-point passengers (feeder flights for connecting passengers being excluded).

Table 2
Additional trains, CO_2e savings and GTTS per marginal policy settings at the European level.

Rail In-vehicle time threshold	Additional trains full [K/year]	Additional trains partial [K/year]	CO_2e Savings full [M kg/year]	CO_2e Savings partial [M kg/year]	GTTS full [M h/year]	GTTS partial [M h/year]
≤2:30 h	36.99	13.60	1036.05 (96.99%)	368.56 (46.66%)	10.01 (10.76%)	15.71 (48.17%)
2:30 < x ≤ 4:00 h	55.94	24.44	1715.66 (96.65%)	732.34 (49.11%)	−4.72 (−4.35%)	14.59 (27.69%)
4:00 < x ≤ 5:30 h	154.25	105.54	4694.72 (96.23%)	3161.09 (70.62%)	−19.49 (−6.63%)	29.88 (12.16%)
5:30 < x ≤ 6:30 h	77.32	54.35	2608.46 (95.81%)	1780.31 (73.11%)	−34.52 (−21.25%)	−6.53 (−6.83%)

Table 3
Additional trains, CO_2e savings and GTTS per cumulative policy settings at the European level.

Rail In-vehicle time threshold	Additional trains full [K/year]	Additional trains partial [K/year]	CO_2e savings full [M kg/year]	CO_2e savings partial [M kg/year]	GTTS full [M h/year]	GTTS partial [M h/year]
≤2:30 h	36.99	13.60	1036.05 (96.99%)	368.56 (46.66%)	10.01 (10.76%)	15.71 (48.17%)
≤4:00 h	92.94	38.04	2751.71 (96.78%)	1100.90 (48.23%)	5.29 (1.66%)	30.31 (35.02%)
≤5:30 h	247.19	143.58	7446.43 (96.44%)	4261.99 (64.69%)	−14.20 (−3.48%)	60.18 (18.26%)
≤6:30 h	324.51	197.93	10 054.88 (96.29%)	6042.30 (67.00%)	−48.72 (−7.74%)	53.65 (11.40%)

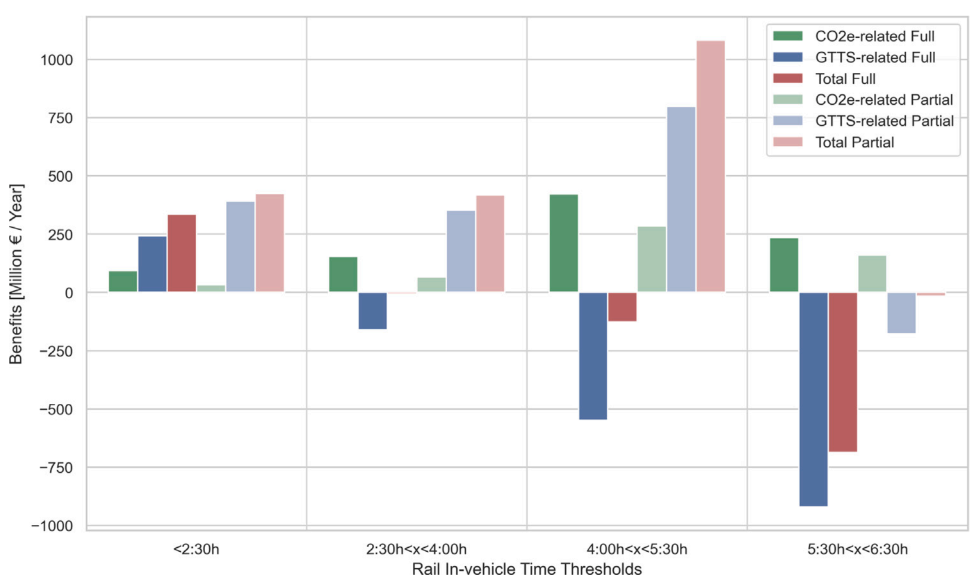


Fig. 4. CO_2e-related, GTTS-related and total benefits per policy setting.

to behind, beyond and bridge (also considered for full substitution) where both modes have more comparable components, based on the specification of door-to-door travel time provided in Section 2.4. The results confirm this expectation. The sensitivity analysis further indicates that the robustness of the baseline estimates for GTTS-related benefits diminishes as rail in-vehicle time thresholds increase. This decline is due to the greater volume of traffic impacted by SHF bans with longer in-vehicle time thresholds.

Table 3 highlights that a full SHF ban policy can be beneficial in terms of both CO_2e savings and GTTS up to 4 h. The scope of the 2.5-h SHF partial ban employed by the French government appears extremely limited concerning both routes affected and CO_2e emissions savings, were it to be employed at the European level. Increasing the threshold by one-and-a-half hours would almost triple the magnitude of its impact, whereas extending the policy to 5:30 h would yield greater CO_2e savings compared to a 4-h threshold. At the same time, the GTTS do not justify the selection of the 2:30-h threshold and would allow for it to be raised to 4 h for a full SHF ban and 6:30 h for a partial SHF ban. Thus, when designing full SHF ban policy measures, rail in-vehicle time thresholds ought to be selected more conservatively.

3.2. Route-level analysis

Next, we delve into a detailed analysis of the policy measure's impact at the route level in terms of CO_2e Savings/GTTS and economic benefits, illustrated in Figs. 6 and 7, respectively. All routes analysed

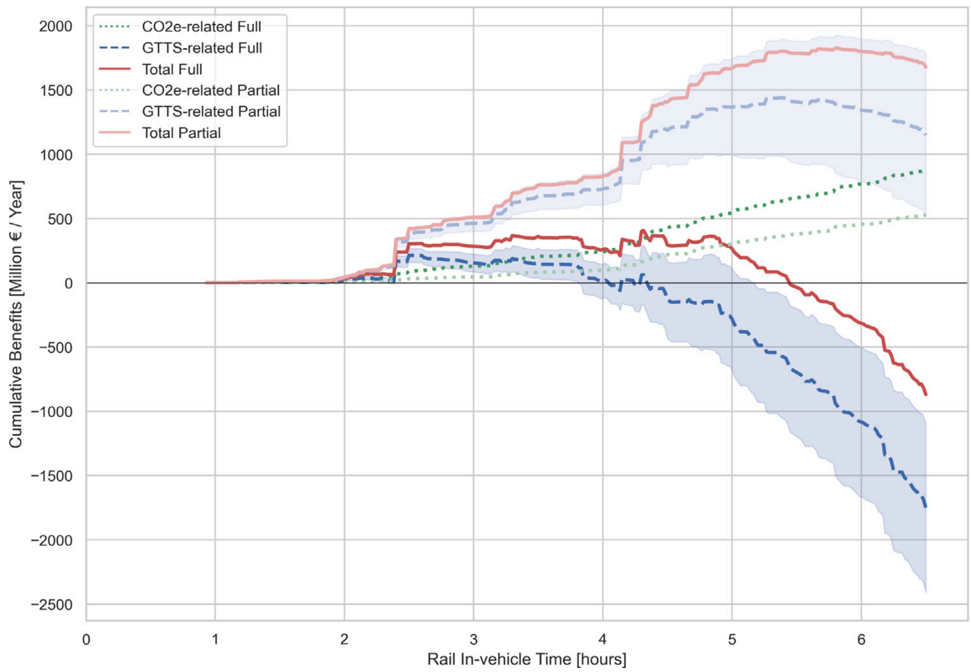


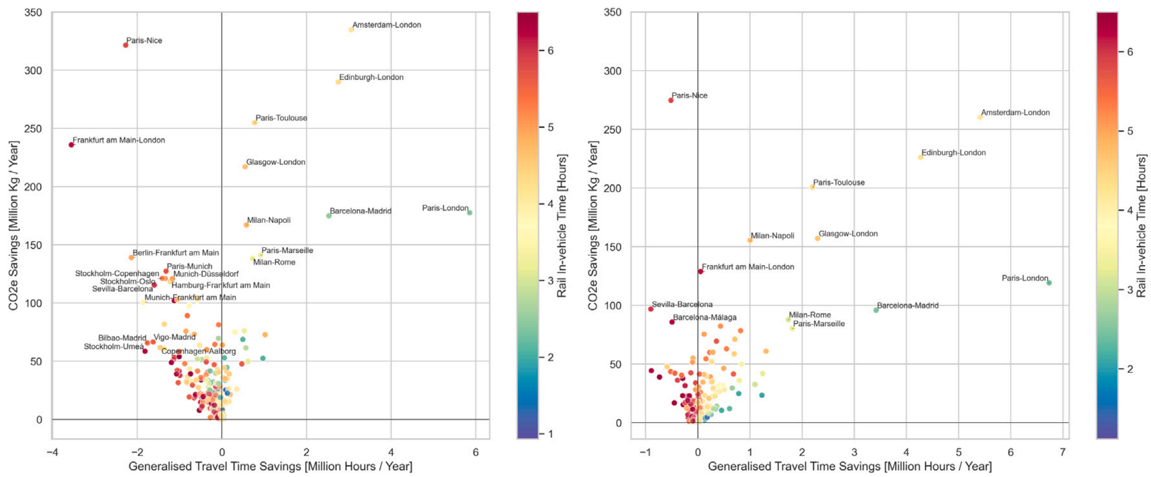
Fig. 5. Distribution of the cumulative CO_2e-related, GTTS-related and total benefits.

are bidirectional, meaning that the results comprise the flows in both directions. As shown by Fig. 6, a majority of the routes feature negative benefits for full substitution and positive for partial substitution. As expected, larger rail in-vehicle times are correlated with more negative benefits. The OD pairs most affected by each ban differ among the two policies depending on the share of connecting passengers on the route. When moving from a full to a partial ban, most routes shift towards lower environmental benefits (as fewer flights are banned) and higher travel time savings (as connecting passengers are more negatively impacted by SHF bans). Two main classes of routes can be identified depending on how pronounced their shifts are, where larger shifts correspond to larger shares of direct passengers. Routes like Paris–Nice (14% connecting passengers), Milan–Naples (7% connecting passengers), and Sevilla–Barcelona (16% connecting passengers) feature larger shares of direct passengers, as opposed to routes like Munich/Berlin–Frankfurt (68/57% connecting passengers), Frankfurt–London (45% connecting passengers), Barcelona–Madrid (45% connecting passengers), Milan-Rome (36% connecting passengers), Stockholm–Oslo (35% connecting passengers), and Stockholm–Copenhagen (32% connecting passengers) that are more heavily traversed by connecting passengers. The former class of routes is similarly affected by both types of SHF bans, whereas a partial SHF ban would have a considerably more limited impact on the latter.

Fig. 6 shows that positive GTTSs are associated with significant CO_2e savings on several routes. Notably, on eight out of the top 10 most polluting routes (i.e., Amsterdam–London, Edinburgh–London, Paris–Toulouse, Glasgow–London, Paris–London, Barcelona–Madrid, Milan–Naples and Paris–Marseille for the full SHF ban or Frankfurt–London for the partial SHF ban) switching to rail would on average save generalised travel time for passengers, in case of both full or partial substitution. Furthermore, seven out of the 10 routes with the highest GTTS (i.e., Paris–London, Edinburgh–London, Amsterdam–London, Barcelona–Madrid, Paris–Marseille, Paris–Toulouse and Glasgow–London) are also among the top-10 CO_2e emitters. The fact that these routes are already connected by frequent rail (and in the case of 4 of them, even by HSR) services combined with the substantial air traffic suggests that either the rail infrastructure capacity is saturated or rail is not as commercially competitive due to factors other than travel time. Previous studies suggest that such factors may include feeder services, the relative ease of transfer, lower fares, ease of booking and journey planning and an underestimation of air door-to-door travel times (Dobruszkes et al., 2022; Witlox et al., 2022; Dällenbach, 2020). This is further supported by the significant supply of flights and air seats on routes where a rail alternative with shorter travel times is (already) available. Presumably, the air-to-rail substitution driven by SHF bans would face important limitations on crucial routes due to the constraints imposed by railway capacity, which could hamper rail alternatives in absorbing the air demand affected by the ban. In such case, SHF bans measures could have negative repercussions, preventing passengers from using rail alternatives and pushing them towards private cars or changing destination altogether.

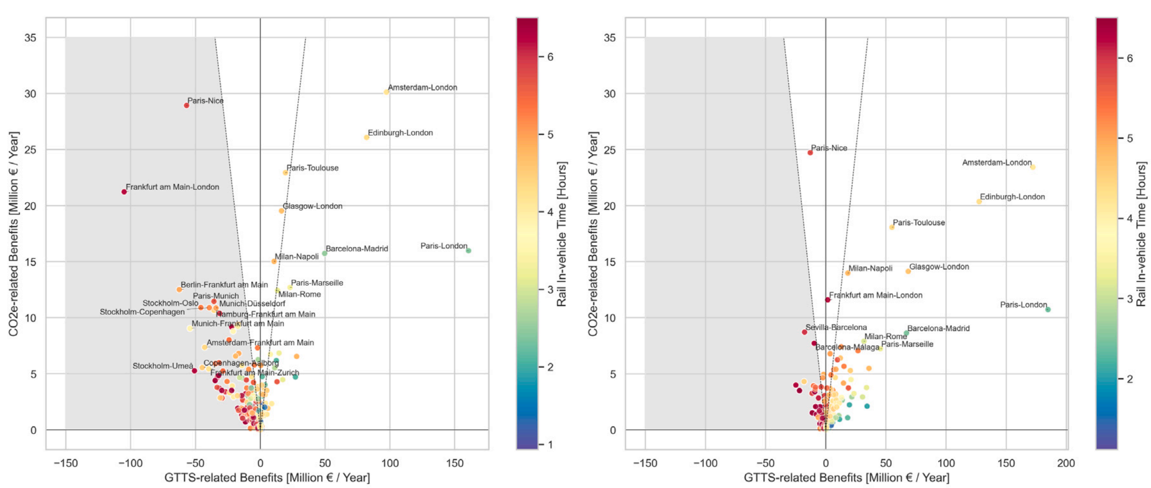
The 1:1 proportionality axes in Fig. 7 highlight the different orders of magnitude of GTTS- and CO_2e-related benefits. Specifically, they distinguish between routes where CO_2e benefits compensate for the GTTS-related costs (e.g., Sevilla–Barcelona for partial) and do not (e.g., Paris–Nice for partial), routes where CO_2e-related exceed GTTS-related benefits (e.g., Frankfurt–London for partial) and the converse (e.g., Paris–London). A grey patch highlights the area with negative total monetary benefits. Within the framework of this study, banning eight of the top-10 CO_2e emitting routes could be defended as benefits are bound to be derived from both CO_2e and generalised travel times savings. The crucial role of direct connections and HSR in making the sector competitive with air is evident: most of the routes with positive benefits feature frequent direct connections and, in most cases, those are offered by HSR services. A detailed inspection of Fig. 7 further suggests that the French SHF ban, as implemented, has a rather marginal effect due to the relatively low threshold employed. In particular, the routes connecting Marseille and Toulouse to Paris, despite showing substantial potential monetary gains stemming from rail's shorter generalised travel times, are not currently affected by the ban.

Another key takeaway from Fig. 7 relates to the distribution of benefits. Most OD pairs are concentrated between −25 and 25 M€/year (around ±1 Million hours) in GTTS and 5 M€/year (±54 Million kg circa) in CO_2e savings. Furthermore, the vast majority of the routes yield up to ±50 M€/year (±2 Million hours circa) in GTTS and a 10M€/year (approximately ±108 Million kg) in CO_2e savings, with a few exceptions only (e.g., London–Paris and Paris–Nice). This pattern



(a) Full SHF Ban (b) Partial SHF Ban

Fig. 6. CO_2e savings and GTTS per route.



(a) Full Ban (b) Partial Ban

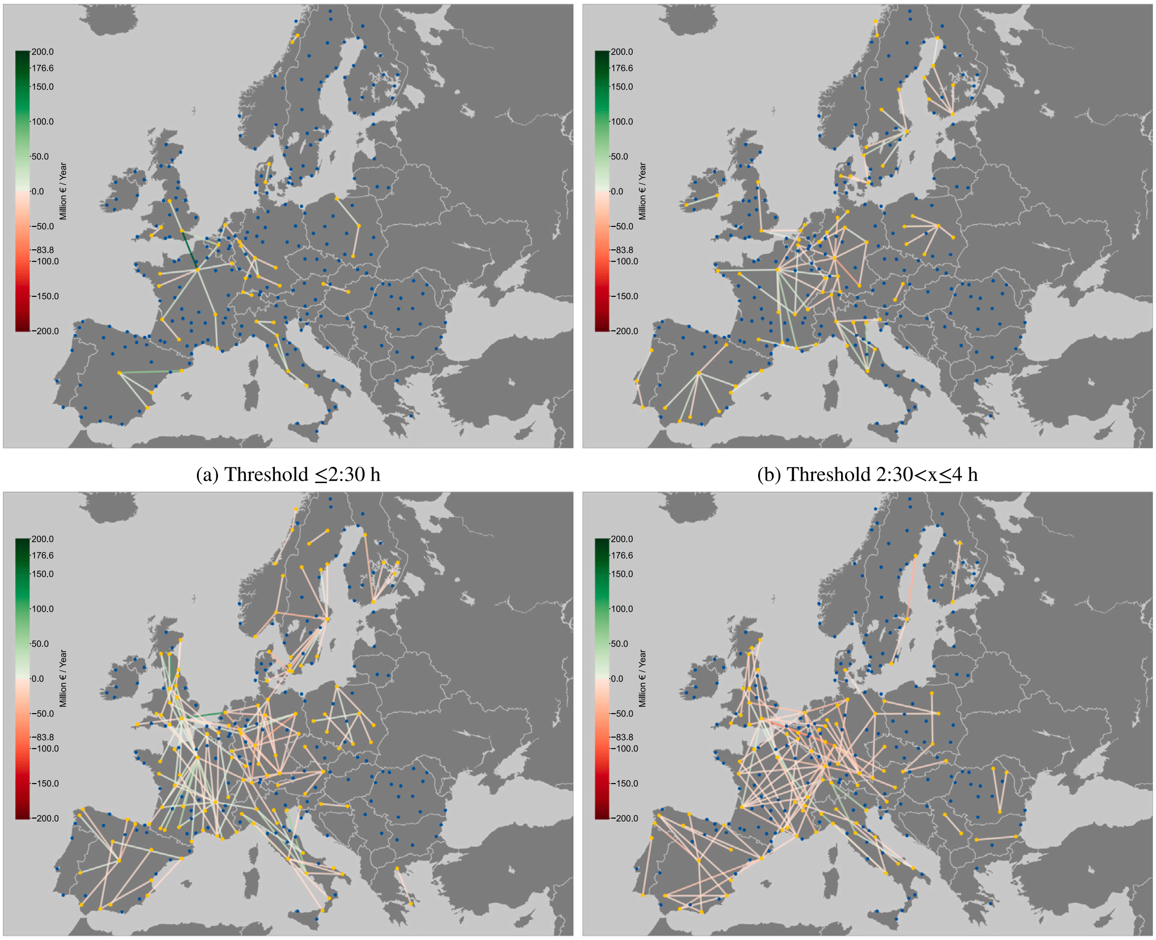
Fig. 7. CO_2e-related and GTTS-related benefits per route.

suggests that the few outlying routes account for a considerable portion of the benefits due to their sizeable traffic flows.

To assess the routes affected by a potential ban, we plot those for both a full SHF ban (Fig. 8) and a partial SHF ban (Fig. 9). In both cases, national (domestic) routes represent the majority of affected routes, probably due to the relatively short travel times by rail and large passenger volumes. Nonetheless, part of the routes with the largest monetary gains are international (e.g., London–Paris and London–Amsterdam). This implies that approaching the matter at the national level, restricting SHF bans to domestic routes only, would severely limit the impact of such policies.

At the same time, the impact of the policy varies greatly across countries. A comparison of Figs. 8 and 9 suggests that Italian airports handle larger than average shares of point-to-point passengers, possibly due to the absence of large continental hubs as well as due to the travel patterns of local passengers (e.g., above average shares of the domestic market). Conversely, the lack of considerable positive benefit routes in Eastern Europe suggests that the region is characterised by non-competitive train alternatives while, at the same time, featuring a more limited air supply compared to the rest of Europe. The latter is probably due to the absence of any important airport hub in the region. In contrast, Western Europe is expected to see quite steep reductions in SHF, and consequently considerably larger environmental benefits, as a result of the policy. Thus, the spatial disparities caused by such policies should be more thoroughly assessed before deciding on their implementation at such a large scale.

Our geographical analysis also allows the identification of crucial air routes that currently do not have sufficiently competitive rail connectivity (e.g. Athens–Thessaloniki, Amsterdam–Bremen/Hamburg, Warsaw–Berlin and Frankfurt–London). Improving rail travel times on these connections could profoundly reshape the outcomes of SHF bans, reducing the negative impacts on GTTS and consequently allowing a wider implementation of the policies. A second group of routes (e.g., Berlin–Munich, Berlin–Frankfurt, Munich–Frankfurt, Frankfurt–London, Barcelona–Madrid, Paris–Marseille, Stockholm–Oslo and Stockholm–Copenhagen) is traversed by substantial shares of connecting passengers (between 30% and 70% of total passengers), suggesting that feeder flights are a crucial cause of traffic. In such cases, a full SHF ban might cause considerable generalised travel time losses. A possible solution could be implementing a partial SHF ban, complemented by alternative policies targeting the reduction of feeder flights (e.g., air–rail integration). Finally, some patterns related to HSR corridors and direct connections are also visible. These include the radial HSR systems of France and Spain, the Italian north–south corridors and the



(a) Threshold ≤2:30 h

(b) Threshold 2:30<x≤4 h

(c) Threshold 4<x≤5:30 h

(d) Threshold 5:30<x≤6:30 h

Fig. 8. Aggregated benefits for routes affected by the full SHF ban per threshold setting.

cross-channel lines connecting London to the continent. This further reinforces the idea that both HSR and direct services (without transfers) are crucial to curb emissions. Thus, if proper rail alternatives are not in place, forcefully imposing the air–rail modal shift with a SHF ban might not be as effective as hoped.

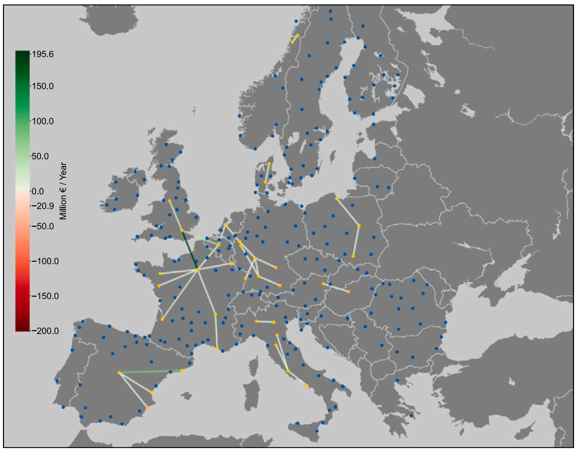
3.3. Infrastructure capacity analysis

Finally, we investigate the impact of the additional train services on the railway infrastructure capacity utilisation across the Swedish rail network, including connections to Oslo and Copenhagen. Figs. 10 to 13 display the progressive variation in capacity utilisation for the four incremental threshold settings. This worsening affects all the line sections where additional train services are to be operated as a consequence of a full SHF ban implementation. Capacity utilisation is analysed at the 24-h level and at the top 2-h level. The 24-h level provides a general benchmark to assess whether operating additional train services is at all possible. The top 2-h level includes only the two contiguous hours with the highest traffic demand per line section. This is used as a proxy for measuring the average utilisation during peak hours, providing information on whether rail frequencies can be increased during periods of high demand.

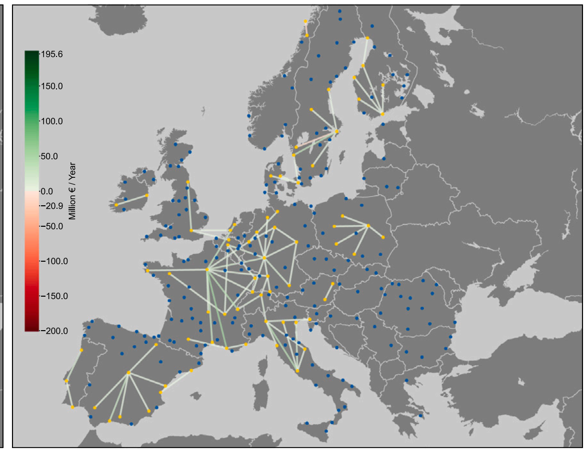
Each line section is classified as low (≤0.6), medium (0.6<x≤0.8), high (0.8<x≤1), very high (1<x≤1.2) or extreme (x> 1.2) based on its capacity utilisation. Values of 1 indicate that the occupied infrastructure time equals the number of infrastructure operational hours (i.e., 18 h for the 24-h and 2 h for the top 2 h). This means that 24-h timetables with capacity utilisation above 1 are not impossible to run. However, running these timetables comes at the cost of shortened times for railway maintenance and reduced buffers to recover from delays. These, in turn, might have considerable implications for the number of disruptions and the delay propagation across the network. Conversely, top-2-h capacity utilisation values above 1 impose rescheduling some services outside peak hours, possibly imposing unattractive departure/arrival times for passengers. This might not be even possible for 24-h values above 1, where banning SHFs would leave a supply gap in the long-distance market. In such cases, SHF bans may induce secondary effects (e.g., modal shift to car, air detours, change of destination), possibly harmful to the environment.

The Swedish case study does not feature any air route that can be substituted by train alternatives within 2:30 h of in-vehicle time. Consequently, the two maps in Fig. 10 correspond to the current state of the infrastructure for 2023. Notably, a significant number of sections, mostly on the main lines between Stockholm and Gothenburg, Malmö/Copenhagen and Oslo, are already at high or very high utilisation levels at the present state. When considering peak hours, the number of line segments with high or very high capacity utilisation increases considerably, occupying almost the entire network. This means that the additional train services added to the current timetable might run unattractive schedules, not necessarily matching the departure/arrival times of the banned flights.

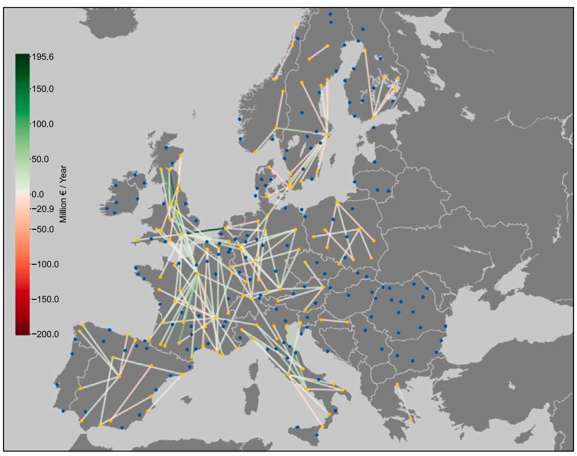
The maps in Figs. 11 to 13 suggest that the additional train services have a rather limited impact on capacity. At the 24 h level, only marginal increases in utilisation are noticeable, with routes connecting the major urban areas being the most critical. In particular, only one new bottleneck, which becomes a binding constraint in increasing the



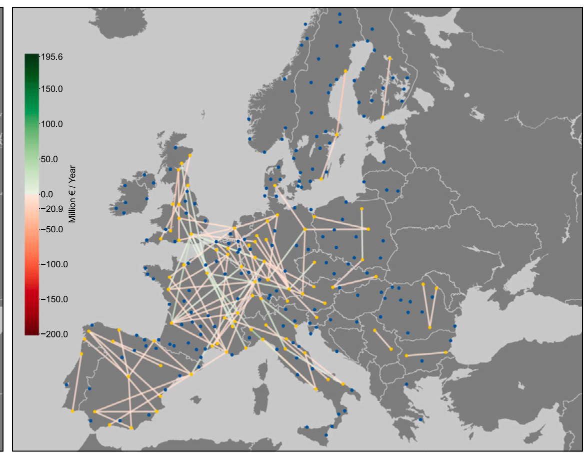
(a) Threshold ≤2:30 h



(b) Threshold 2:30<x≤4 h



(c) Threshold 4<x≤5:30 h



(d) Threshold 5:30<x≤6:30 h

Fig. 9. Aggregated benefits for routes affected by the partial SHF ban per threshold setting.

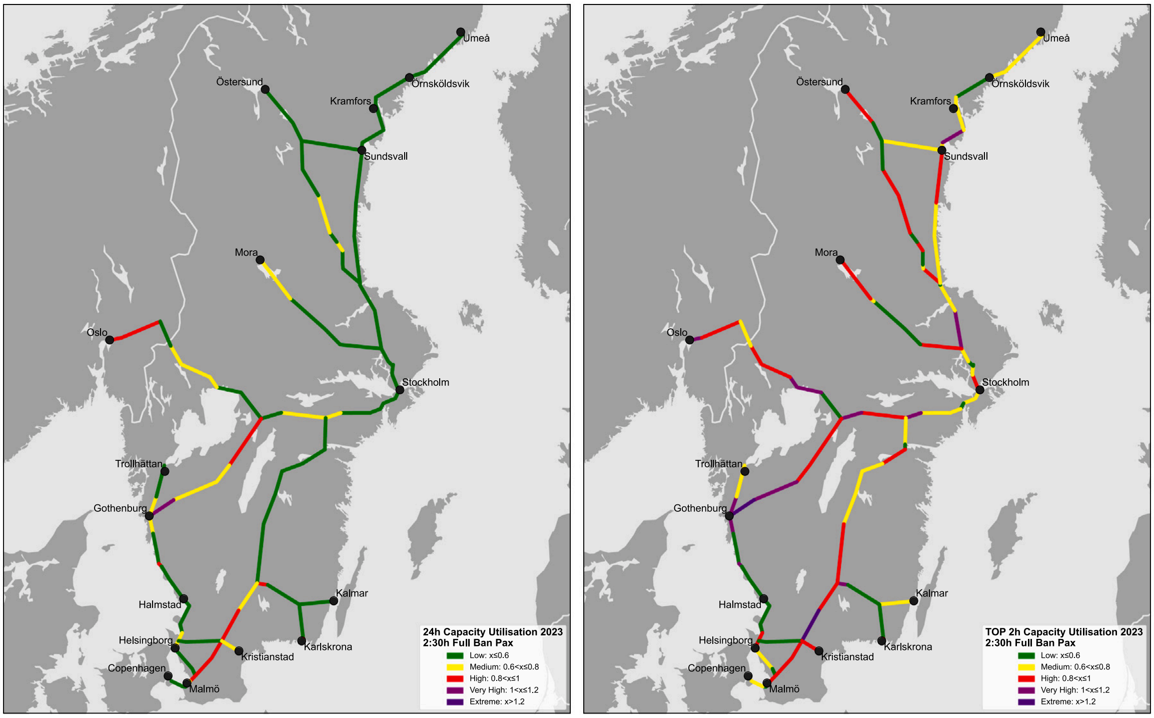
number of daily services, appears for the 5:30-h threshold (i.e., the Arvika-Charlottenberg line section on the Stockholm–Oslo line) on top of the one already present today (i.e., the Alingsås-Gothenburg line section on the Stockholm–Gothenburg line). Adding to the conservative capacity calculations, this suggests that the infrastructure capacity on the Swedish network may allow for the implementation of a full SHF ban in terms of offering sufficient rail capacity to absorb all the demand switching from air passengers. However, two of the routes with the most banned flights (i.e., the Stockholm–Oslo and Stockholm–Gothenburg) are exceptions to this, requiring upgrades in infrastructure capacity, due either to limitations in railway capacity (i.e., presence of single line sections on the Stockholm–Oslo) or to considerable mixed traffic (i.e., presence of many local and commuter services between Alingsås and Gothenburg). Excluding two of the three routes (the third being the Stockholm-Malmö-Copenhagen) most affected by the SHF ban would substantially curb its positive environmental impact. At the same time, it is important to consider the significant environmental (and economic) costs of improving existing rail infrastructure or building new lines.

At the top-2-h level, higher thresholds cause more substantial, albeit still marginal, variations. However, the base-case capacity utilisation during peak hours is already considerably worse than during the entire day. The impacts are widespread on the whole network, and just a few sections are still in the low and medium utilisation levels. Thus, additional trains, despite only marginally influencing the possibility of running the timetable, considerably impact peak-hour traffic and congestion management on the network. This implies that, in order to allow for increased timetable flexibility, delay recovery and avoid knock-on delays, capacity ought to be increased not only in some critical sections but across extensive portions of the network. In particular, to ensure passengers' shift from banned flights to rail, it is paramount to guarantee the comparability of the alternative frequencies offered. For rail services to run within the desired departure/arrival times, increased capacity is sorely required. Building new infrastructure and improving capacity on current infrastructure are both viable solutions, but require several years to realise at a national scale. Although planning for long-term solutions such as the above is fundamental, other solutions, such as train coupling, could help increase capacity in the short term.

It is important to note that the Swedish case study might not necessarily be representative of the average European country. In particular, SHF bans are expected to impact more substantially the capacity of infrastructure located in the central parts of the case study area, due to the much larger number of banned routes, the centrality of the infrastructure at the European level (implying a higher number of long-distance passenger services and freight) and the higher population densities and rail traffic density.

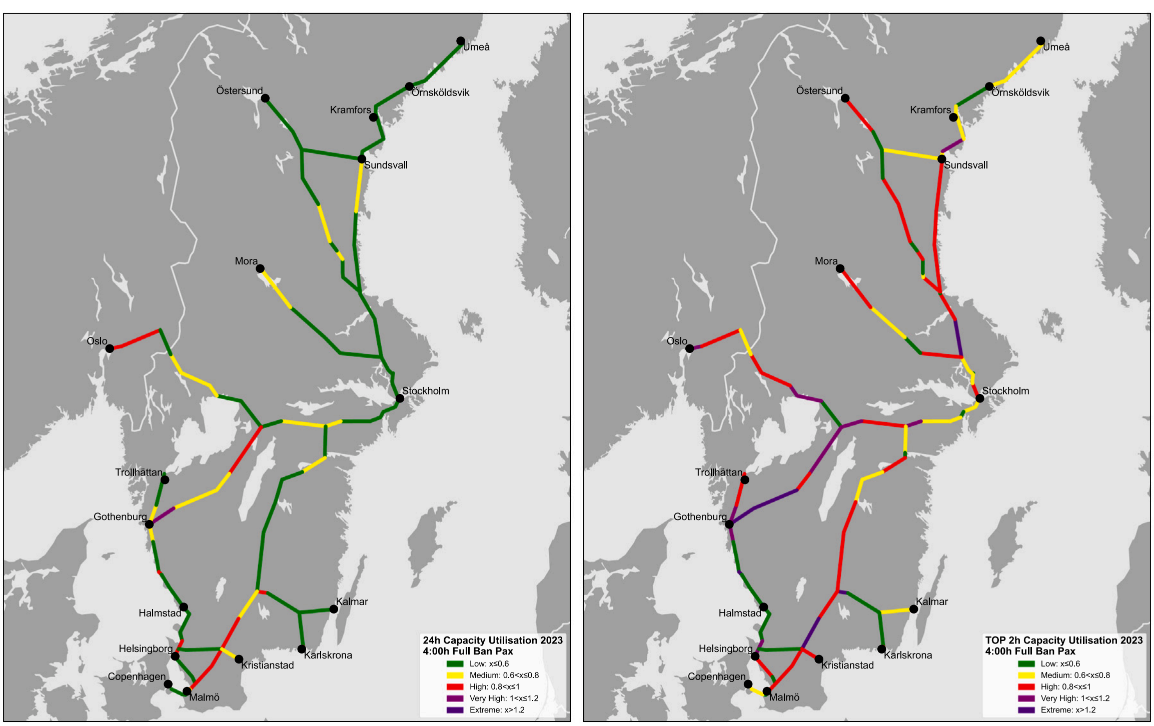
4. Discussion and policy implications

Our findings suggest that the 5-h threshold proposed by Szymczak (2021) and the 6-h thresholds considered by Reiter et al. (2022) might not be undesirable at the European level when accounting only for generalised travel times and CO_2e emissions. However, the Swedish case study questions the feasibility of rail to entirely absorb the existing



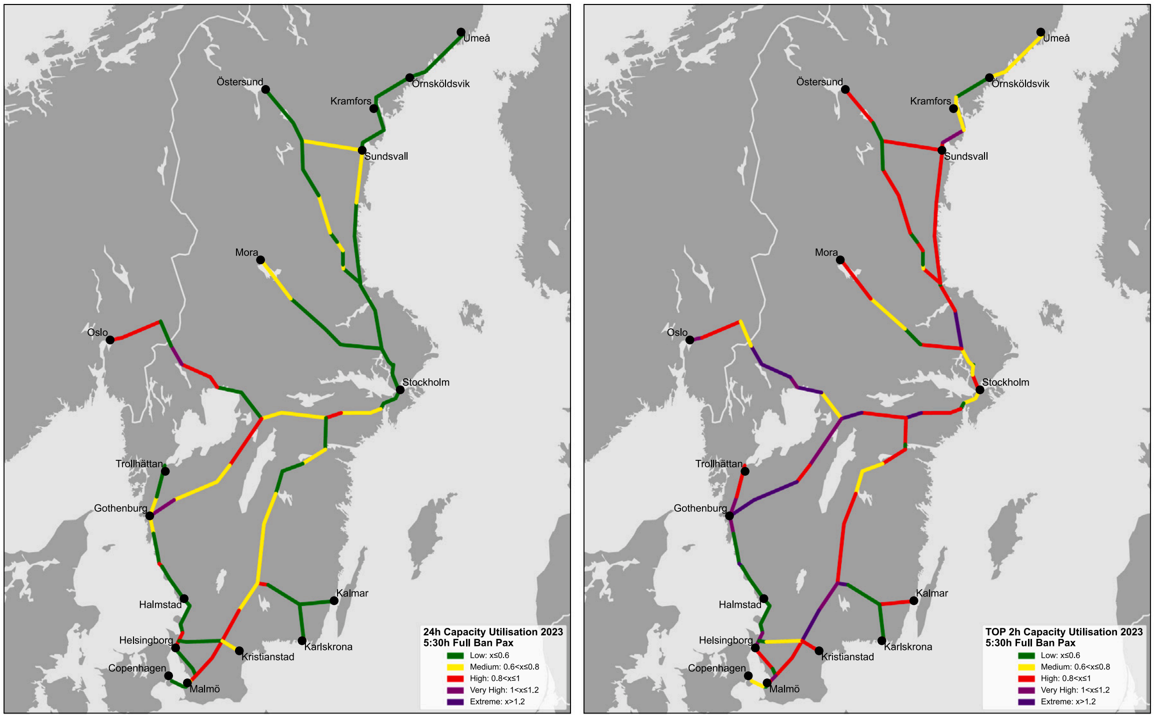
(a) 24h (b) Top 2h

Fig. 10. Capacity utilisation on the routes affected by the full SHF ban for threshold ≤2:30 h.



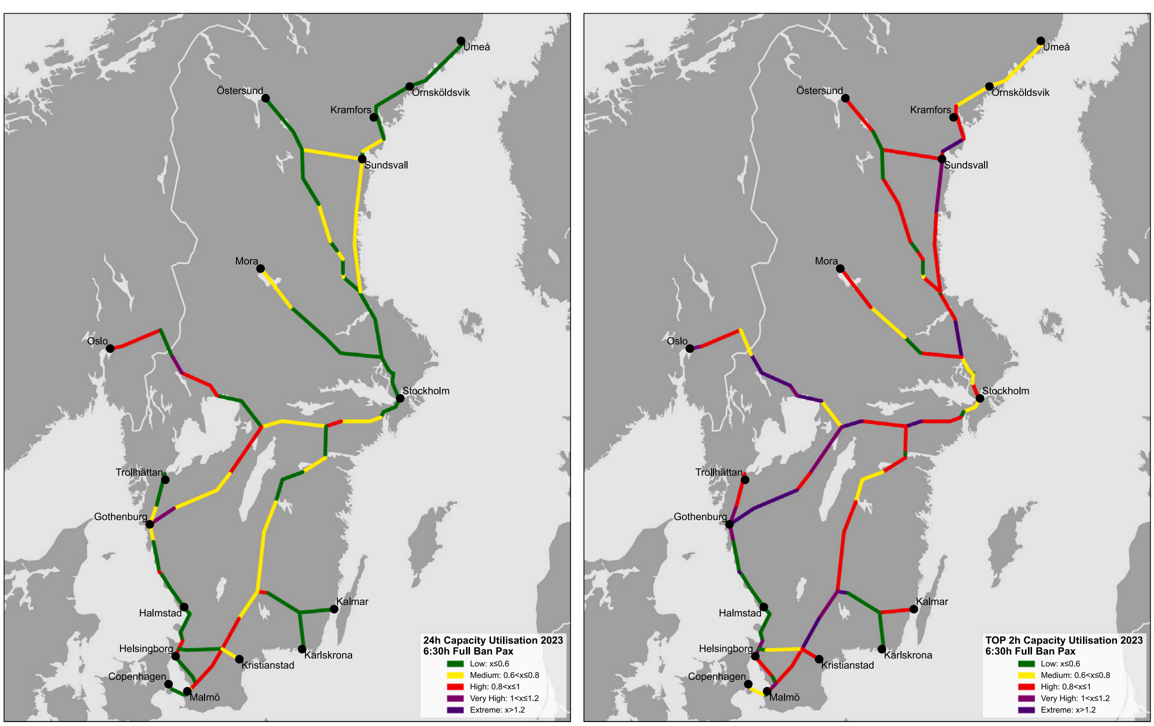
(a) 24h (b) Top 2h

Fig. 11. Capacity utilisation on the routes affected by the full SHF ban for threshold ≤4:00 h.



(a) 24h (b) Top 2h

Fig. 12. Capacity utilisation on the routes affected by the full SHF ban for threshold ≤5:30 h.



(a) 24h (b) Top 2h

Fig. 13. Capacity utilisation on the routes affected by the full SHF ban for threshold ≤6:30 h.

air demand at such thresholds without significant and diffused improvement in infrastructure capacity. Such infrastructural constraints, limiting rail supply, could push existing air passengers towards other modes, especially road transport, consequently negatively affecting the environmental benefits. Hence, it is important to note that the results are not to be read as a realistic forecast of the most likely impact of the policy, but rather as an assessment of the best-case scenario potential offered by the policy to reach policymakers' environmental targets and goals.

Furthermore, it is also important to consider that SHF bans carry major implications that could cause problems or unwanted consequences if left unaddressed, and that could, in turn, limit or even eliminate the aforementioned environmental benefits. The first important implication is the elimination of intermodal competition between air and rail. A direct consequence, especially in case intra-modal competition within the rail sector is absent, is the risk of higher fares and reduced levels of comfort on rail services. Risks concern not only mode but even destination and itinerary choice. Passengers might opt for further destinations or longer detours if no valid alternative is provided when cancelling flights. By increasing the travel distances and the number of flights, this phenomenon would heavily curb, if not completely offset, the environmental benefits of the policy. The elimination of intermodal competition, thus, calls for a set of complementary policies to ensure the competitiveness of rail with alternatives (car or indirect flights). These may include increasing aviation taxes and introducing or strengthening both competition within the rail market and collaboration between air and rail through air–rail integration agreements. Other risk sources relate to the reaction of airlines to SHF bans. Considering that strategic fleet planning requires long time horizons (i.e., generally more than 5–10 years), carriers may reposition their aircraft on alternative routes. This would cause emissions to shift towards routes where rail is not competitive, completely defying the essence of SHF ban policies. The results of this study suggest that a similar process of carbon leakage could also happen across countries, with most flights – and consequently emissions – concentrating in areas with poorer rail connectivity (i.e. eastern European countries). Moreover, banning SHF will liberate some airport slots, which may be used to launch new long-haul flights, especially in major hubs already at capacity (e.g., London Heathrow). The additional emissions of long-haul flights would overcome the savings due to the SHF ban. In both cases, policymakers should put in place mechanisms to govern these replacement phenomena, for instance, by limiting the introduction of new flights (Socorro and Viecens, 2013) or by capping capacity at large hubs. The results also underscore the larger magnitude and volatility of GTTS, as opposed to CO_2e savings. Since the marginal costs of CO_2e emissions under EU-ETS carbon pricing are relatively low when compared to the economic valuation of travel times, the overall benefits of the policy are particularly sensitive to travel time changes. This means that even minor improvements in rail speeds and connectivity would positively influence the impact of SHF ban policies, allowing for higher thresholds to be considered. However, it is worth noting that, over time, HSR would reduce the overall impact of SHF bans by making rail more commercially competitive and attracting air passengers.

Despite the considerable environmental benefits of SHF ban policies, it is important to note that these savings represent only a limited portion of the total CO_2e emission of intra-European flights, whose magnitude is incomparably small relative to the GhG emissions of all flights departing and arriving in Europe, not to mention those of the entire aviation sector. Our findings support previous research suggesting that SHF bans alone are insufficient to meet the ambitious environmental targets highlighted in Section 1. Other complementary measures, such as sustainable aviation fuels (Braun et al., 2024) and Tradable Mobility Credits (TCS) (Provoost et al., 2023), affecting short- and long-haul flights alike, are required to limit the emission of the long-distance sector. The introduction of push measures like SHF bans or TCS might face considerably stronger resistance from stakeholders and the public compared to pull measures such as increasing rail frequencies, routes and comfort, which are more expensive to implement. Future research may investigate acceptance levels amongst various user groups and stakeholders and their potential implications for designing relevant policy pathways. Furthermore, exploring the environmental impacts of policies targeted at promoting SAFs and comparing them with the impacts of SHF bans constitute grounds for further research. To give an idea of the expected extent of the impact of SAFs under TCS schemes, Tanner et al. (2024) highlight that a usage of 5% SAF, expected for 2030, would increase by 2% the modal share of air, whereas a 15% increase in SAF would impose a 7% increase in the modal share of air. In both cases, the results suggest that SAFs would mostly affect the number of cancelled trips rather than the modal share of rail.

It is important to note that market players may respond to SHF bans by revisiting their offerings, which may, in turn, impact the outcomes of said policies. In the absence of empirical underpinning, our analysis did not account for how supply and, consequently, demand would react to the implementation of SHF bans. However, analysing the supply and demand dynamics for the long-distance sector constitutes grounds for future research. Such frameworks could aid in understanding how supply and its levels of service would react to a sudden elimination of intermodal competition and how traveller behaviour would, in turn, adapt. The triangular modal choice interaction between car, rail and air is not as straightforward for policymakers to address, and further research is required to model the behavioural responses to SHF bans. Such responses extend beyond mode choice to involve destination and itinerary choice, trip cancellation and the total number of long-distance trips generated. Future research may support the consideration of such responses by offering relevant empirical behavioural underpinning, which would allow introducing feedback loops to mode choice, trip destination and trip generation choice.

To avoid overestimating the positive impact of SHF ban policies, conservative assumptions were consistently made throughout our investigation. For example, we do not account for the seat availability on the existing rail supply, consequently underestimating CO_2e savings and overestimating the increase in rail capacity utilisation. To reduce the cumbersomeness of calculations, geographic centroids rather than population-weighted centroids are employed. This assumption imposes some limitations in the case of urban areas with uneven population distributions. Relaxing both these assumptions can contribute to improving the accuracy of the results. Furthermore, to limit the data requirements and reduce modelling complexity, airports are considered to be connected to only one urban area. This assumption can be especially limiting in the case of demographically dense polycentric regions, and regional and multi-city airports. Future research can avoid relying on this assumption by modelling the catchment areas of all airports and identifying the actual distribution of passengers' origins and destinations (Lieshout, 2012). Finally, it is worth noting that despite employing demand figures for 2023, the method can accommodate demand projections for future years disaggregated at the route level. Future research may estimate future demand distribution and thereby allow for re-assessing the impacts of SHF bans.

5. Conclusion

This study has investigated the implications of SHF bans on the environment, generalised travel times and rail capacity, under the assumption of a complete modal shift from air to rail. Accordingly, the results represent a conservative estimate of such potential implications under a best-case scenario in which all passengers choose and are accommodated by rail alternatives. To answer the first research question, the environmental impact of SHF bans is found to be largely dependent on the policy design (i.e., affected journey types and rail in-vehicle time thresholds), ranging from 0.6% to 12.3% of the CO_2e emissions generated by commercial intra-European aviation. In particular, CO_2e savings vary between 0.4 Mt for a 2:30-h partial SHF ban to 7.5 Mt in the case of a full SHF ban affecting air routes where rail alternatives within 5:30 h are available. International connections account for a fair share of the environmental benefits in all settings, pointing to the importance of adopting broad geographical and jurisdictional scopes in the design and implementation of SHF policies. However, the complexity of defining an international legal framework to capture these routes and the implications of the related geographical disparities should be considered.

Answering the second research question, results confirm that substituting short-haul flights with rail alternatives could theoretically bring about significant CO_2e savings, with limited negative effects on GTTS. We estimate that a European-wide implementation of a 4-h full SHF ban would enable cutting up to 2.8 million tonnes of CO_2e (considering the CO_2e caused by the additional train alternatives), or 4.5% of the total intra-European air market CO_2e emissions, without imposing generalised travel time losses on average. However, further increasing the threshold would come at the cost of accepting reduced connectivity (i.e., negative GTTS). Results suggest that full SHF bans impose considerable trade-offs between CO_2e and GTTS, especially for higher thresholds. The magnitude of such trade-offs can be limited with partial SHF bans, whereby only connecting passengers are permitted on affected flights. Despite inducing comparatively lower CO_2e savings, a partial SHF ban would allow employing higher thresholds without excessively burdening passengers' generalised travel times. For example, a 5:30-h partial SHF ban would enable a 7% reduction in CO_2e emissions, equivalent to over 4.2 Mt. Despite being more limited compared to the 12% of a 5:30 full SHF ban, its environmental impact would be significantly higher than the 4.5% of a 4-h SHF full ban, which would already impose a much larger burden on passengers' travel times. In light of our findings, we argue that thresholds over 2:30 h are required for SHF bans to have a noticeable environmental impact. However, we note that larger thresholds and wider scopes require rail to be more competitive, to limit travel time losses and to curb the risks related to the removal of intermodal competition.

To answer the third research question, the Swedish case study underscores that increased rail capacity is required to provide attractive departure and arrival times. At the 24-h level, the few existing bottlenecks only slightly worsen as thresholds rise, suggesting that the additional trains have a limited marginal impact on capacity. Adding trains within operational hours seems possible on most lines with minimal capacity improvements. Notwithstanding, the two exceptions (i.e., the congested Stockholm–Oslo and Stockholm–Gothenburg routes) account for a considerable share of the air traffic and emissions. Furthermore, capacity is considerably more limited during the top 2 h, constraining the possibility of operating during peak hours. These infrastructure capacity constraints could be managed in the short term by coupling train sets to increase seat capacity during peak hours. However, planning for expanded capacity seems to be the more sensible solution in the long term. At the same time, future research shall consider the environmental and economic costs of building new infrastructure and upgrading existing capacity. Further analyses are also required to develop a complete overview of the impact of SHF ban policies on capacity for different countries and regions. In some situations, such as central parts of the European rail network and high-demand corridors, we expect capacity to be more restrictive. In these cases, to ensure the provision of comparable rail alternatives, policymakers should adopt cautious measures, gradually or selectively (e.g., only on specific routes) implementing SHF bans tailored to the binding constraints imposed by rail infrastructure capacity.

SHF bans are often seen as a low-hanging fruit to curb transport emissions due to the relative ease of implementation. We conclude that this attractiveness quickly fades with growing values of rail in-vehicle time thresholds that would cause the cancellation of substantially more flights. This is, however, exactly where the measures would have a noticeable impact on the environment, curbing considerable shares of GhG emissions. When implementing SHF ban policies for longer rail travel time thresholds and wider geographical scopes, we argue that complementary measures are required to address the significant risks associated with SHF bans and the capacity constraints imposed by railway infrastructure. By showing that the plausible environmental benefits of SHF bans are limited and subject to multiple constraints even in a best-case scenario, under the assumption of a complete modal shift to rail, the results of this paper contribute to informing policymakers of the limitations of these policy measures.

CRediT authorship contribution statement

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

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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.

Data availability

The dataset supporting the findings of this study is publicly available in the 4TU.ResearchData repository at https://doi.org/10.4121/f2c5db91-48b9-4b5d-945e-2052481edb1f.

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