Possibilities to Replace Short-haul Flights with Train Travel when Accounting for Rail Capacity

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Short summary

To address the rising environmental concerns for transport-related GhG emissions, European governments are considering the implementation of increasingly restrictive policies targeting air traffic, such as SHF bans. This study investigates the impact of a series of SHF ban measures at the European level in terms of affected flights, offered seats and additional train services required to fill the supply gap. The CO2e savings, Travel Time Gains and relative monetary benefits are quantified at the route level and for a series of policy scenarios. Furthermore, the impact on the rail sector in terms of increase of capacity utilisation is estimated for the Swedish case study. Results suggest that for flight-ban policies to succeed, the international scope and higher thresholds (i.e., up to 5 hours) are paramount. At the same time, considerable focus should be placed on improving air-rail integration, developing the high-speed network, and removing infrastructural bottlenecks.
Keywords: Air-to-rail modal shift, High-speed rail, Greenhouse gas emissions, Policy implications, Railway infrastructure capacity, Short-haul flights

1 Introduction

Over the last two decades, environmental concerns have increasingly taken centre stage in the political discourse. In an effort to limit the GhG emissions of short-haul flights (SHF) below 800 km, rail is widely eyed as a viable and ideal substitute, being able to offer comparable travel conditions (e.g., travel times and travel costs) with a reduced environmental impact (Grimme & Jung, 2018). The growing awareness of environmental concerns pushed different governmental bodies across Europe to take action following three main approaches to aid rail in substituting SHF: applying additional taxes for flights within certain spatial limits (i.e., below 500km in Belgium and 350km in Austria), banning all those flights where a rail alternative within certain time boundaries is available (i.e., 2.5 hours in France and 3 hours in Austria) and increasing the competitive pressure on the air sector, opening the rail market to competition and relying on the substitution dynamics of the free market (Dobruszkes et al., 2022).

To guide future policy development, literature has investigated the impact of such approaches on the transport market. 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 domestic air passengers, the growth of low-cost airlines has caused a greater surge in air passenger traffic. This suggests that more stringent measures might be necessary. Thus, Szymczak (2021) analyses the impact of a potential SHF ban on European Airports, considering only routes where rail alternatives are available, whilst Avogadro et al. (2021) broadens the scope focusing on alternative transport modes, which include but are not limited to rail. The former concludes that a SHF ban with a threshold below 4-hour travel time of the rail alternative would hardly affect the emissions, suggesting that to contribute to the reduction of aviation emissions 5-hour thresholds (or above) would be required. Following a different approach, Reiter et al. (2022) assess the impact of a potential SHF ban in Germany, focusing specifically on minimum shares of connecting passengers, excluded from the French SHF ban implemented in 2023 (Le Monde, 2023).

Despite literature highlighting that the policy measure appears promising, the feasibility of its implementation has not been directly addressed or evaluated yet. The potential impacts on the rail sector, have to the best of our knowledge not been assessed thus far. To bridge this gap, we aim (1) to provide an overview of the European routes that could potentially be substituted by rail, (2) to assess the impact of a SHF ban in terms of travel times, CO2e emissions and monetary terms, and (3) to evaluate the extent to which rail infrastructure would be capable of absorbing the consequent modal shift of demand from air to rail by increasing its supply in terms of the required additional train services while accounting for their infrastructure capacity consequences. This study provides novel insights into the socio-economic implications of a SHF ban applied to the broader European context. Furthermore, the limitations posed by current infrastructural constraints at the Swedish level (including Oslo and Copenhagen) are highlighted, proposing a methodology based on track capacity utilisation. The results provide crucial insights to refine existing policy measures and shape future policies targeting the air-to-rail modal shift in Europe to meet the ambitious environmental goals set by the European Commission.

2 Methodology

Model Setup

An overview of the methodology is provided in Figure 1.

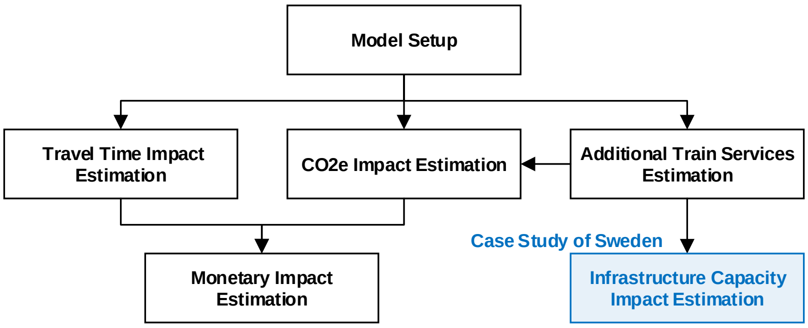


Figure 1: Methodology overview

A set of 5 distinct policy scenarios is generated using hourly flight-ban thresholds ranging from 2.5 to 6.5 hours of rail alternatives' in-vehicle time. This approach follows the structure of the policy adopted by the French Government in 2023 (Le Monde, 2023) and the methodology employed by Szymczak (2021). The upper and lower boundaries are defined based on the possibility for rail to provide similar door-to-door travel times, guaranteeing comparable service levels. Bruno (2022) highlights that the distribution of door-to-door travel time for all the connections among the 125 major European urban areas is mostly concentrated between 210 and 420 minutes, 3.5 and 7 hours respectively. Thus, considering an average of 60 minutes out-of-vehicle time for rail it is possible to conclude that rail and air tend to compete for in-vehicle travel times between 2.5 and 6 hours, rounded to the next half-hour for consistency. Door-to-door travel time is defined as the sum of in-vehicle and out-of-vehicle travel times, where the latter is composed of access, egress and wait (at origin and destination terminal) times, and is characterised by distinct travel time compositions

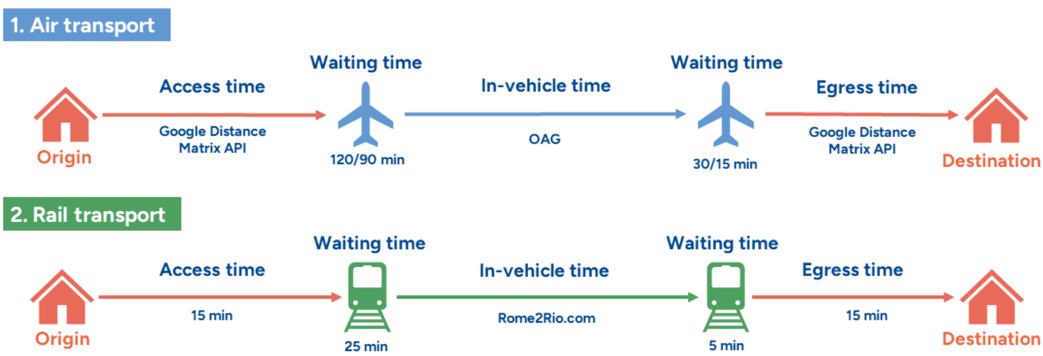


Figure 2: Door-to-door travel time composition per mode

per mode, as illustrated by Figure 2. Differently from the aforementioned French SHF ban, in this research, we assume that (1) both international and domestic flights are subject to the SHF ban and that (2) all passengers are banned on such routes, including connecting passengers.

Estimation of Travel Time Impact

The impact of the SHF ban on travel time is measured in terms of Travel Time Increase (TTI) and Travel Time Gains (TTG). The former represents the percentage increase in travel time and is calculated as:

$$TTI_{ij} = \frac{tt_{ij}^{rail} - tt_{ij}^{air}}{tt_{ij}^{air}} \cdot 100 \tag{1}$$

where tt_{ij}^{rail} and tt_{ij}^{air} are door-to-door travel times for rail and air on a route ij respectively. The data is then aggregated at the scenario level weighting the travel time increases per route by the extra seats required to compensate for the cancellation of the air seats affected by the SHF ban:

$$TTI = \frac{\sum_{ij} seats_{ij}^{air} \cdot TTI_{ij}}{\sum_{ij} seats_{ij}^{air}} \tag{2}$$

where $seats_{ij}^{air}$ is the total number of seats offered by air on a route ij subject to the SHF ban. TTG_{ij} represent the total number of seat-hours gained/lost on route ij by imposing the SHF ban, considering a complete modal shift to rail, which affects all air seats:

$$TTG_{ij} = (tt_{ij}^{air} - tt_{ij}^{rail}) \cdot seats_{ij}^{air} \tag{3}$$

The measure is further generalised, representing the total gain in travel time at the scenario level, as follows:

$$TTG = \sum_{ij} TTG_{ij} \tag{4}$$

Estimation of Additional Train Services

The number of additional trains at_{ij} required to fill the seat supply gap caused by the cancellation of the flights affected by the SHF ban is computed for each route using equation 5.

$$at_{ij} = \lceil \left(\frac{S_{ij}^{air}}{C} \right) \rceil \tag{5}$$

where S_{ij}^{air} is the number of seats offered by air and C is the capacity of an average European Intercity train (Iraklis, 2018). It is assumed that each train runs on a fixed wagon configuration with a specific number of seats that cannot be decomposed. Consequently, the number of additional trains is always rounded up to the next integer value.

Estimation of CO2e Impact

To compute the CO2e emissions for air, the fuel burnt F, obtained using the FEAT method (Seymour et al., 2020), is employed as a reference metric. F_{ij} depends on two factors, the flight distance d_{ij} and the aircraft type r of each flight f:

$$F_{ij} = \sum_{f} \alpha_r \cdot d_{ij}^2 + \beta_r \cdot d_{ij} + \gamma_r \tag{6}$$

Flight distance is defined as the great-circle distance between the origin and destination airport, as the model already accounts for average detours of flight routing. The aircraft type is introduced using aircraft type-specific parameters $\alpha_r, \beta_r, \gamma_r$. Finally, the CO2e emissions are computed by multiplying the fuel burnt by a CO2 Emission Index and an Emission Weighting Factor, considering a Global Warming Potential with a 100-year time horizon (Lee et al., 2010), to take into account the non-CO2 effects:

$$CO2e_{ij}^{air} = F_{ij} \cdot 3.16\ gCO2/gF \cdot 1.9\ gCO2e/gCO2 \tag{7}$$

This factor captures all the effects of aviation on climate that are not CO2-related, including Nitrogen Oxides (NOx), water vapour, sulphate and soot aerosols, linear contrails and aviation-induced

cirrus cloudiness (Lee et al., 2010).
Conversely, CO2e Emissions for rail $CO2e_{ij}^{rail}$ are calculated as a function of the energy consumption per route E_{ij} using a GhG emission factor (EEA, 2023):

$$CO2e_{ij}^{rail} = E_{ij} \cdot\ 251\ gCO2e/kWh \tag{8}$$

where d_{ij}^{track} represents the track distance measures using a railway detour factor (Kim & Wee, 2011), $EUSK$ is an energy usage factor in kWh per seat-kilometre (Iraklis, 2018), and the energy consumption is computed as:

$$E_{ij} = d_{ij}^{track} \cdot C \cdot at_{ij} \cdot EUSK \tag{9}$$

Finally, the CO2e Savings are computed by subtracting these to $CO2e_{ij}^{air}$.

Estimation of Infrastructure Capacity Impact

Infrastructure capacity is estimated based on the capacity utilisation rates provided by the Swedish and Norwegian Infrastructure Managers (IM) and computed using approximations of the UIC 405/406 methods. The additional trains per day required on each route affected by the SHF ban are added to the daily trains currently running on all the line sections traversed by the route. Following the guidelines provided by the IMs the increase in capacity utilisation rates is then estimated and the most critical sections are identified. The results are generally conservative due to the rounding up from yearly to daily number of additional trains. As the rail traffic mix is disregarded, the estimated increase in capacity utilisation is not exact but provides an approximate indication of the actual value.

Translation of Travel Time and CO2e Impact in Monetary Terms

Finally, to estimate the impact of the SHF ban policy, TTG and CO2e Savings are translated into monetary terms. Mode-specific Values of Time (VoT) for air travel estimated by (Trafikverket, 2023) for 2017 are employed as TTG multipliers and scaled to all other European countries using country-specific price level indices (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 (HICP) for transport services (Eurostat, 2023a; Office for National Statistics, 2023). For international flights, the VoT is obtained by averaging the values for each country, consequently assuming that flights are boarded by an equal number of passengers from each origin-destination country. Given the volatility of the emissions allowances' price established by the EU Emission Trading System (ETS), CO2e savings are multiplied by an estimate of 90 €/tonne CO2e, as between 2022 and 2023 the carbon emission price has been generally floating between 80 €/tonne CO2e and 100 €/tonne CO2e with a few exceptions only, mostly due to the breakout of the Russia-Ukraine war (Statista, 2023).

3 Results and discussion

A general overview of the data analysed in this research is provided by the descriptive statistics per policy scenario shown in Table 1. The analysis shows that the routes affected by the SHF

Table 1: Descriptive Statistics per Policy Scenario at the European Level

Policy Scenario	Routes	Flights [K/year]	Offered Seats [M/year]	CO2e Decrease [%]	TTI [%]
≤2.5 h	41 (1.05%)	104.52 (3.06%)	15.60 (2.85%)	96.41	-34.61
2.5<x≤3.5 h	45 (1.15%)	129.29 (3.79%)	18.11 (3.31%)	96.05	-9.57
3.5<x≤4.5 h	77 (1.97%)	235.55 (6.90%)	33.08 (6.04%)	95.86	11.61
4.5<x≤5.5 h	99 (2.54%)	240.05 (7.03%)	36.35 (6.64%)	95.37	28.89
5.5<x≤6.5 h	107 (2.74%)	217.30 (6.36%)	31.26 (5.71%)	95.10	51.15
≤6.5 h	369 (9.45%)	926.72 (27.13%)	134.41 (24.54%)	-	-

ban feature on average higher frequencies and lower than average aircraft capacity. This suggests that many feeder flights between major European hubs are affected by the policy. Considering a comparable increment in rail seat supply, CO2e would on average decrease between 95% and 96% depending on the scenario. The slight decline in percentages for longer travel times highlights

the higher fuel efficiency of longer flights. TTI indicates that travel time on average drops when switching to rail alternatives for a policy ban threshold of up to 3.5 hours, slightly increases for routes up to 4.5 hours and substantially rises beyond that point.
The TTG reported in Table 2 further confirms that for the first two scenarios, the SHF ban policy is beneficial in terms of both CO2e savings and travel time gains. Above the 3.5-hour threshold, the considerable travel time losses make the policy increasingly less appealing. In particular, considering the marginal impact induced by each scenario, over the 3.5-hour threshold the policy does not appear to bring about enough environmental benefits to offset the additional travel time losses. However, between 3.5 and 4.5 hours the monetary savings related to CO2e emissions are still able to compensate for most of the additional costs related to travel time losses. This allows us to conclude that policymakers could push the threshold up to around 4 hours while attaining a break-even between the additional costs related to longer travel times and the benefits related to CO2e savings when considering both in monetary terms. The scope of the 2.5-hour threshold employed by the French government appears to be rather limited in terms of both routes affected and CO2 emissions savings. Increasing the threshold by one hour would more than double the magnitude of its impact, whereas the third scenario alone would yield greater CO2e savings compared to the first two combined.

Table 2: KPIs of the Policy Scenarios at the European Level

Policy Scenario	**Additional Trains [K/year]**	**CO2e Savings [M Kg/year]**	**TTG [M h/year]**	**CO2e-related Benefits [M €/year]**	**TTG-related Benefits [M €/year]**	**Aggregated Benefits [M €/year]**
≤2.5 h	52.04	1150.88 (1.69%)	25.62	103.58	632.57	736.15
2.5<x≤3.5 h	60.40	1406.59 (2.07%)	8.11	126.59	200.93	327.53
3.5<x≤4.5 h	110.29	2697.91 (3.97%)	-15.77	242.81	-426.22	-183.41
4.5<x≤5.5 h	121.21	3010.52 (4.42%)	-45.65	270.95	-1179.31	-908.36
5.5<x≤6.5 h	104.26	2892.16 (4.25 %)	-71.07	260.29	-1819.54	-1559.24

When considering the cumulative impact of the policy measure in Table 3, a higher threshold of up to slightly below 5.5 hours could be defended, as the additional costs between 4 and 5.5 hours are almost completely compensated by the benefits below that level.

Table 3: KPIs of the Cumulative Policy Scenarios at the European Level

Policy Scenario	**Additional Trains [K/year]**	**CO2e Savings [M Kg/year]**	**TTG [M h/year]**	**CO2e-related Benefits [M €/year]**	**TTG-related Benefits [M €/year]**	**Aggregated Benefits [M €/year]**
≤2.5 h	52.04	1150.88 (1.69%)	25.62	103.58	632.57	736.15
≤3.5 h	112.44	2557.47 (3.76%)	33.73	230.17	833.50	1063.67
≤4.5 h	222.73	5255.38 (7.72%)	17.95	472.98	407.28	880.27
≤5.5 h	343.94	8265.91 (12.15%)	-27.69	743.93	-772.03	-28.09
≤6.5 h	448.20	11158.06 (16.40%)	-98.77	1004.23	-2591.56	-1587.34

Next, we delve into a more detailed analysis of the policy measure's impact at route level in terms of CO2e Savings/TTG and economic benefits, as illustrated by Figures 3 and 4 respectively. Figure 3 demonstrates that in 4 out of the top-10 most polluting routes switching to rail would on average save travel time for passengers. The fact that many flights/seats are currently offered on routes for which a shorter rail alternative is (already) available suggests that other factors contribute to the attractiveness of air for these connections. Interestingly, Figure 3 shows that a considerable number of seats is offered on the routes with significant TTGs. Notably, two of these routes (London-Paris and Barcelona-Madrid) are also among the top-10 CO2e emitters. Considering that they are both already connected by frequent HSR services, the substantial air traffic suggests that (1) the route is served by a large number of feeder flights and (2) either rail infrastructure capacity is saturated or rail is not as attractive in relation to factors other than travel time. Thus, a SHF ban measure might face important limitations on some crucial routes due to the capacity constraints of the rail infrastructure which could prevent rail alternatives from absorbing the demand shifting due to banning air seats and/or frequencies. Evaluating the possibility of increasing the train seat supply can aid in understanding whether rail capacity constraints are the main factor hindering its competitiveness. In that case, a policy such as the SHF ban could have important repercussions on the market.

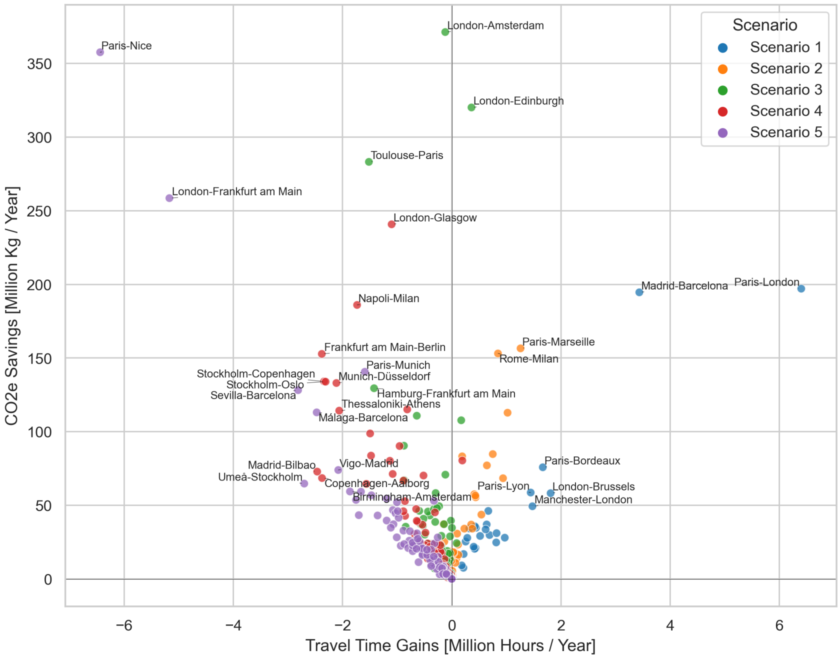


Figure 3: Scatterplot of CO2e Savings and TTG

The 45-degree axes in Figure 4 distinguish routes where CO2e benefits compensate for the TTG-related costs (e.g., London-Amsterdam) and do not (Toulouse-Paris), routes where CO2e-related exceed TTG-related benefits (e.g., London-Edinburgh) and the converse (e.g., Paris-London). The case can be made that half of the top-10 CO2e emitting routes should be banned because CO2e savings more than compensate for the extra costs related to the longer rail door-to-door travel times. The crucial role of HSR in making the sector competitive with air is evident: except for the Milan-Naples, all other routes with negative benefits are not connected by HSR. Figure 4 also

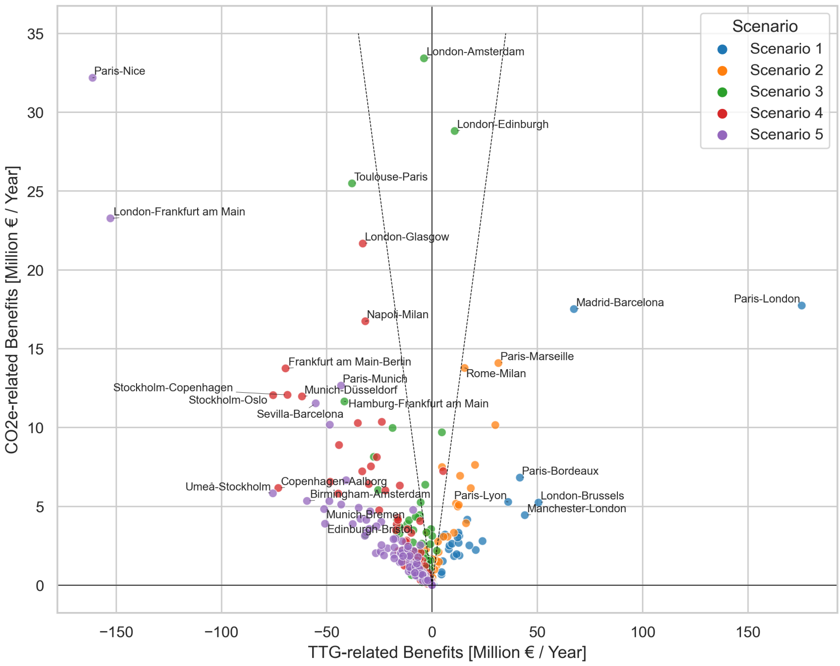
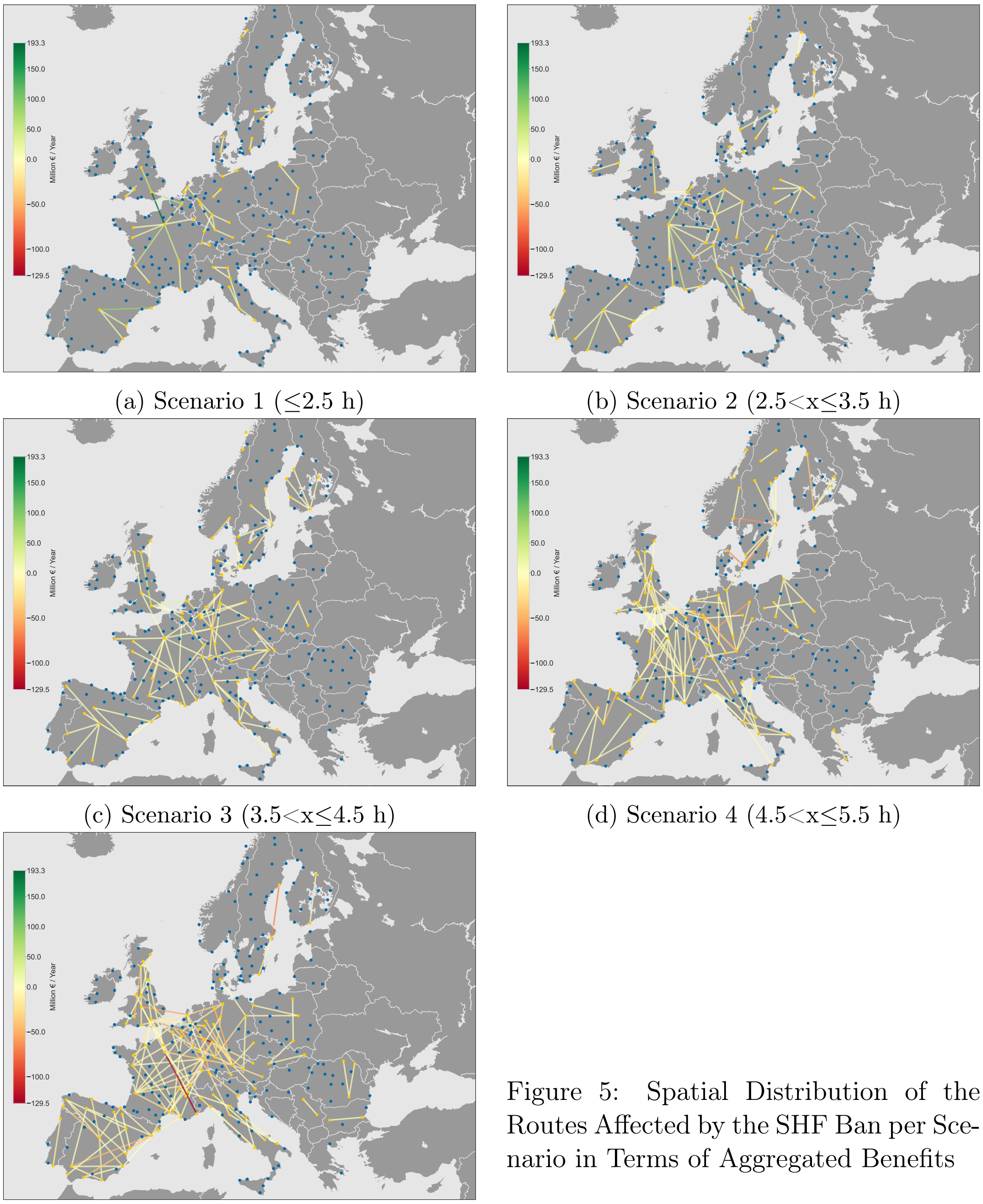


Figure 4: Scatterplot of CO2e-related and TTG-related Benefits

suggests that the French SHF ban as implemented has a rather marginal effect. The Lyon-Paris and the Bordeaux-Paris despite being affected by the policy still feature considerable TTGs that could be captured. However, it is important to note that the model most likely overestimates these TTGs, considering that only connecting passengers, not accessing/egressing the hub, are allowed on these routes. This further highlights the fundamental importance of air-rail integration to guarantee seamless direct rail connections to and from airports to substitute feeder flights and allow for a comprehensive SHF ban policy. Another limitation of the French policy resides in the low threshold employed, as shown by the Marseille-Paris that despite not falling into the currently banned routes shows considerable potential monetary gains stemming from the shorter rail travel times.

To assess the spatial distribution impacts of a potential ban, we plot the routes affected by alternative policy thresholds. Figure 5 shows that national (domestic) routes represent the majority of affected routes, probably due to the limited international rail connections and their relative poor performance. Nonetheless, some of the routes with the largest monetary gains are international



(a) Scenario 1 (≤2.5 h)

(b) Scenario 2 (2.5<x≤3.5 h)

(c) Scenario 3 (3.5<x≤4.5 h)

(d) Scenario 4 (4.5<x≤5.5 h)

(e) Scenario 5 (5.5<x≤6.5 h)

Figure 5: Spatial Distribution of the Routes Affected by the SHF Ban per Scenario in Terms of Aggregated Benefits

(e.g., London-Paris and London-Amsterdam). This implies that approaching the matter at the national level could limit the impact of such a policy and thereby put its success at risk. At the same time, the impact of the policy varies greatly across countries. Eastern Europe, for instance, is characterised by a lack of competitive train alternatives, while, at the same time, featuring a more limited air supply compared to the rest of Europe. Another key takeaway relates to the benefits of most OD pairs being distributed between -50 and 50 M€/year with a few exceptions only (e.g., London-Paris and Paris-Nice), suggesting that a few routes account for a considerable portion of the traffic affected. It is also possible to identify crucial air routes that currently suffer from not sufficiently competitive rail connectivity (e.g. Athens-Thessaloniki, Frankfurt-London, Stockholm-Oslo and Stockholm-Copenhagen). Improving rail travel times on these connections could profoundly reshape the outcomes of such policies.

Figure 6 shows the number of critical and semi-critical sections on the lines affected by the ban

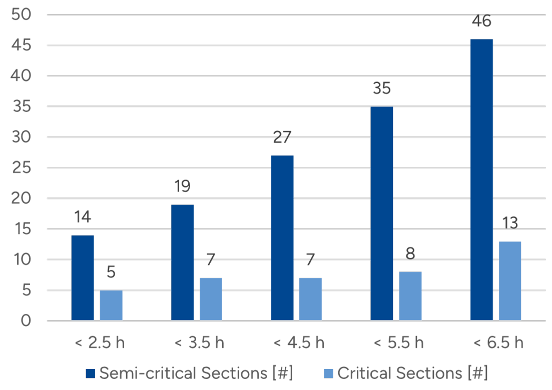


Figure 6: Critical Sections per Scenario at Swedish Level

considering a 24-hour timetable. This means that trains might run unattractive schedules unless capacity is increased by coupling train units. Notably, a considerable number of sections, mostly on the Stockholm-Göteborg/Malmö main lines, are already at critical capacity at the present state. The impact of the additional trains appears rather marginal in terms of the possibility of running the timetable, however quite considerable in terms of peak-hour traffic and congestion growth on the network. This implies that capacity ought to be increased in some sections to allow for increased timetable flexibility, delay recovery and to avoid knock-on delays.

4 Conclusion and Outlook

This study confirms that substituting short-haul flights with rail alternatives has the potential to bring about considerable benefits in terms of CO2e emissions and TTG. We estimate that implementing a 4.5-hour ban would enable cutting 7.72% of the total intra-European air market CO2e emissions (considering the CO2e of the additional train services), capturing around €880 Million benefits without causing excessive travel time losses for passengers. We suggest that further increases of up to 1 hour could be defended considering the cumulative impact of the policy. Thus, at the European level, the 5-hour threshold suggested by Szymczak (2021) might not necessarily be economically and politically undesirable, albeit results suggest that implementing this policy at the national level might lead to sub-optimal results, as international routes account for a fair share of the benefits. We argue that this policy, as implemented in France, has rather marginal effects on the total CO2e of European aviation and call for more ambitious measures, alternative or complementary to the SHF ban, if the EC targets are to be met.

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