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Is air/high-speed rail integration the panacea to curb the impact of aviation on climate change? The case of Frankfurt Airport

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Abstract

This paper revisits the concept of air/high-speed rail (HSR) integration in the specific case of congested airports, in which airport slots for (super) short-haul flights are freed by replacing them with high-speed trains. Freed slots are then likely allocated to longer flights, which leads to an increase in GHG emissions induced by flights from/to the airport into question. Such an unexpected effect is investigated through the case of Frankfurt Airport, where the HSR infrastructure was designed to connect smoothly with the airport. The ex post investigation isolates the time window during which airport capacity is stable. It confirms the increase in aviation climate impact. This illustrates that air/HSR integration is not always a relevant solution to curb the impact of aviation on climate change.

1 Introduction

High-speed rail (HSR) infrastructures and services were first developed to address railway network capacity issues and increasing competition from air transport in medium-distance markets. The ability of high-speed trains (HSTs) to curb airline flows later emerged as a way to turn medium-distance mobilities "greener", thanks to mode substitution (Givoni, 2007b). As Buier (2023) stated, HSR has thus become "the iconic transport technology of an environmentally sustainable capitalism". Air/rail relationships became more complex from 1994 onward, when Paris Charles de Gaulle and Lyon airports, France, were served by HSR services through new dedicated HSR stations (Perl, 1998). After HSR services became available at a couple of other airports, including Frankfurt, Germany, the very concept of air/HSR integration and intermodal complementarity gained attention (Givoni and Banister, 2006). At the time of writing, about 15 airports across China and Europe offer such air/HSR complementarity thanks to dedicated infrastructures. Serving an airport with HSTs induces two interdependent effects (Pagliara et al., 2021). First, it expands the airport's catchment area far beyond its usual surroundings. Second, and notwithstanding the various degrees of integration between airlines and HSR operators (Chiambaretto and Decker, 2012; Givoni and Chen, 2017; Grimme, 2007), air/HSR complementarity makes it possible for airlines to move their (super) short-haul passengers to HSTs and to curb the related air services. Public authorities, the airline industry and scholars have mostly welcomed this integration as a means of mitigating climate change. For instance, the EU 2011 Roadmap to a Single European Transport Area has set "Ten Goals for a competitive and resource efficient transport system: benchmarks for achieving the 60% GHG emission reduction target" (EC, 2011), including:

> *(6) By 2050, connect all core network airports to the rail network, preferably high-speed*

In addition, when Frankfurt Airport started to be served by HSR services in 2002, the airport's subsequent annual report stated that:

> *Furthermore, in connection with the key issue of intermodality, the systematic linking of road, rail and air transport systems at the Frankfurt Airport hub contributes to optimizing traffic flows for the benefit of environmental protection. By making more suitable means of transportation available, such as rail, many short-haul flights can be avoided. Passengers departing from, or arriving at, Frankfurt Airport have a direct connection to German Rail's high-speed ICE (InterCityExpress) network at the AIRail Terminal.* (Fraport, 2003)

In the same vein, Air France highlights four benefits of its so-called 'Air + Rail' product, including:

> *Reduce your environmental impact: By choosing a combined trip, you are opting for a travel option that emits less CO_2 on short trips*[1].

Scholars, too, have joined the clamour of support for air/rail integration. Among them, Chiambaretto and Decker (2012) state:

> *Air–rail intermodal agreements have the potential to reduce polluting emissions and congestion by improving the efficiency and the integration of different transport modes. In this respect they have the potential to provide considerable long-term societal benefits consistent with environmental policies and targets.*

However, as the next section argues, such an approach neglects the crucial role of the distance travelled in climate change issues and policies. This "tyranny of distance" (Dobruszkes and Ibrahim, 2022) prevails in aviation-induced climate change in the sense that a longer flight emits

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[1] https://wwws.airfrance.fr/en/information/prepare/voyages-combines-avion-train (accessed 27.06.2023).

more greenhouse gases than a shorter one. Such "tyranny" is accounted for by the fact that the climate benefits of (super) short-haul flights replaced by HSR services could be low and, above all, that if freed slots are taken over by longer flights, the climate benefits could eventually be negative. This invites us to revisit air/HSR integration through the lens of the distance mix between flights that are cut versus those that are developed. In this context, this paper aims to investigate the counter-effects of air/HSR integration in terms of climate change, considering Frankfurt Airport, Germany, as a case study. Frankfurt Airport is an appropriate case because it is possible to isolate a period of time when the infrastructure was constrained and the only option to accommodate more passengers (until the opening of a fourth runway in 2011) was to rely on HSR services. The investigation is conducted through a combination of airline data (change in the provision of air services) and a simplified model of fuel consumption. The remainder of this article is organised as follows. The next section proposes a review of air/HSR relationships. The section thereafter introduces the case study and methodology, including data sources. The results are then presented, followed by the conclusions.

2 The pros and cons of air/HSR integration: A literature review

Although air/HSR integration has been less popular in academic research than air/HSR competition, several research studies have been published since the seminal papers of Perl (1998) and Givoni and Banister (2006). Air-HSR integration refers to infrastructure (high-speed line passing through an airport and HSR station located on the airport site), services (HSTs routed via and calling at an airport station) and commercial arrangements between airlines and HSR companies. Table 1 summarises the expected benefits and risks of air/HSR integration according to various authors, making the distinction between the parties (ranging from travellers to transport companies to society as a whole). Most authors have highlighted the economic benefits airlines, HSR operators and airports can gain on various fronts (enlarged catchment area, increased incomes, competitive advantage, focus on more profitable, longer routes, freed airport slots etc.) of what would thus be win-win-win operations (Bory, 1999; Givoni and Banister, 2006; Givoni, 2007a; Givoni and Banister, 2007; Socorro and Viecens, 2013; Pagliara et al., 2021). Air/HSR integration, in particular, is seen as a means to increase airport capacity without having to build new runways (Givoni, 2007a). And indeed, Givoni and Banister (2006) have computed that 7.8% to 17.5% of London Heathrow Airport's slots could be freed if this airport was served by HSR, provided the two dominant airlines at the time would adopt air/HSR joint operations. Givoni and Chen (2017) found than one third of Shanghai Hongqiao Airport's slots and seat capacity could be released if the existing air/HSR facility would be valued through genuine intermodal integration, considering 27 destinations under 900 km. As for travellers' perspectives, the balance between benefits and drawbacks depends on an array of factors, including timetables, door-to-door travel times and the degree of air/HSR integration (which influences baggage handling and the consequences of a missed connection) (Givoni and Banister, 2006; Grimme, 2007; Chiambaretto et al., 2013; Reiter et al., 2022). The share of passengers who could effectively switch to air/HSR products instead of air/air (and therefore the environmental benefits) crucially depends on thresholds considered to maintain long-haul connectivity, as evidenced by Reiter et al. (2022) in the case of Germany.

Table 1. The pros and cons of Air/HSR integration in the academic literature

Who	Pros	Cons
Travellers	Easier access to the airport if poor or no short-haul air services (4),(5),(7) Transfer at global hubs with more timetable options on the long-haul routes (4),(8) Passengers get miles also from the HSR leg (10)	Uncomfortable transfers (subject to degree of integration and to HSR station design) (7),(8) HSTs cannot be held to maintain transfers in case of delay (10) Longer journeys subject to actual timetables (11) Decrease in long-haul connectivity subject to actual timetables (11)
Airlines	Efficiency gains (2) Focus on more profitable longer routes (2),(6) Larger catchment area (2),(7),(8),(12) Penetrating protected markets (5) Economic value of freed slots (5),(12) *Greenwashing*	Competition concerns since the HSR legs are not included in airline antitrust monitoring (2)
HSR operators	More passengers (2),(5),(6) More revenues (2),(5),(6) Higher load factors (2),(3),(5)	Detours required to serve the airport, which penalise passengers who do not connect with flights (4),(10)
Airports	Larger catchment area (1),(5),(12) Freed slots (5),(7) Less capacity issues; no or less need for new runways and/or terminals (5),(6),(8),(12) *Greenwashing*	*Smaller airports cannot be justified any longer*
Society	Expected decrease in GHG emissions and in less airport noise (2),(5),(7),(9),(10),(13)	Risk of increase in GHG emissions and airport noise (4),(5),(7),(9),(10),(12)

Sources: (1) Bory (1999), (2) Chiambaretto and Decker (2012), (3) Chiambaretto et al. (2013), (4) Dobruszkes and Givoni (2013), (5) Givoni and Banister (2006), (6) Givoni and Banister (2007), (7) Givoni and Chen (2017), (8) Givoni (2007a), (9) Givoni (2007b), (10) Grimme (2007), (11) Reiter et al. (2022), (12) Socorro and Viecens (2013), (13) Zanin et al. (2012). Items *in italics* are proposed by the author.

The main controversy is actually about the environmental benefits of air/HSR integration, as proposed by Socorro and Viecens (2013). On the one hand, several authors maintain that replacing (super) short-haul passengers with HSR services would result in a decrease in greenhouse gas (GHG) emissions, since the latter are much more energy efficient than the former (Chiambaretto and Decker, 2012; Zanin et al., 2012; Pagliara et al., 2021). Not surprisingly, the airline industry has supported this view as the quotes in the introduction have shown. This could be understood as greenwashing, a tangible corporate communication means in the airline industry (Guix et al., 2022; Amankwah-Amoah et al., 2023).

However, the idea of climate benefits from air/HSR integration has been criticised in two complementary ways related to the distance flown. First, physical laws underscore the fact that the longer a flight, the more energy it needs. In other words, even though (super) short-haul flights are energy inefficient (Figure 1, left), longer flights need more fuel, and thus emit more GHGs (Figure 1, right). Hence, the “tyranny of distance” concluded by Dobruszkes and Ibrahim (2022). In addition, long-haul flights operated by wide-body jets are usually less energy efficient (i.e. they burn more fuel per passenger-km) than they could be given their size because of their cabin layout, which allocates significant space to low-density business and first-class passengers (Park and O’Kelly, 2014). As a result, Dobruszkes and Givoni (2013) showed that GHG savings offered by air/HSR integration can really be trivial compared to the emissions of the connecting long-haul flight. Table 2 illustrates this with updated figures.

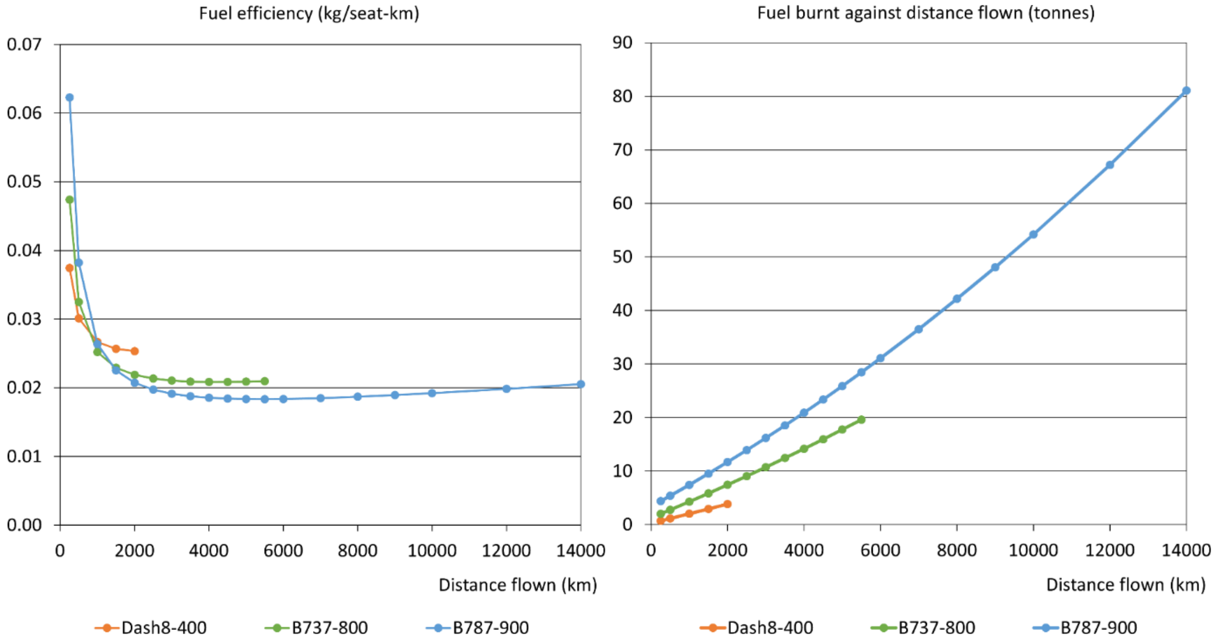

Figure 1. Fuel burnt and distance flown relationships for selected modern airliners: efficiency perspective (left) and absolute figures (right). Source: based on equations proposed by Seymour et al. (2020) for fuel burnt and on OAG Schedules for average seat capacity.

Table 2. GHG emissions of short-haul vs medium- and long-haul legs (CO_2eq. per passenger, economy class)

Routing	Short-haul	Medium/long-haul	Short-haul share
Brussels – Amsterdam – Trondheim	30 kg (158 km, Embraer 190)	298 kg (1,293 km, Embraer 190)	9.1%
Stuttgart – Frankfurt – New York	26 kg (157 km, Dash8-400)*	1030 kg (6,206 km, Boeing 787-9)	2.5%
Lyons – Paris – Tokyo	77 kg (413 km, Airbus 320)	1974 kg (9,733 km, Boeing 777-300ER)	3.8%

Distances are inter-airport great-circle distances.
*Denotes a hypothetical flight (not operated anymore).
Source: https://www.atmosfair.de/en

Second, the key importance of distance on kerosene burnt (and thus on GHG emissions) raises the issue of the flight distance mix. Especially at congested airports, it is likely freed slots will be reused, and for longer flights than those replaced by HSTs since longer flights are usually more profitable than shorter flights (Latrille et al., 2014)[2]. This can only increase GHG emissions and thus contradicts the alleged 'green' dimension of air/HSR integration. One rationale for this is the higher economic value of long-haul flights for both airlines and airports (Givoni, 2007a). Several

[2] One may then wonder why a global airline such as Lufthansa still operated short-haul flights from/to Frankfurt Airport at the time the airport was congested. This was because many long-haul flights are significantly filled, thanks to short-haul flights that play a feeder role.

authors have alerted the literature to this unexpected effect or air/HSR integration (Givoni and Banister, 2006; Givoni, 2007b; Grimme, 2007; Dobruszkes and Givoni, 2013), which can occur only if the airport is constrained and would offset the welfare benefits gained by the passengers, transport companies and airports (Socorro and Viecens, 2013). In a nutshell, the environmental benefits of air/HSR integration are conditional and

Airline and railway integration offers clear advantages, but is not a panacea to the environmental (…) problems (Givoni and Banister, 2006).

However, these warnings have been mostly overlooked and, to the best of the author's knowledge, have not been followed by empirical studies. In this context, this paper assesses ex post the climate consequences of HSR services having freed slots at a constrained airport, taking Frankfurt as a case study.

3 Investigating the unexpected climate impact of air/HSR integration: Case study and methodology

3.1 Introducing the Frankfurt Airport case study

Frankfurt Airport is by all metrics the biggest German airport and one of the largest airports in Europe. It has long been the primary hub of German flag carrier Lufthansa, considering the divide of Germany between West and East and its ban at Berlin airports until 1990. Table 3 introduces key figures to appreciate the position of Frankfurt Airport within the German context. Back to 2000, Frankfurt Airport concentrated roughly one quarter of all of Germany's departing flights and one third of seat capacity, while 320 destinations were offered out of 412 (if Germany was one single departing airport). Importantly, Frankfurt Airport then offered around 8/10 of Germany's long-haul flights and seat capacity. In comparison, 2018 absolute figures are larger but the market share of Frankfurt Airport has decreased. Indeed, Lufthansa has developed a second hub at Munich Airport (including long-haul flights) due to congestion at Frankfurt Airport.

Table 3. Scheduled passengers air services from Frankfurt, Munich and Berlin compared to the whole of Germany

Y2000	Whole Germany	Frankfurt Airport		Munich Airport		Berlin airports	
Flights (all)	838,212	203,611	24%	139,787	17%	80,569	10%
Of which >4000 km	41,170	31,930	78%	5,341	13%	132	0%
Seats (millions)	99.49	33.73	34%	16.19	16%	8.74	9%
Of which >4000 km	12.09	9.80	81%	1.33	11%	36.14	0%
Destinations	412	320		202		184	
Of which >4000 km	137	128		49		17	

Y2018	Whole Germany	Frankfurt Airport		Munich Airport		Berlin airports	
Flights (all)	976,149	242,863	25%	197,312	20%	133,502	14%
Of which >4000 km	65,468	42,173	64%	15,413	24%	1,364	2%
Seats (millions)	158.52	44.43	28%	30.78	19%	22.06	14%
Of which >4000 km	20.43	13.30	65%	4.75	23%	401.71	2%
Destinations	478	344		272		211	
Of which >4000 km	138	135		55		8	

Source: Authors' calculations based on OAG Schedules.

At the turn of the 21st century, Frankfurt Airport was indeed notoriously congested most of the time, as shown by Figure 3.5 in NERA (2004: 29) in an hourly perspective (summer 2002) and in Figure 2 in an annual perspective. Most of the available slots were then at unattractive times. In addition, plans for a fourth runway floundered (Knippenberger, 2013). In 1999, a new long-distance railway station opened very close to the passenger airport terminal as part of the new Cologne-Frankfurt high-speed line (HSL). The new station was serviced by HSTs from 2002 onward. Since runway capacity was roughly stable at the time (Figure 2 and Figure 3), HSR services were a lifeline for both the airport company and Lufthansa. Especially with Lufthansa, air/HSR integration was pushed to an unprecedented degree at the time through the so-called AIRail "hard" integration that notably included baggage handling from/to Stuttgart and Cologne railway stations (Grimme, 2007). More cities across Germany were later added. Lufthansa could cut frequencies on (super) short-haul routes and even terminate some of them (Grimme, 2007).

HSR services across Germany and to/from neighbouring countries concretely added capacity that could not be obtained from the runways until the fourth runway was eventually opened in 2011. Indeed, declared airport capacity remained stable at around 80 hourly movements from the late 1990s to the opening of the new runway in 2011, which increased declared capacity by roughly one quarter (Figure 3). In other words, the 2002-2011 period was a critical time during which air/HSR integration made it possible to free slots that were likely taken over for longer flights.

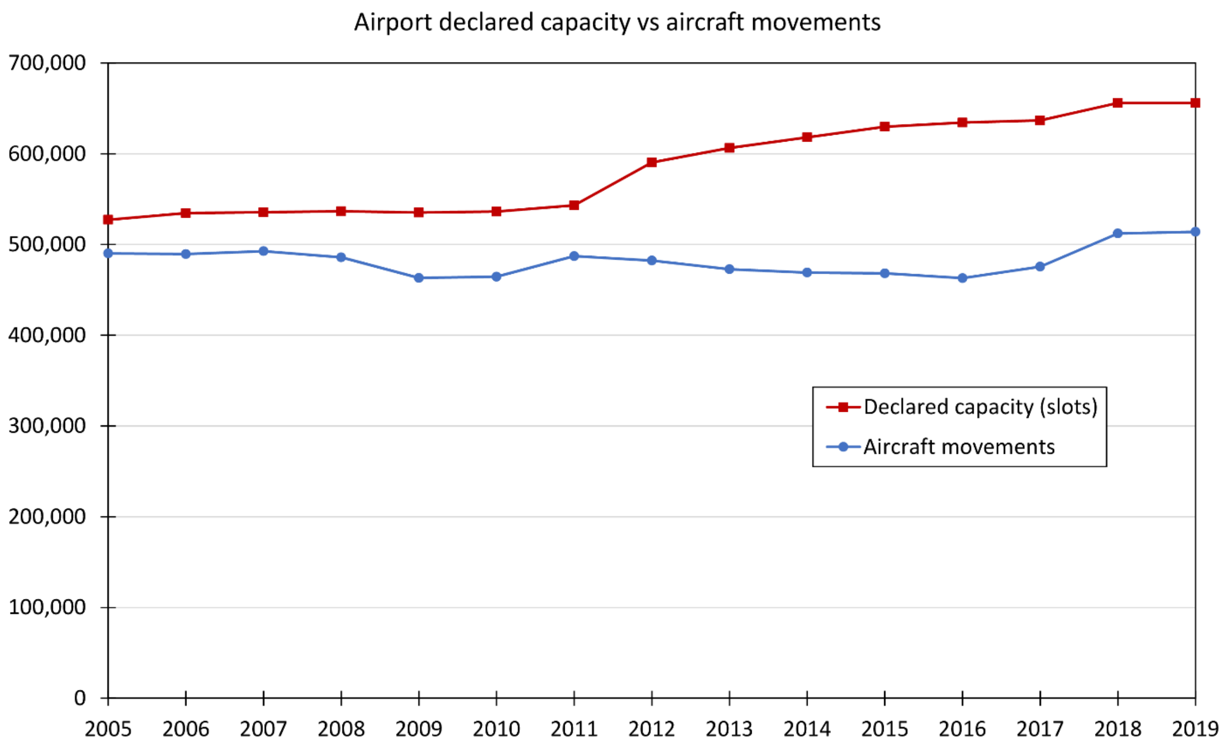

Figure 2. Declared annual capacity at Frankfurt Airport vs actual traffic. Source: obtained from Fraport AG.

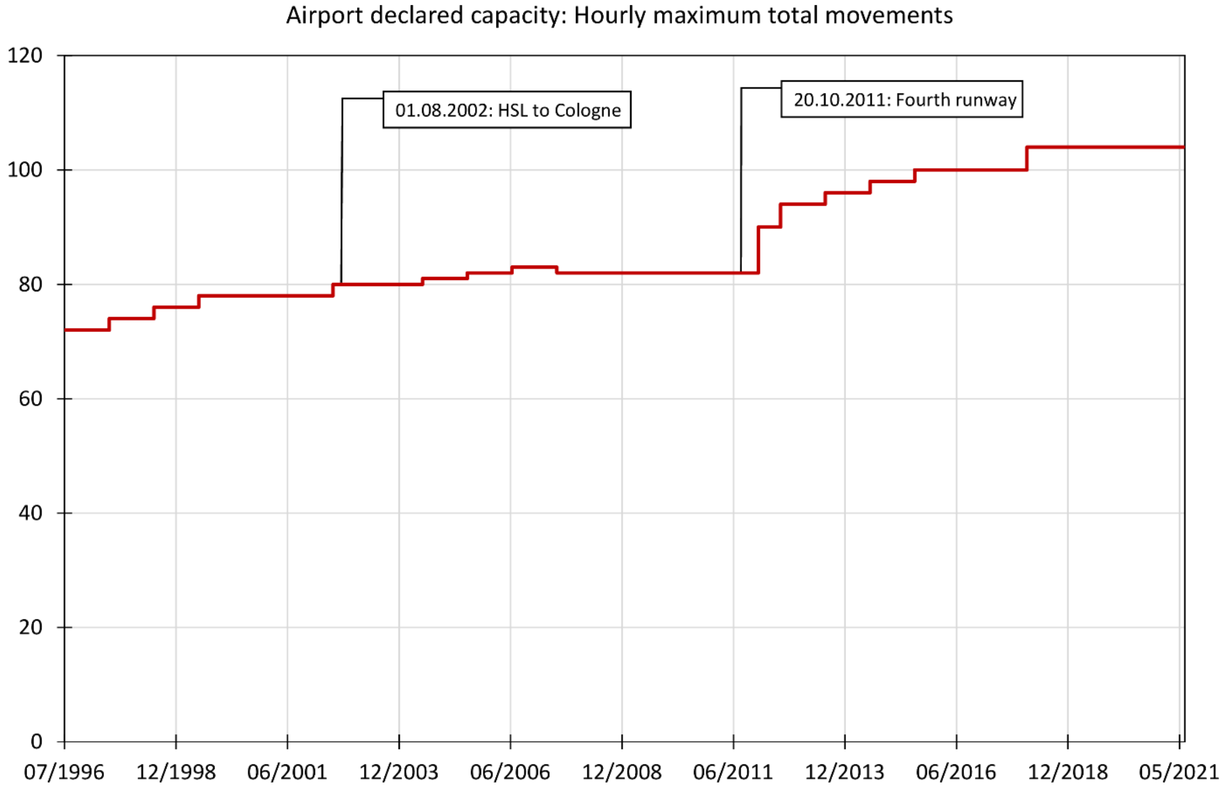

Figure 3. Declared hourly capacity at Frankfurt Airport (maximum total movements in the afternoon). Source: obtained from Fraport AG.

3.2 *Research strategy*

Like many empirical papers on aviation and climate change (e.g., Budd and Pere-Sanchez, 2016; Baumeister, 2017; Lo et al., 2020; Sun et al., 2020; Yang and O'Connell, 2020; Zhang et al., 2021), this paper is based fundamentally on aviation data (changes in the provision of air services) that feed a simplified model of fuel consumption.

The focus remains at the fuel burnt level instead of estimating GHG emissions or climate change. The reason for this is that aviation's impact on climate – estimated through radiative forcing [RF] or effective radiative forcing [ERF] techniques – is not strictly proportional to GHG emissions. The non-CO_2 component of aviation-induced climate change is estimated at two thirds, i.e., a ratio of 3 between total aviation ERF and CO_2-only aviation ERF (Lee et al., 2021). However, the magnitude of the non-CO_2 component depends on atmospheric conditions where/when emissions take place (van Manen and Grewe, 2019; Dahlmann, 2021) and are therefore altitude, latitude and time (day/night and month) dependent. This suggests that factor 3 should not be applied to one single flight (Lee et al., 2021) and calls for sophisticated modelling and heavy computations beyond the scope of this paper, which thus remains at the stage of fuel burnt estimates. It is explicitly assumed not to show CO_2 emission figures. In the case of aviation, indeed CO_2 emissions are strictly proportional to fuel burnt but have the drawback of masking the non-CO_2 climate effects.

Several simplified models for aviation fuel consumption are available. These are all based on aircraft type and distance flown. Beyond similar results (see Figure 5 in Dobruszkes et al., 2022b), the FEAT (Fuel Estimation in Air Transportation) model proposed by Seymour et al. (2020) has been considered for several reasons, including:

- Quadratic functions that take into account the extra fuel needed for longer flights, and thus the extra aircraft weight at take-off (Figure 1, right).
- Equations (one per aircraft type) are published so easily usable for any distance flown.
- Wide range of airliners being covered (175).
- Calibration that already includes detours faced by commercial flights compared to the hypothetical shortest route (great-circle distance).

3.3 *From airline data to fuel burnt*

The ex post investigation of air service provision from Frankfurt Airport is based on passenger aviation data supplied by private company OAG. The OAG Schedules product offers an extensive description of scheduled passenger flights disaggregated at the flight level. For the purpose of this paper, relevant fields are origin airport (Frankfurt Airport), destination airport, operating airline, frequency, seat capacity, detailed aircraft type and inter-airport great-circle distance. Data were extracted for the following years:

- 2000: Reference year before the introduction of HSR services at Frankfurt Airport.
- 2004: First effects of air/HSR integration on the provision of air services.
- 2010: Last year before the opening of the fourth runway in 2011.
- 2018: Pre-pandemic year that includes traffic growth allowed by the new runway.

Operating carrier and seat capacity are not needed per se. However, aircraft type in OAG Schedules is sometimes vague (e.g.: "Boeing 737 all pax models") while FEAT equations need the specific model (e.g., B737-800). This calls for disambiguation. For this purpose, the AeroTransport Data Bank (ATDB)[3] was useful since it proposes historical, detailed fleet records for thousands of airlines. Along with seat capacity, this made it possible to clarify aircraft type when needed.

The last step was thus to compute fuel burnt for each flight based on aircraft type and distance flown and to multiply the result by its annual frequency. Results are presented mostly as graphs split by distance range (<500, 500–1,000, 1,000–4,000 and >4,000 km). Although there is no consensus on thresholds in the literature, these ranges can be considered as super short-haul, short-haul, medium-haul and long-haul, respectively.

It is worth noting that this methodology could be replicated to other case studies since the datasets used in this paper are global. However, one limitation is that the fuel-burnt functions proposed by Seymour et al. (2020) have not been completed for the newest airliners, which have entered commercial service since then (e.g., the A330-800) or would later be certified (such as the B737 Max 7 and 10).

4 Results

Figure 4 shows changes in the number of passenger flights operated from Frankfurt Airport. Overall traffic has increased, but with opposite trends according to distance ranges. During the 2000-2010 decade, one notes a decrease in super short-haul flights (i.e., less than 500 km) (–6,640) but an increase in longer flights (+24,720, of which +10,725 were over 4,000 km). The net change is thus +18,080 flights. At this stage however, one does not know how much these dynamics can be attributed to the development of HSR services from/to Frankfurt Airport. To clarify this, Table 4 disaggregates the 2000-2010 trend in the number of flights shorter than 500 km, i.e., the market in

[3] See http://www.aerotransport.org

which mode substitution can reasonably occur. It appears that for the group of routes where efficient HSR services (less than three hours of travel time) have opened, airline frequencies have decreased by 32.8%. On the other routes shorter than 500 km, airline frequencies have remained stable (+1.2%). Interestingly, the share of Lufthansa flights in 2000 was 99% for the former group against 74% for the latter group. Lufthansa is therefore the airline which has cut back on super-short haul flights, thanks to its air/HSR "hard" integration. The HSR effect is thus very clear, and HSR operations made it possible to free 7,225 annual slots when comparing 2010 and 2000, of which only 585 were reused for super short-haul flights. The remaining freed slots have contributed to the increase in flights longer than 500 km.[4]

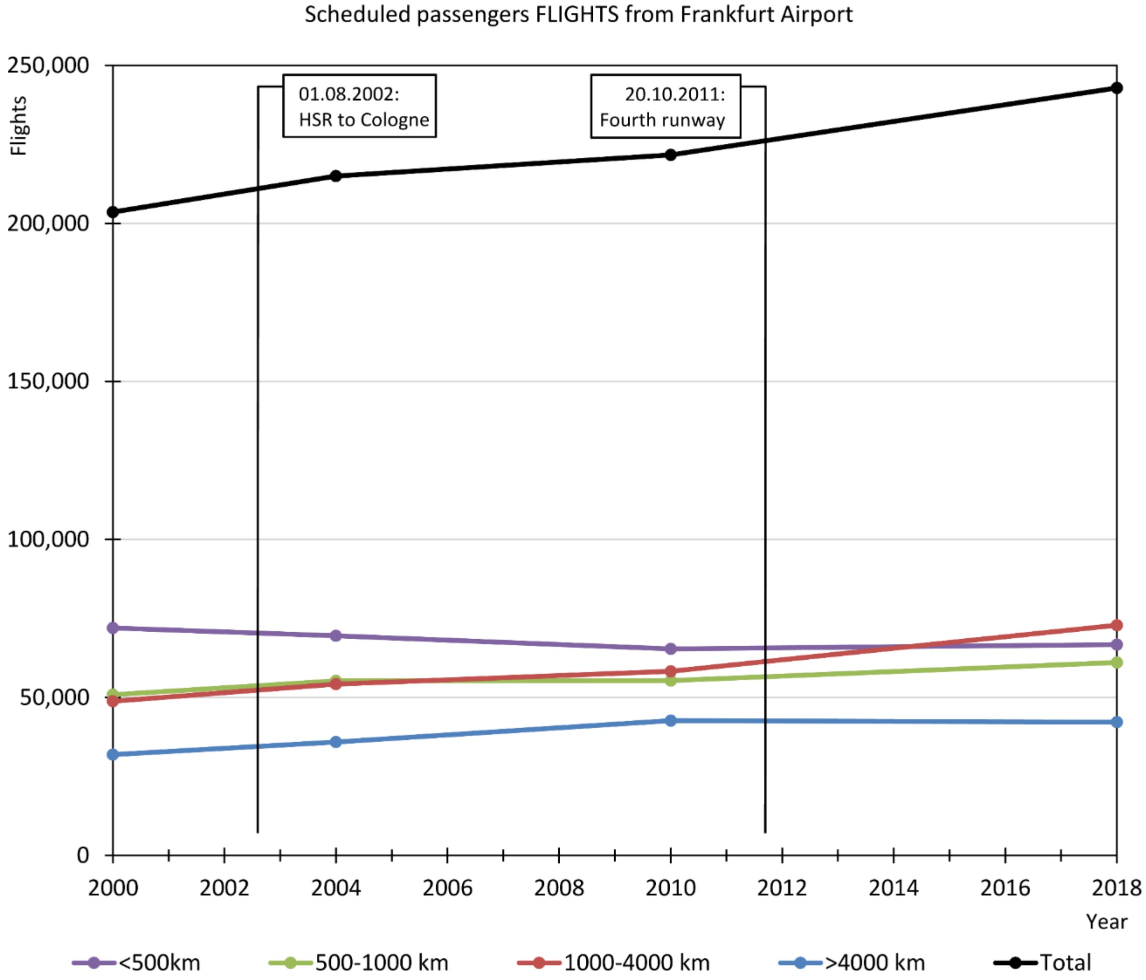

Figure 4. Change in the number of scheduled passenger flights departing from Frankfurt Airport by distance range. Computed by the author from OAG Schedules.

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[4] The remainder of the increase was arguably due to a decrease in cargo, charter and general aviation flights.

Table 4. 2000-2010 change in the number of passenger flights departing from Frankfurt Airport and shorter than 500 km

	2000	2010	2000-2010 change	
On airline routes with HSR services up to three hours	22,061	14,836	–7,225	–32.8%
Other airline routes (no HSR or HSR services longer than three hours)	49,943	50,528	+585	+1.2%
All airline routes shorter than 500 km	72,004	65,364	–6,640	–9.2%

The following decade, which started with the opening of the fourth runway, saw an increase in flights in the 500-1,000 and 1,000-4,000 km ranges. Note super short-haul flights (which include spokes to Frankfurt Airport hub from/to cities where HSR services are non-existent or likely too long) re-increase, while long-haul flights (>4,000 km) slightly decrease, so the net change is eventually +21,172 yearly flights when comparing 2018 to 2010.

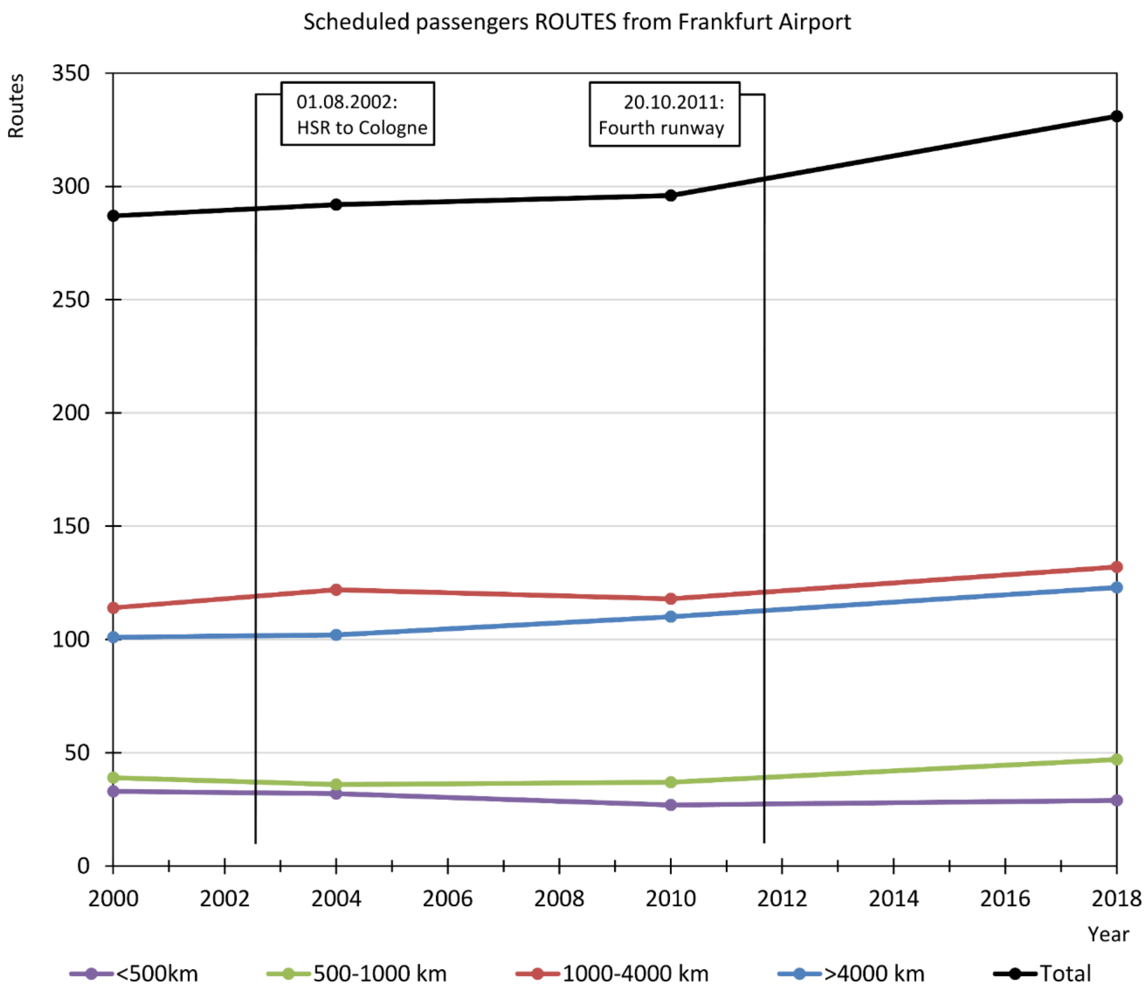

Figure 5. Change in the number of scheduled passenger routes servicing Frankfurt Airport by distance range. Computed by the author from OAG Schedules.

All these changes are the result of an increase/decrease in frequencies on pre-existing routes and of airline network dynamics, with both routes terminated and routes opened. The net result of these dynamics per distance flown can be found in Figure 5. When comparing 2010 to 2000, the total number is nearly stable (292 routes versus 287). However, one observes a decrease in routes shorter than 1,000 km (–8) and an increase in longer routes (+4 routes of 1,000-4,000 km and +9 routes longer than 4,000 km). Beyond these aggregated changes, Figure 6 unveils the geography of the main routes that were operated from Frankfurt Airport in 2010 but not in 2000. The map highlights the dominance of interregional routes among these creations (to North America, the Caribbean, Sub-Saharan Africa, the Middle East and Asia) compared to the European area. There are more route creations than suggested by Figure 5, which shows only the net change. Having said that, before the new runway opened in 2011, these new routes could not have been opened without new capacity notably offered through air/HSR integration. Then, during the 2010–2018 period, there was a significant increase in the number of routes, mostly over 500 km, with a net increase of 35.

Figure 6. New scheduled passenger air routes operated from Frankfurt Airport (2010 vs 2000). Computed by the author from OAG Schedules.

The key issue is of course how all these dynamics, along with airlines' fleet modernisation over time, result in fuel burnt. The answer is given in Figure 7 and in Table 5. During the 2000–2010 period, some fuel burnt could be saved, thanks to the decrease in flights shorter than 500 km (–33.6 thousand tonnes or –20%). Nearly no change is observed on the 500-1,000 km market (+1.8 thousand tonnes or +1%). In contrast, the increase in fuel burnt was significant on flights from 1,000 to 4,000 km (+56.3 thousand tonnes or +15%) and sharp on flights longer than 4,000 km (+443.3 thousand tonnes or +19%). The climate gain on super short-haul flights is thus trivial compared to the adverse impact from the 500+ km markets (+501.5 thousand tonnes), and the net estimated change is eventually +467.8 thousand tonnes or +16% (i.e. +46.8 thousand tonnes per year on average). In contrast, the 2010–2018 period saw a smaller, although significant, further increase in fuel burnt (+188 thousand tonnes or +5%, i.e. +23.4 thousand tonnes per year on average) (Figure 6).

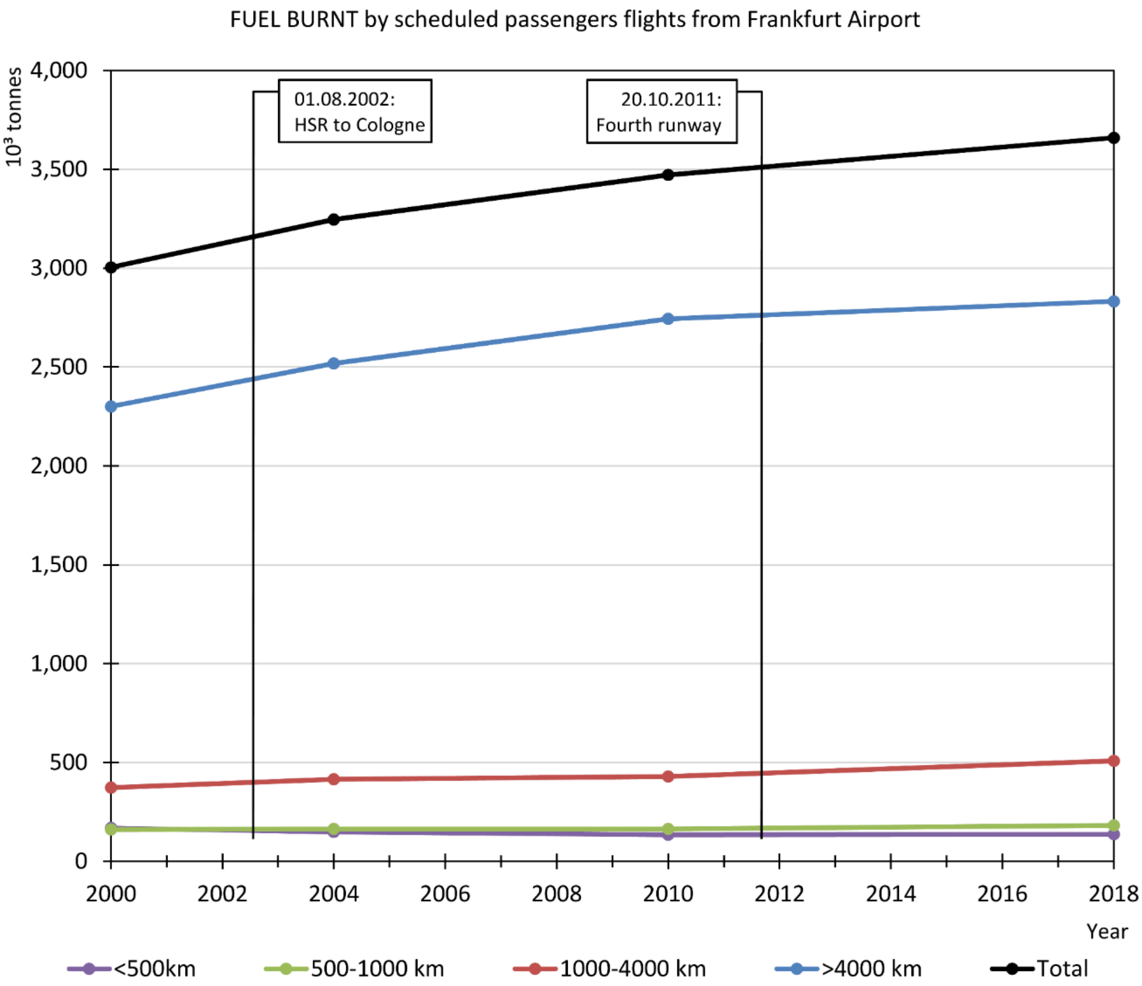

Figure 7. Change in fuel burnt by scheduled passenger flights departing from Frankfurt Airport by distance range. Computed by the author from OAG Schedules and Seymour et al. (2020).

Table 5. 2000-2010 change in absolute fuel burnt by scheduled passenger flights departing from Frankfurt Airport by distance range and by route history (thousand tonnes)

Distance flown	Pre-existing routes	New routes	Ended routes	Total 2000-2010 change	
<500 km	–28.2	0.0	–5.4	–33.6	–20%
500–1000 km	+8.6	+4.9	–11.7	+1.8	+1%
1,000–4,000 km	+28.0	+58.4	–30.0	+56.3	+15%
>4,000 km	+236.1	+374.9	–167.7	+443.3	+19%
All routes	+244.5	+438.2	–214.8	+467.8	+16%

5 Discussion and conclusions

The development of high-speed rail networks has induced research on counter-effects, including spatial equity issues (e.g., Cavallaro et al., 2023), social inequality in usage (Dobruszkes et al., 2022a), freeing capacity on the traditional network for local and freight services (Cheng and Chen, 2023), the complex relationships between transport modes and induced traffic (D'Alfonso et al., 2015; Avogadro and Redondi, 2023), and the gap between direct GHG emissions assessment versus life-cycle perspectives (Jiang et al., 2021). This paper complements these perspectives in assessing the potential unexpected effect of air/HSR integration. It also contrasts with theoretical papers (such as Socorro and Viecens, 2013, and D'Alfonso et al., 2015) by observing the real world.

It has generally been known that air/HSR substitution only results in limited climate change benefits given the low (if not very low) share of emissions induced by short flights compared to long flights (Avogadro et al., 2021; Dobruszkes et al., 2024; Reiter et al., 2022). This paper goes further and confirms that if air/HSR integration takes place at a congested airport, it can result in increased fuel burnt, and thus in aviation climate change from/to the airport into question. This is due to a transfer of slots from super short-haul flights to longer flights, which have a greater impact on fuel burnt than fleet modernisation. This paper also confirms the disproportionate impact of longer flights on aviation-induced climate change compared to the shortest ones (Dobruszkes et al, 2024). The warning of Givoni and Banister (2006), among others, was thus pertinent, and the tyranny of the distance flown in aviation-induced climate change is confirmed again. Interestingly, similar conclusions have been found in the context of car and public transport multimodality (Heinen and Mattioli, 2019).

However, one limitation of the estimate presented here is uncertainties about passenger behaviour if HSR had not freed slots at Frankfurt Airport. In such a case, several non-exclusive scenarios could have happened. First, passengers may not have flown, considering that the existence of direct services can encourage people to fly, all other things being equal (Koo et al., 2017). Second, passengers may have flown on alternative routes, and started their journey from another airport (e.g., at Cologne or Dusseldorf Airport) and/or connecting in any other airline hub. In other words, capacity issues at Frankfurt Airport would then have resulted in traffic growth somewhere else. Finally, airlines themselves may have cut shorter flights to develop longer flights to generate more profits. However, this option is limited by the need to articulate shorter and longer flights to feed the latter.

In addition, the results in this paper have policy implications. They highlight that under specific circumstances (namely, a congested airport with potential demand for more long-haul air services), the development of integrated air/HSR options can induce counter-effects in terms of energy consumption and thus of emissions, at least at the level of the airport into question. The debate then, is between at least two very opposed options. On the one hand, to continue business as usual and thus expand airports when needed, considering that in any case, competitors will do so and will capture long-haul traffic (e.g., mega-hubs in Gulf countries). On the other hand, curbing air traffic growth, which means not accepting further capacity increases and no air/HSR combinations that circumvent airport congestion issues and can make airports more attractive. However, such options could have favourable impacts on climate change only if passengers renounce flying. If they fly through alternative routings, or drive to reach their longer flights, no environmental benefits should be expected.

Between these two opposing options, one could also try to persuade travellers to choose a destination closer to home. This is only possible for those leisure passengers who can freely choose their holiday destination (in contrast to business travellers and those who visit friends or relatives in a specific location). For those "free" passengers, the very attraction of HSR services is the offer of potential tourist spots at a reasonable time from home. In that sense, HSR services could be considered not only for head-on competition on the short-haul market, but also as a means to guide tourists to more or less close places. For instance, HSR services could be considered a means to guide Madrid's residents to the Spanish coast instead of to the Bahamas.

This paper also paves the way for further research. The investigation was conducted considering changes in the supply of air services, which makes sense considering that fuel burnt and emissions are produced by planes flying. However, it would also be interesting to investigate changes in passengers' behaviour to better understand the case. This presupposes access to historical, disaggregated data and/or heavy surveys. It would also be interesting to compare changes at Frankfurt Airport with a series of other airports based on HSR/no-HSR service at the airport, various degrees of air/HSR integration, congested/non-congested airports and Asian vs European cases.

Contributor Statement

Conceptualisation, Formal analysis, Investigation, Methodology, Visualization, Writing – Original Draft, Writing - Review & Editing: Frédéric Dobruszkes

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Conflict Of Interest (COI)

There are no conflict of interest.

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