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Modal choice and passenger behavior in the aviation industry: modeling and evaluating air-to-rail shift initiatives to reduce emissions

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"The arrival matters but those you travel with count even more"

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Chapter 1 – Introduction

Nowadays, air transport is the most widely used transport mode for medium and long-distance travel. Indeed, as a result of deregulation, the primitive air transportation industry evolved exponentially to finally establish itself as a major industry in the modern global economy. The relevance of this industry lies not only in its direct economic and employment impact, rather mostly in its effect on world economic growth through the boosting of trades in people and goods. The increase in competition and the advent of low-cost carriers with the consequent downward pressure on tariffs stimulated by the liberalization process enhanced the possibilities for mobility, making previously inaccessible destinations reachable to the majority. In this respect, it is worth emphasizing the beneficial effect of air transport development for promoting the connection of remote areas to the core ones even in the absence of adequate landside infrastructure.

Since its inception, the air transport industry has been growing at a fast pace, doubling in size about every 15 years, more than most other industries. To get an idea of the size of the industry, one can refer to the data from 2019, the last year prior to the outbreak of the COVID-19 pandemic that severely affected the industry. In 2019, airlines regularly operated more than 22,000 unique city pair routes globally (IATA, 2020). This value represents an increase of almost 1,000 over the number of city-pair connections in the previous year, more than doubled compared to the values registered at the beginning of the century. Moreover, airlines carried worldwide 4.5 billion passenger journeys on a flight-segment basis in 2019, corresponding to a considerable 5.3% CAGR since 2000. The evolution of the average period between two air flights for an average citizen is representative of the enormous growth the industry has experienced over the last two decades. This value halved from 44 months in 2000 to just 20 months in 2019. As regards the economic impact, it has been estimated that the air transport industry directly sustains more than 11.3 million jobs worldwide and generates around US$ 961 billion GDP. These values increase respectively to 87.7 million jobs and US$ 3.5 trillion GDP considering the sum of direct, indirect, induced, and tourism-catalytic impacts (ATAG, 2020).

However, the rapid growth of the air transport industry does not come without drawbacks and side effects. Over the recent years, increasing concerns about the sustainability of the air industry as currently conceived, mainly because of its environmental impacts, developed.

According to the latest data from the European Environment Agency (EEA, 2021), transport is the only major European economic sector whose greenhouse gas (GHG) emissions continuously increased over the period between 2013 and 2019, accounting for around one-quarter of the EU's total emissions in 2019. Within the transportation industry, albeit road transport generates the highest proportion of the overall emissions (i.e., 72%), aviation poses the utmost concern, mainly due to its high growth rates. Indeed, air industry emissions more than doubled since 1990 reaching about 3.9% of EU GHG emissions in 2019 (EEA, 2019). Furthermore, over the period 2013-2017, emissions from the sector increased at an average rate of 3% each year (EEA, 2019). The COVID-19 pandemic has reverted this trend, seriously affecting the industry and leading to lowering international aviation emissions by 54% in 2020 compared to the previous year (EEA, 2021). However, the decline in traffic level (and accordingly emissions) due to the pandemic will be likely outdated soon. During the last months of 2021, thanks to progressive vaccination and the consequent lightening of mobility restrictions, air traffic activity raised to almost 78% of 2019 levels (Eurocontrol, 2021). This trend was confirmed during the first half of 2022, reaching traffic values of about 87% of pre-pandemic volumes in the summer months (Eurocontrol, 2022). Based on the recovery pattern, the number of EU flights is expected to return to 2019 levels between mid-2023 and the end of 2026 (Eurocontrol, 2021). The COVID-19 pandemic has therefore only postponed the issue of aviation emissions for a few years, nevertheless providing an opportunity to rethink the industry's sustainability as a whole and implement policies to reduce its environmental impact.

Among the plethora of initiatives and policies aimed at reducing aviation emissions for short and medium-haul air connections, the fostering of a modal shift towards alternative transport modes, especially high-speed rail (HSR), stands out. One of the main statements to justify such an approach refers to the *greenness* of HSR compared to air transport on a per-seat basis (Jiang et al., 2021). However, the competitiveness of HSR with air transport decreases as route length and onboard travel time increase. As a result, greater competition between the two types of modes takes place for short and medium-haul routes. Over the last decades, the competition between the two transport modes on this type of route exacerbated due to the fast widespread high-speed network all across the world. The length of in-operation high-speed networks worldwide has indeed exponentially grown, passing from almost 6,000 km in 2000 to more than 56,000 km in 2020 (UIC, 2021). This trend is expected to continue in the next years with over 22,500 km of HSR lines currently under construction that will be completed. Alongside the growth of the infrastructure, the HSR mode became increasingly popular, reaching over three billion passengers carried in 2020, mainly concentrated in Asia (especially, in China and Japan) and Europe (UIC, 2021). The rapid extension of the HSR network has progressively led many short-haul air markets to be subject to the threat of this new competitor, opening up a stream of research about the competitive dynamics between the two transport modes as well as the evaluation of the market outcomes resulting from the encouragement of one mode over the other.

In such a context, the aim of this thesis is to contribute to this rapidly growing stream of research by assessing the potentialities of substitution between air transport and HSR as well as identifying the effects of supply-side changes and regulatory policy initiatives on both air-to-rail mode diversion and induction or repression of the overall level of demand. To accomplish this, we formulate an innovative integrated methodological approach able to jointly model passenger choice and traffic generation in a multimodal context. The final goal is to provide policymakers with a series of suggestions on the effectiveness of the different policy initiatives and a number of aspects to focus on in order to maximize the outcome while containing detrimental effects on passenger welfare.

The remainder of this thesis is organized as follows. Chapter 2 discusses the state of the art of the literature about air transport and HSR and the ongoing initiatives promoted by the European Commission (EC) to reduce GHG emissions, particularly focusing on measures related to aviation. Chapter 3 details the integrated nested logit formulation adopted to jointly model demand distribution and generation and how it has been extended to the application in a multimodal context. Eventually, it provides some insights into how this framework can be integrated with airlines' and HSR operator's profit maximization problems and social welfare maximization problem. Chapter 4, Chapter 5, and Chapter 6 consist of stand-alone academic papers, each of which addresses a specific aspect of the objective of this research. Lastly, Chapter 7 provides a general conclusion outlining avenues for future research based on the limitations of the present work.

Chapter 2 – Background

2.1 Literature review

The aim of this Section is to provide a general overview of the state of the art concerning the growing research strand on the competition between air transport and HSR. This revision is far from being exhaustive[1] and is instrumental in describing the research context in which the three contributions are grounded. Each contribution will include a further literature sub-Section necessary to introduce the reader to concepts peculiar to the analyzed context.

Parallel to the widespread of HSR, a substantial body of research on the competitive mechanisms between HSR and air transportation has developed. The early research efforts in this direction investigated air-HSR interaction through the lens of competition between HSR and airlines, eventually identifying the extent to which the former is a viable substitute for the others and the resulting impact on airlines. Regarding the former aspect, most previous studies outlined strong competition between HSR and air transport in short-medium-haul markets (Givoni and Banister, 2006; González-Savignat, 2004; A. Zhang et al., 2019). Specifically, HSR has been recognized as the dominant transport mode for travel distances between 300 and 800 km, with HSR attractiveness and market share gradually decreasing as travel distances and travel times increase (Dobruszkes, 2011; Román et al., 2007; Rothengatter, 2011). Limitedly to the Chinese context where faster HSR services exist, Zhang and Zhang (2016) and Fu et al. (2012) proved that the influence of HSR competition could extend up to 1300 km. As regards the effects on airlines, evidence documented the downward pressure exerted by the introduction of a parallel HSR service on air transport service in terms of air capacity, frequency, and fares (Castillo-Manzano et al., 2015; Cheng et al., 2015; Dobruszkes et al., 2014; Givoni and Dobruszkes, 2013) and the resulting implication at both tactical (airline scheduling optimization) and strategic (market coverage and airline network choices) levels (Cadarso et al., 2017; Jiang and Zhang, 2016). Focusing on the European context, Albalate et al. (2015) revealed a significant reduction in the number of offered seats but not in the frequency of air services of routes facing HSR entrance, obtained through the use of smaller aircrafts. Jiménez and Betancor (2012) documented a reduction of air operations by 17% following the opening of four HSR lines in Spain. On the Paris-Marseilles route, the introduction of TGV brought a

[1] For in-depth literature reviews see Li et al. (2019), Zhang et al. (2019), and Dobruszkes et al. (2014).

decrease in air traffic of around 40% in the period 2000-2010 (Dobruszkes, 2011). Very radical transformations of market dynamics induced by HSR link opening are reported even in the Chinese context. Air travel demand fell by 34% after the opening of the Beijing-Shanghai HSR connection (Chen, 2017). Jiang and Zhang (2014) outlined an 80% drop in air ticket price following HSR entrance on the Wuhan-Xiamen route. Li et al. (2019) found strongly different growth rates in the number of air passengers for Chinese routes without and with an HSR alternative over the period between 2010 -2014. Indeed, the former exhibited an average annual growth of 6.4%, while the latter a decline by 0.2% annually. Although the introduction of HSR generally leads to gradual changes to the existing market equilibrium (Albalate et al., 2015), the literature is not exempt from presenting cases where substitution patterns brought rapid effects. For instance, in March 2010, all the flights between Zhengzhou and Xi'an were canceled just seven weeks after the introduction of the HSR service (Fu et al., 2012). Another example is the Guangzhou–Wuhan air route that one year after the HSR line opening suffered a 48% drop in offered seats despite the remarkable reduction of airfares by more than 50% (Fu et al., 2012).

Alongside research about air-HSR competition market outcomes, both theoretical models and empirical assessments have been developed and implemented to investigate how different modes' attributes impact the choice of one or the other transport mode, thus resulting in heterogeneous market shares. Theoretical papers include contributions by Wang et al. (2018), Xia and Zhang (2016), and Yang and Zhang (2012) investigating ways in which travel times of HSR and airlines and HSR speed influence passengers' choice of travel mode. Empirical studies confirmed these findings: HSR average speed and travel time, as well as HSR frequency and offered seats, result important factors affecting the outcome of air-HSR competition (Albalate et al., 2015; Castillo-Manzano et al., 2015; Dobruszkes, 2011; Jiménez and Betancor, 2012). Nevertheless, although most studies agree on the influence of these variables, heterogeneous results emerge concerning the attribute with the greatest impact. By analyzing the Madrid-Seville route, it has been shown that speed, travel time, and comfort are the main reasons passengers choose HSR (Coto-Millán et al., 2007). Likewise, Cascetta et al. (2011), leveraging a revealed preference survey on the Rome-Naples route, confirmed that travel time is the main factor in HSR choice. Li and Loo (2017) found that airline demand in China decreases as a result of the increase in railway speed. Behrens and Pels (2012) identified frequency and travel time as the primary determinants of passengers' choice in the intermodal passenger market between London and Paris. Furthermore, Behrens and Pels (2012) outlined heterogeneous behaviors of leisure and business passengers regarding these dimensions. By analyzing a number of Chinese routes, Li et al. (2019) attributed the strong decline in the number of air passengers to the increase of HSR daily frequency of service, thus highlighting the importance of the frequency of service. Zhang et al. (2017) found that HSR travel time is a more central determinant of air traffic than frequency of service, albeit both are significant. Besides the attributes of the different transportation modes, also socio-economic characteristics of the individuals affect the choice of one or the other transport mode. Some studies suggest upper social occupational groups are over-present in HSR passengers compared to the whole population and that the introduction of HSR can boost the share of these groups among rail passengers (Dobruszkes et al., 2014; Pagliara et al., 2012). Dobruszkes et al. (2022) by analyzing *ex post* data at both national and corridor levels for various countries found that, compared to the whole population, passengers traveling using HSR are predominantly male, with higher income, highly educated, and belonging to higher social-occupational groups. Furthermore, based on mixed stated and revealed preference data from Southern Italy, Bergantino and Madio (2020) highlighted that the probability of changing the modal choice towards HSR increases with age, income and education as well as the purpose of the trip (business), but the latter only for long-distance connections (above 500 km).

Apart from being a competitor, HSR in some cases is proven to complement air transport. Indeed, under a joint-decision-making scenario, the two transport modes can collaborate with each other in offering intermodal services (Jiang and Zhang, 2014). In this regard, a rising body of literature focuses on air-HSR cooperation. Airline-HSR service integration has been increasingly advocated as a possible solution to relieve hub airport congestion, to mitigate the negative environmental externalities of air transport, and extend airport catchment areas (Givoni and Banister, 2006; Miyoshi and Givoni, 2013). In this respect, cross-modal collaboration has emerged as an effective way to serve as a feeder to air, especially under hub airport capacity constraints (Socorro and Viecens, 2013; Xia and Zhang, 2016).

Investigating the market structure of competing or collaborating transport modes (i.e., HSR and air) is crucial even from an environmental perspective. Over recent years, air-to-rail substitution has been often promoted in an attempt to reduce GHG emissions. One of the main statements to justify such policies refers to the *greenness* of HSR compared to air transport on a per-seat basis. In this regard, several empirical evidence showed that the (per-seat) GHG emissions of airlines are higher than those of HSR (Givoni and Banister, 2006; Givoni and Dobruszkes, 2013; Janic, 2011; Jia et al., 2021; Jiang et al., 2021; Robertson, 2016). Robertson (2016) pinpointed that the substitution of HSR for short-haul aviation resulted in CO_2 avoidance in an Australian case study. Jia et al. (2021) found that substitution toward HSR reduces CO_2 emissions. Givoni and Banister (2006) reported for the London Heathrow–Paris Charles De Gaulle route lower local air pollution emissions for HSR compared to air. Nevertheless, the introduction of new HSR services does not necessarily lead to overall environmental advantages. New HSR services may stimulate further passenger demand, offsetting the overall benefits of the air-HSR substitution effect (D'Alfonso et al., 2015). Empirical evidence in this direction found quite mixed results. Dalkic et al. (2017) highlighted a reduction in CO_2 emissions due to a shift to HSR on Ankara-Eskisehir and Ankara-Konya routes, taking into account induced demand and emissions from other modes. Zanin et al. (2012), investigating air-HSR complementarity in Madrid Barajas Airport, found a 10% reduction in emissions. Other studies considering induced demand report less favorable outcomes (e.g., D'Alfonso et al., 2016, 2015). Jiang et al. (2021) argued that induced demand may fill airline or airport capacity when substitution to HSR takes place. This side effect could take place not only considering induced demand at the route level but considering the airport as a whole. Indeed, newly generated traffic induced by the complementary relationship between air and HSR as well as when the runway capacity freed is used to accommodate more (long-haul) flights can dampen, or even erase, modal substitution environmental benefits (Jiang and Zhang, 2014; Li and Sheng, 2016; Liu et al., 2019; Xia et al., 2019). Lastly, the least favorable effects of substitution to HSR are highlighted considering in the assessment not only emissions that occur during the operation phase but those generated over the entire life cycle. Indeed, infrastructure construction and manufacturing and maintenance of vehicles, in general, generate larger negative impacts on the environment (Jiang et al., 2021). For instance, Westin and Kågeson (2012) estimated the amount of traffic diversion from other modes required to offset the embedded emissions from constructing a new 500 km HSR line in at least 10 million annual one-way trips. Similar conclusions are reported by Miyoshi and Givoni (2013) for the London-Manchester route. Ultimately, due to the novelty of the debate, mixed and inconclusive evidence emerges when assessing the absolute environmental benefits of HSR introduction. Positive outcomes are generally reported considering the per-seat emission level of HSR compared to air transport. Nevertheless, it clearly appears that traffic generation patterns due to the introduction of a new HSR connection cannot be overlooked.

Albeit the importance and relevant effort to estimate the magnitude of HSR induced demand, so far, only a few studies have focused on explicitly modeling its generation in a multimodal context (D. Zhang et al., 2019). Some examples are proposed by Ben-Akiva et al. (2010), Cascetta et al. (2013), and Cascetta and Coppola (2014). In detail, Ben-Akiva et al. (2010) modeled the induced demand based on the relationship between existing HSR demand to current HSR travel times and costs, including as covariates socioeconomic variables related to population and employment for the Naples-Rome corridor. Furthermore, Cascetta et al. (2013) evaluated Italian national passenger demand before and after HSR major openings based on a retrospective survey gathered between 2008 and 2011, while in a subsequent study Cascetta and Coppola (2014) extrapolated induced demand applying a trip-frequency model which estimates the probability that a user undertakes a given number of ex-province trips for a given purpose in a reference period. The main reason for the lack of explicit modeling of induced demand in a multimodal context can be attributed to the difficulty of modeling induced demand via the conventional 4-step travel demand modeling in which trip generation is not sensitive to changes in the level of service (Kitamura et al., 1997). Moreover, it proves to be difficult to disentangle the portion of new passengers traveling due to improved supply from the portion resulting from demand growth due to GDP fluctuations and, more in general, to the macro-economic context. A possible solution to these problems is to aggregate trip generation and distribution modeling in an integrated model able to capture the sensitivity of demand to supply attributes. Indeed, by including an explanatory variable capturing the level of service into the generation model, trip generation will become sensitive to the changes in service level. Therefore, at least short-term effects on demand can be estimated (Yao and Morikawa, 2005). Such a type of approach has recently received increasing attention in the field of air transportation to understand and model supply-demand interactions. Specifically, several studies have adopted it formulating integrated nested logit model (Birolini et al., 2020; Hsiao and Hansen, 2011; Wei and Hansen, 2005). In a multimodal context, only Yao and Morikawa (2005) proposed such a type of approach, introducing in trip generation model an accessibility measure able to capture the short-run behavioral effects such as changes in travel departure times, routes switches, modes switches, longer trips, changes of destination, and new trip generation.

2.2 EU climate policy and ongoing initiatives

Today, the European Union (EU) is at the forefront of efforts aimed at tackling climate change. Although the first initiatives promoted by the European Commission (EC) to fight climate change date back to the 1990s, the major initiatives have been deployed since 2000, when EC launched the European Climate Change Programme (ECCP). The programme aimed to identify the most environmentally and cost-effective EU measures with the potential for reducing GHG emissions to fulfill the Kyoto protocol targets. One of the most significant contributions of the ECCP is the development of the EU Greenhouse Gas Emission Trading Scheme (EU ETS), still today one of the largest GHG emissions trading schemes in the world. In 2020, the EU became the first continent to pledge to reach climate neutrality by 2050 through the European Green Deal (EC, 2019). To this aim, the EC adopted a set of proposals to make the EU's climate, energy, transport, and taxation policies fit to achieve the intermediate goal of reducing net GHG emissions by at least 55% by 2030, compared to 1990 levels. These new targets represent a further tightening on previous objectives set in 2011 at -40% and -80% by 2030 and 2050, respectively (European Commission, 2011).

Within these initiatives, transportation industry policies play an outstanding role. The transport industry indeed accounts for a quarter of the EU's GHG emissions, and is still growing (EEA, 2021). To achieve the European Green Deal target, a 90% reduction in transport emissions compared to 1990 levels by 2050 is needed. This objective increases by 30% the previous goal of GHGs reduction defined within the 'Roadmap to a Single European Transport Area' in 2011 (i.e., reducing emissions by 60%). The EU vision for the (future) transport system (i.e., Sustainable and Smart Mobility Strategy) is based on three pillars: (i) make all modes of transportation more sustainable, (ii) make sustainable alternatives widely available in a multi-modal transport system, and (iii) put in place right incentives to drive the transition (EC, 2020a). For its part, as far as the first pillar is concerned, the air transport industry comprising aircraft manufacturers, airlines, airports, and air navigation service providers is committed to reaching net zero CO_2 emissions from all flights within and departing from the EU by 2050 (SEO, 2021). This ambitious target, in line with the goals set in the European Green Deal and the Paris Agreement, will be achieved through different sustainability measures including the improvements of aircraft energy efficiency, new aircraft technologies (e.g., electric-powered aircraft), more efficient air traffic management (to be pursued through the improvement of the Single European Sky), and transition to the use of sustainable aviation fuels (SAFs). In this regard, the ReFuelEU Aviation initiative includes the first-ever obligation for fuel suppliers to include an increasing share of sustainable aviation fuel (SAF) in fuel supplied at EU airports. The second pillar entails EC to create appropriate conditions for the higher uptake of sustainable travel alternatives that are safe, competitive, and affordable. To this end, EC set the objective of tripling the length of the existing HSR network by 2030 and promoted the connection of core airports to the rail network within the Trans-European Transport Network (TEN-T) project (EC, 2011). Furthermore, EC aims to convert the majority of medium-distance passengers to rail and double HSR traffic in Europe by 2030 placing rail transportation at the forefront of its transportation policy (European Council, 2021). Indeed, similarly to air transportation deregulation during the 1990s, since 2001 EC has started the process of liberalization of the European rail passenger market with the ultimate goal of developing an efficient and competitive EU-wide railway network through the creation of a Single European Railway Area. The legislative packages in this direction aim to make the industry more competitive relative to other transportation modes by leading railway operators to become more responsive to customer needs and improve the quality of their services as well as their cost-effectiveness. Lastly, the third pillar refers to the internalization of external costs of transport. The price of transport indeed should reflect the impact that different modes of transport have on the environment in order to give passengers the right incentives for adopting sustainable behaviors. At present, the most important instrument of carbon pricing in order to internalize the cost of CO_2 emissions is the EU ETS, applied to intra-European flights since 2012. In the 'Fir for 55' package, the EU committed to reduce the ETS allowances allocated for free to airlines as well as end the current tax exemptions for aviation fuel. These initiatives will be coordinated with action at the global level, such as the inclusion of extra-European flights in the ICAO Carbon Offsetting and Reduction Scheme for International Civil Aviation (CORSIA) initiative.

Overall, reducing the environmental footprint of the transportation industry is a core feature of the Commission's strategic vision. This results in a wide plethora of initiatives and policies that are being and will be implemented in the next years at the European level. Most of them, as discussed, aim at fostering a modal shift on medium-short passenger routes from air to rail, both by promoting competition and efficiency within the railway industry and charging airlines (and consequently air passengers) for the environmental costs of the negative externalities generated. Analyses and tools to assess the effectiveness of the different ongoing initiatives in the light of the competitive dynamics of the different transport modes and their supply characteristics are therefore urgently and increasingly needed to provide the regulator with the best possible information set to on which deliver their decisions. This study seeks to provide answers (at least partially) to these concerns.

2.3 Research contribution and outline

This thesis is deeply rooted on the emerging literature concerning multimodal competition and the different ongoing initiatives promoted to reduce aviation emissions. The main contributions of the current thesis to the state of the art are twofold. First, from a methodological perspective, an innovative methodological approach to jointly model demand distribution and generation in a multimodal context has been proposed. More in detail, borrowing from aggregated nested logit models previously applied to estimate air transportation supply-demand interaction, we structured a methodological setting able to deal with the application to a multimodal context taking into account all the specificities required (i.e., heterogeneity in characteristics of transport modes and passenger preferences). Such an integrated approach represents an advancement in methodologies currently applied for modeling supply-demand interactions in a multimodal context, overcoming the limitations of *ex post* counterfactual analysis representing to date the state-of-the-art procedure used by policymakers to estimate diverted and induced demand. Second, from an empirical perspective, a comprehensive evaluation of the possibilities of substitution between air and HSR at the European level as well as the assessment of the effectiveness and the impacts of different policy initiatives in this direction has been conducted. The final goal is to provide policymakers and researchers suggestions on the effectiveness of the different policy initiatives intended to stimulate air-to rail shift and a number of critical aspects to focus on when implementing such type of measures.

The thesis follows the ‘collection of papers’ format. While the first contribution (Chapter 4) constitutes a stand-alone academic paper, Chapter 5 and Chapter 6 share the same innovative methodological approach. This methodological setting is thoroughly defined in Chapter 3 together with a general formulation of airlines’ and HSR operator’s profit maximization problem and the social welfare maximization problem that constitute the basis for potential future follow up research.

More in detail, Chapter 4 evaluates the degree of technical substitutability of intra-European short and medium-haul routes with alternative transport modes. This assessment stems from the regulatory initiatives implemented by different countries (e.g., France and Austria) following the recent COVID-19 pandemic crisis. The research aims at mapping at the European level the air routes whose alternative travel infrastructures would guarantee substitutability, estimating also the potential environmental benefit of discontinuing air flights on these routes and outlining the main challenges that policymakers need to address to enable the successful policy implementation. Both the second (Chapter 5) and the third contribution (Chapter 6) leverage the innovative methodological approach developed in order to jointly model trip distribution and generation in a multimodal context. Specifically, Chapter 5 deals with the investigation of the effects on the overall demand following changes in supply characteristics or the implementation of regulatory policy initiatives. Indeed, as previously described in Section 2.1, one of the main determinants of the effectiveness of air-to-rail modal shift in reducing GHG emissions derives from the induced demand. By analyzing the mature multimodal market between London and Paris, we simulate the effects of some possible regulatory initiatives as well as changes in the characteristics of supply on the overall demand, providing useful information for policymakers on the level of demand induction (or, conversely, repression) deriving from policies to incentivize or discourage rail transport mode. Chapter 6 focuses instead on a much less mature market that witnessed the opening to HSR competition only in recent years, namely the market between London and Amsterdam. In this context, we investigate the impacts of possible measures to enhance the market share of the HSR alternative with the final aim to decrease GHG emissions, taking into account that such a policy may increase overall demand. The effectiveness of the different policy initiatives is discussed both examining their potential to stimulate diversion and their impacts on passengers' welfare, thus providing insights about the optimal levers on which to act in order to increase HSR market share.

The three essays composing this thesis are thoroughly described in the following.

Chapter 4: *Replacing short-medium haul intra-European flights with high-speed rail: impact on CO_2 emissions and regional accessibility.*

The research evaluates the extent to which intra-European air routes are also operated by other competitive transport modes and identifies which short-medium haul routes could potentially be subject to a cancellation policy considering the current infrastructural provision. Route substitutability is evaluated based on not only the increase in travel time faced by passengers due to the enforced modal shift, but also the corresponding change in their generalized travel costs. The contribution estimates the overall reduction in offered seats and CO_2 emissions following the cancellation of substitutable air routes as well as how the above-mentioned potential substitution patterns characterizing intra-European routes would impact the regional accessibility. The analysis reveals that about 26.5 million (3.02% of intra-European) offered seats may be cancelled and substituted with alternative trips without any significant increase in travel time for passengers. The French domestic market and flag carrier Air France lead the standings both in terms of the number of substitutable offered seats and potential CO_2 savings. At the regional level, we outline that banning short-haul flights would preserve disadvantaged regions by placing the burden of reducing emissions from aviation mainly on areas already efficiently served by alternative transport modes.

The paper was co-authored by Mattia Cattaneo (University of Bergamo), Stefano Paleari (University of Bergamo), and Renato Redondi (University of Bergamo). The early version of the paper was presented during the Junior researchers' session of the 2020 Aviation Management Economics Conference (AMEC). The paper was published in 2021 in *Transport Policy*.

Chapter 5: *Diverted and induced demand: evidence from the London-Paris passenger market.*

The contribution investigates how both variations in supply characteristics and implementation of regulatory policy initiatives affect demand distribution and contribute to inducing or reducing overall demand in the multimodal London-Paris passenger market. To this aim, the methodological approach defined in Chapter 3 has been applied to an extensive dataset about passenger flows between the Greater London Area and Paris during the period 2009-2019. The research confirms the importance of supply attributes, such as travel times, fares, and frequencies on passenger modal choice. Furthermore, the results find that *ceteris paribus* in the market under consideration a one-trip increase in the daily frequency of Eurostar would stimulate demand for more than 94,500 passengers per year (2.3% of current ridership), while infrastructural investments aimed at reducing HSR travel time by 10 minutes would increase current passenger flows by about 1.3%. The empirical analysis also quantifies demand implications (i.e., reduction in current demand) of a possible policy of ending air routes for environmental purposes in about 6% of current traffic level.

The paper was co-authored by Renato Redondi (University of Bergamo). The early version of the study was presented during the 24th Air Transport Research Society (ATRS) World Conference in 2021.

Chapter 6: *Policy impacts on the propensity to travel by HSR in the Amsterdam – London market.*

The research explores the impacts of possible measures to enhance HSR market share in the London-Amsterdam market. The use of the integrated model formulated in Chapter 3 allows us to evaluate the effectiveness of different policies taking into account that the tested initiatives may increase or decrease the overall demand. The results show that both the reduction of HSR fares and the application of an air ticket tax, albeit with different impacts in terms of stimulus or reduction effect on overall demand, are ineffective in increasing HSR market share, if not adequately supported by improving HSR service. Increasing HSR frequency and reducing HSR travel times constitute the best opportunities to sharp HSR ridership by stimulating a higher substitution effect than modifications in relative fares. Lastly, the recent queueing at airports, following staff shortages and strikes, significantly lower air transport demand and potentially has a substantial upward effect on HSR market share.

The paper was co-authored by Eric Pels (Vrije Universiteit Amsterdam) and Renato Redondi (University of Bergamo). The paper was developed during a visiting period at the Department of Spatial Economics & Operations Research — School of Business and Economics of the Vrije Universiteit Amsterdam, whom I thank for the hospitality. The contribution was presented during the 25th Air Transport Research Society (ATRS) World Conference in Antwerp (Belgium). The paper is currently under review in *Transportation Research Part A: Policy and Practice*.

I would like to express my deepest gratitude to all my co-authors (also to those whose contributions are not included in this thesis) for the support I received and for allowing me to grow considerably as a researcher through the experience I gained working with them. I am fully responsible for all adaptations to the contributions necessary to reorganize them within this thesis.

Chapter 3 – Methodology

In this Chapter, we first describe the integrated nested logit structure adopted in previous literature studies to estimate air transportation supply-demand interaction on which the innovative methodological approach developed in the current thesis extensively relies. Then, we detail its estimation procedure and how this methodological setting has been extended and adapted to the application in a multimodal context. The formulated model will be adopted in Chapter 5 and Chapter 6 to estimate the impacts of policy initiatives on demand diversion and induction. Afterward, we provide a general formulation of the companies' profit maximization and social welfare maximization problems by referring to a simplified version of the integrated passenger choice and traffic generation model. These latter formulations, further refined, may constitute the basis for future studies focused on the strategic responses in terms of frequency and fares of different companies following the implementation of regulation initiatives as well as the identification of the optimal level of environmental taxation that maximizes social welfare.

3.1 The integrated passenger choice and traffic generation model

To jointly analyze diverted and induced demand in a multimodal context, in the current thesis we rely on an integrated model able to simultaneously describe traffic generation and distribution patterns in a single framework. More in detail, we take a cue from the two-level aggregate nested logit model firstly adopted by Wei and Hansen (2005) to estimate air transportation supply-demand interaction, and subsequently applied in different studies on air transportation demand (e.g., Birolini et al., 2020; Hsiao and Hansen, 2011) and we structure and implement appropriate adaptations to enable its application to a multimodal context.

3.1.1 Model formulation

In this sub-Section, we present the two-level aggregate nested logit formulation adopted in the previous studies to model air transport demand generation and distribution. Figure 3.1 depicts the two-level nesting structure. The upper nest models the binary choice of whether or not to make a trip in period t and in sub-market m,[2] the lower nest models the passenger choice of the single itinerary (i.e., joint decision of the mode, route, and carrier). This structure permits to

[2] To practically estimate the model, it is useful to break down the overall market under examination in different sub-markets ($m \in M$) defined as the combination of a departure zone o and an arrival zone d.

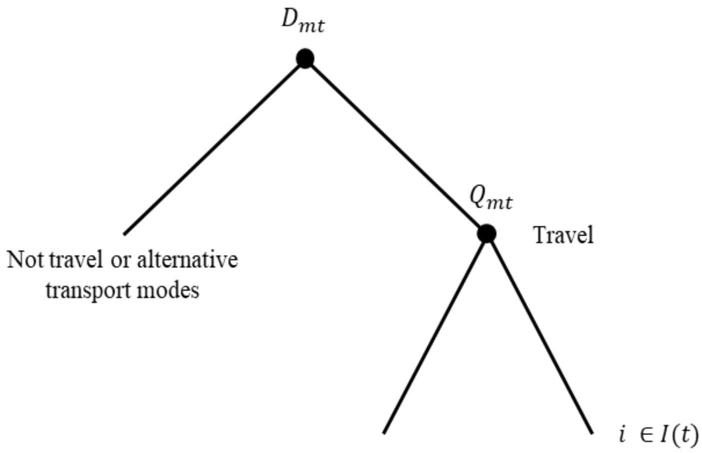

Figure 3.1: Two-level nesting structure.

estimate the determinants of passengers' choice to travel, based on inherent attributes of the connected zones (such as socio-economic characteristics) and pull-factors, namely supply-side attributes such as low travel impedance and multiplicity of available itineraries. Furthermore, given the choice to travel, this structure also allows estimating the determinants of the passengers' itinerary choice, based on the attributes of the different travel alternatives.

Considering the two-level structure described in Figure 3.1, the integrated trip decision-making process in sub-market *m* and period *t* can be formulated as follows:

$$P_{i,mt} = P_{Travel,mt} \cdot P_{i|Travel,mt} \tag{3.1}$$

where $P_{i,mt}$ is the probability of choosing travel alternative *i* in sub-market *m* and period *t*, and is the product of the probability to travel by rail or air, $P_{Travel,mt}$, and the conditional probability of choosing alternative *i* given the choice of traveling, $P_{i|Travel,mt}$. Due to the aggregated form of the model, the latter term ultimately represents the market share of alternative *i* in sub-market *m* and period *t*, which can be defined as:

$$P_{i|Travel,mt} = \frac{\exp\,(V_{i,mt})}{\sum_{j\in I(t)} \exp\,(V_{j,mt})} \tag{3.2}$$

where *I(t)* is the set of available alternatives during period *t* and $V_{i,mt}$ ($V_{j,mt}$) is the deterministic part of passenger utility of making a trip using alternative *i* (*j*) in sub-market *m* and period *t*.

Considering the upper nest, potential demand (D_{mt}) is split between travel and no-travel alternatives, with the latter representing the "outside good" that encompasses both the no-travel option and the passengers traveling using other transport modes than those considered. Previous literature studies (Birolini et al., 2020; Hsiao and Hansen, 2011; Wei and Hansen, 2005) considered as travel alternatives all the air connection in the market under examination, including in the no-travel option all the trips carried out using alternative transport modes (e.g., HSR, conventional rail, car, and ferry). Such an assumption will be relaxed in sub-Section 3.1.3 to extend the applicability of the model to a multimodal context.

Following the usual logit formulation, the probability of deciding to travel in Equation 3.2 ($P_{Travel,mt}$) depends on the aggregate utility of available alternatives in the travel nest and the utility of not traveling. Specifically, denoting $\bar{V}_{0,mt}$ the utility of not traveling, which can be normalized to zero without loss of generality,[3] the passenger traffic flow in each sub-market and period, Q_{mt},[4] can be expressed as a share of potential demand D_{mt}:

$$Q_{mt} = D_{mt} \cdot P_{Travel,mt} =$$

$$D_{mt} \frac{\left(\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)\right)^{\theta}}{\exp\left(\bar{V}_{0,mt}\right) + \left(\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)\right)^{\theta}} = D_{mt} \frac{\left(\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)\right)^{\theta}}{1 + \left(\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)\right)^{\theta}} \quad (3.3)$$

where $\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)$ is the log-sum term, hereinafter denoted as LoS (level of service), namely the aggregate utility provided by travel alternatives of the lower branch. The nesting coefficient θ measures the sensitivity of total demand to changes in supply attributes and represents the degree of similarity of the elementary alternatives in the lower nest (i.e., travel itineraries) compared to the alternatives in the upper nest (i.e., not making a trip at all and other transport modes). θ coefficient can be used to determine whether the nested logit model is consistent with utility-maximizing behavior (Train, 2009). Specifically, if $\theta = 1$, then the model reduces to an unnested model, and the alternative of not traveling is treated essentially as another travel alternative. Otherwise, for $0 < \theta < 1$, the total market demand is sensitive to the service level, but to a less degree than in the unnested model.

[3] The normalization of an outside good's utility is commonly reported in the literature as a method for overcoming a lack of information on unobserved alternatives and consistently estimating the model parameters (Berry, 1994).
[4] The total number of passengers travelling in the market at hand in each period *t* can be derived as $Q_t = \sum_{m\in M} Q_{mt}$, where *M* is the set of sub-markets composing the overall market.

Assuming that the actual demand (i.e., part of the demand that is met) is far less than the overall saturation demand (Wei and Hansen, 2005), the formulation of Q_{mt} can be approximated to:[5]

$$Q_{mt} \approx D_{mt} \cdot {Los_{mt}}^{\theta} \tag{3.4}$$

Saturated and more in general intercity travel demand has been typically modeled in transportation studies through a Cobb–Douglas function in which travel demand on a specific origin-destination is assumed to be dependent on socio-economic characteristics (demand-side attributes) such as GDP and population (Miller, 2004). Modeling the potential demand on a specific origin-destination according to this specification as a function of population and per-capita GDP, the passenger traffic flow in each sub-market and period, Q_{mt}, can be expressed as:

$$Q_{mt} = \exp(K_{mt}) \cdot {Pop_{mt}}^{\rho} \cdot {GDP_{mt}}^{\tau} \cdot {Los_{mt}}^{\theta} \tag{3.5}$$

where K_{mt} is a set of time and sub-market-specific constants. Thus, the number of passengers traveling in each sub-market and period rides on socio-economic characteristics of the analyzed origin-destination (demand-side attributes) and a composite measure of the characteristics of transportation systems (supply-side attributes). The inclusion of the latter term (i.e., LoS) into the trip generation model allows us to disentangle the contribution on trip generation of changes in service level from that related to population and GDP fluctuations.

All in all, Equation 3.2 and Equation 3.5 fully describe the integrated model. The use of such a structure is enabled by the exploitation of aggregated data and, unlike most demand assignment models leveraging on individual choices that are completely distinct from demand generation, it combines demand allocation and distribution in a single framework. The advantages of this approach are twofold. First, the model permits to describe the competitive dynamics across different transport modes understanding passengers' preferences concerning different supply attributes. Second, the integrated modeling approach making demand generation sensitive to supply variation enables to understand how both socio-economic characteristics and supply attributes contribute to capturing a higher or lower portion of potential travel demand (demand generation), thus implicitly estimating induced and reduced demand effects.

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[5] This assumption simplifies the trip generation model, allowing it to be estimated by a log-linearization of the demand Cobb-Douglass function.

3.1.2 Model estimation

Nested logit models can be estimated either simultaneously using maximum likelihood techniques or sequentially, by decomposing it from the bottom to the top level into simple multinomial logit models. Albeit the simultaneous approach has proven to be more efficient, the sequential approach constitutes the base strategy for estimating nested logit models when dealing with aggregate data ensuring consistent estimates (Allenby and Rossi, 1991; Forinash and Koppelman, 1993). Coherently with previous studies estimating the two-level nested logit model presented above (Birolini et al., 2020; Hsiao and Hansen, 2011; Wei and Hansen, 2005), the sequential approach has been adopted within the current thesis.

More in detail, to practically estimate the trip distribution model (lower nest), the deterministic utility function of a passenger traveling with alternative *i* in sub-market *m* and period *t* needs to be specified. According to previous literature studies, passenger utility is typically modeled as a function of supply characteristics of alternative *i* including frequency, travel time, access and egress time and cost. Chapter 5 and Chapter 6 adopt different formulations of the passenger utility function which will be further detailed in the single Chapters. Equation 3.6 provides a general formulation of the deterministic utility function of a passenger traveling with alternative *i* in sub-market *m* and period *t*.

$$V_{i,mt} = \boldsymbol{\vartheta} \cdot \boldsymbol{X}_{i,mt} \tag{3.6}$$

where $\boldsymbol{X_{i,mt}}$ is the vector of alternative-specific attributes of alternative *i* and the vector of coefficients $\boldsymbol{\vartheta}$ represent passengers' sensitivities toward the different supply characteristics.

Considering the deterministic utility function and Equation 3.2, the trip distribution model can be estimated by regressing the difference between the log market shares on the difference-in-attribute variables. Indeed, due to the aggregate nature of the model, $P_{i|Travel,mt}$ ultimately represents the market share of alternative *i* in sub-market *m* and period *t*. Accordingly, the difference between logarithms of market shares of two alternatives *i* and *j* can be expressed as follows:

$$\ln\left(MS_{i,mt}\right) - \ln\left(MS_{j,mt}\right) = \boldsymbol{\vartheta}\left(\boldsymbol{X}_{i,mt} - \boldsymbol{X}_{j,mt}\right) + \varepsilon_{ij} \qquad i,j \in I(t) \tag{3.7}$$

where ε_{ij} is the difference between the unobserved utility components of alternative *i* and *j*. By regressing this log-linear format of the market share model on the difference in attribute variables of two alternatives, the parameters of interest $\boldsymbol{\vartheta}$ (i.e., coefficients of the utility function) can be estimated.[6] Alternative-pairs to compare need to be identified before running the regression. Hsiao and Hansen (2011) randomly pick for each analyzed sub-market and period one alternative as the base alternative for the others. In the current thesis we adopt the same approach. Due to the well-recognized different behaviors of leisure and business passengers, heterogeneous sensitivities for these two types of travelers to the different components of the deterministic utility function are expected. Thus, both trip distribution and generation models need to be estimated separately for leisure and business passengers. Note that other socio-economic characteristics such as gender, age, income and education affect individual modal choices (Bergantino and Madio, 2020; Dobruszkes et al., 2022; Pagliara et al., 2012). In the current thesis, due to the lack of specific information in the dataset used as well as the aggregate nature of the model itself (requiring to compute accurate market shares), passengers are not segmented according these characteristics. However, brief evidence on the effect of gender and age on modal diversion are provided in Chapter 5 and Chapter 6.

Once estimated the trip distribution model, the LoS measure for each sub-market and period is derived aggregating the utilities provided by each travel alternative evaluated considering coefficients estimated in the trip distribution model and entered into the trip generation model.

$$LoS_{mt} = \sum_{i \in I(t)} \exp\left(V_{i,mt}\right) \tag{3.8}$$

Trip generation model parameters can then be estimated by ordinary least square regression (OLS) linearizing the Cobb-Douglass demand function by applying the logarithmic operation to both sides of Equation 3.6 and considering the total amount of passenger Q_{mt} traveling during each period *t* in sub-market *m.*

$$ln(Q_{mt}) = K_{mt} + \rho\ ln\ (Pop_{mt}) + \tau\ ln\ (GDP_{mt}) + \theta\ ln\ (Los_{mt}) \tag{3.9}$$

3.1.3 Application to a multimodal context

In this sub-Section, we describe how the integrated passenger choice and traffic generation model described above, for the purpose of the current thesis, has been adapted and extended to

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[6] According to the aggregate nature of the model, all time- and sub-market-specific effects on the utility (with the same values for all alternatives in the same sub-market and period) are systematically differentiated out. Thus, the estimates implicitly take these effects into account.

be applied in a multimodal context, ensuring explicit modeling of demand generation and distribution patterns where air transport and HSR compete. This generalization of the model can be achieved by relaxing the previous models' assumption of including among travel alternatives (travel nest) only air travel itineraries. Two are the main objectives to be considered when deciding how to adapt the integrated model to this purpose. First, the need to explicitly model among travel option, in addition to air itineraries, connections operated by other transportation modes, such as, in our case, HSR. Second, ensuring the adequate modeling of the peculiarities of the different transport modes as well as of the heterogeneous passenger propensities toward air or HSR.

A first solution to extend model applicability to a multimodal context would be to identify a more complex nesting structure, moving to a 3-level nested logit model (Figure 3.2). In such a formulation, travel and no-travel option represent the first level of the nesting structure, followed by the mode choice (i.e., air or HSR) and, in turn, by itinerary choice. The advantage of this solution lies in recognizing the similarities and commonalities between groups of travel alternative (alternative in the same nest). An alternative is indeed more likely to substitute for an alternative in the same nest, than for an alternative in a different nest.

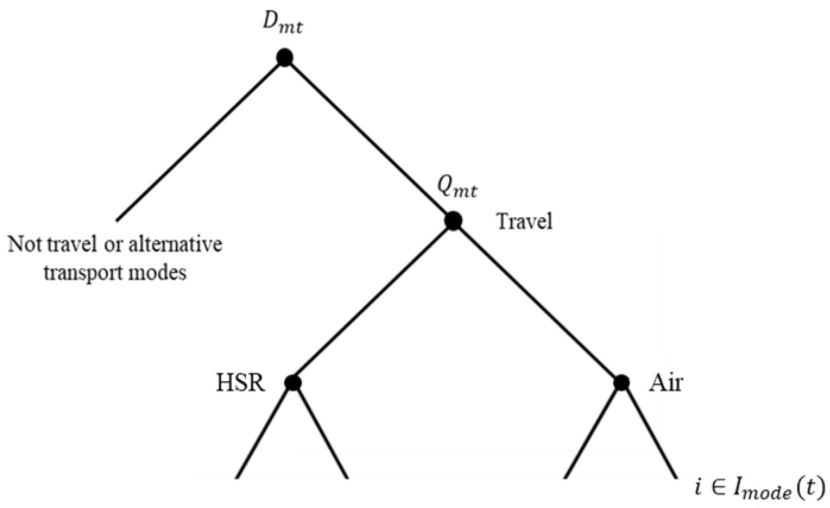

Figure 3.2: Possible three-level nesting structure to extend model applicability to a multimodal context.

A second solution to extend model applicability is to relax the assumption of including among travel alternatives only air travel itineraries still maintaining the two-level nesting structure unchanged, thus modeling the different travel alternatives (both air and rail ones) into the travel nest. On the one hand, this approach ensures the simplicity of the model; however, it requires specific expedients when defining the passenger deterministic utility function to explicitly model (albeit within the single nest) the intrinsic differences between air and HSR travel modes.

The final decision on the approach to be used in the present thesis to extend the applicability of the integrated model to a multimodal context has been guided by the current structure of the HSR industry in the market under consideration (i.e., Europe). To date, despite different policies implemented or promoted by the EC, most of the routes served by HSR at the European level, are indeed characterized by a low level of on-track competition, being operated by a single provider.[7] Because the integrated model considers as (air or HSR) alternative not the single elemental alternative (single flight or train operated by a specific company between given travel facilities and at a given time), yet aggregate alternatives obtained not considering the departure time, in case of adoption of the 3-level structure in such a context the HSR nest would result composed by a single travel alternative (i.e., the unique HSR alternative operated). This would cause the degeneration of the HSR nest, leading to difficulties in estimating passenger sensitivity to HSR mode characteristics. For this reason, in the current thesis we extended the application of the integrated trip generation and distribution model by maintaining the two-level formulation and introducing a set of specific variables aimed to disentangle the specificities of the single transport modes (albeit they are still considered in the same nest). More in detail, the specificities of the HSR alternative compared to those of the air alternatives are extrapolated by specifying within the deterministic passenger utility function a set of constants (alternative specific constants - ASC) designed to highlight intrinsic properties of the individual transport mode not captured by attributes generically analyzed for all the travel alternatives (i.e., travel time and cost) and, more in general, the passenger personal perception of the single mode. The aspects whose effect is captured by the ASCs include but are not limited to the possibility to work on-board, the comfort, the possibility to carry luggage on-board, and the perceived reliability and safety. Furthermore, an additional effort in modeling the different propensities toward air and HSR travel alternatives, albeit maintaining the two-level model, was made by including interaction variables in the deterministic utility function. These variables aim to highlight potential heterogeneity in passengers' evaluation of travel attributes such as travel time, cost, and frequency when choosing between air and HSR.

[7] This picture is expected to change in the coming years as a consequence of the ongoing liberalization process of the rail sector promoted by the EC. For an exhaustive overview of the initiatives in this direction, please refer to sub-Section 2.1.

This innovative approach, namely the integrated model proposed in the literature for air transportation modified and extended to include among the modeled transport mode the HSR alternative, enables the estimation of supply-demand interaction in a multimodal context and will be exploited in Chapter 5 and Chapter 6 where it will be applied to specific contexts.

3.2 Airlines' and HSR operator's profit maximization problem

A major limitation of the integrated trip distribution and generation model just described, applied *per se*, is the lack of modeling carriers' competitive reactions (in terms of price and frequency of service) introduced by supply variation or the implementation of policy initiatives to promote air-to-rail modal shift. Although this aspect is not explicitly covered in the current essay, in the following, for the sake of completeness, we provide a general formulation of the companies' profit maximization problem. This formulation represents a first attempt to identify company strategic responses in a multimodal context, ultimately allowing to derive the optimal fare and frequencies. Such information paves the way for future research efforts aimed to a more comprehensive assessment of the impacts following the implementation of policy initiatives aimed to promote modal shift.

Airlines' and HSR operator's maximization problems are formulated and derived with reference to a simplified version of the integrated passenger choice and generation model presented above. More in detail, without loss of generalizability, we focus on a single period and a unique multimodal market between two regions served by *n* air alternatives and a single HSR connection.[8] For the purposes of this sub-Section, similarly to previous literature studies, we define a simple formulation of the deterministic utility V_i associated to each alternative, as follows:

$$V_i = \alpha_i + \beta \cdot ln(f_i) + \gamma \cdot TT_i + \delta \cdot TC_i + \varepsilon \cdot HSR \cdot ln(f_i) \qquad (3.10)$$

where f_i is the aggregated frequency of alternative i, TT_i the travel time of alternative i, TC_i the total cost of alternative i, and lastly HSR a dummy variable. Frequency is included in logarithmic form for two main reasons (Hansen, 1990). First, because we consider the single alternative as an aggregation of individual flights/trains, the logarithmic form is required for characteristics that capture the size of an aggregated alternative (Ben-Akiva and Lerman, 1985)(Ben-Akiva and Lerman, 1985). Second, to account for the expected decreasing marginal utility of frequency. TT_i is the travel time of alternative i, and includes on-board travel time, departure waiting time,[9] expected delay, and finally average access and egress time to reach departure HSR station or airport (arrival zone) from the departure zone (arrival HSR station or

[8] The analysis of a market in its entirety relaxes the assumption of subdividing into sub-markets previously required for the empirical estimation of the model parameters.

[9] Minimum time passengers are advised to arrive in advance at the airport/station with respect to the scheduled time for security checks and check-in activities.

airport). $HSR \cdot ln(f_i)$ is an interaction term between frequency and HSR mode, thus modeling the additional utility of HSR frequency compared to the average value of the utility associated to the generic frequency parameter. α_i are mode- and airline-specific constants. Finally, TC_i is the travel cost of alternative i, and is composed as follows:

$$TC_i = p_i + AEC_i + Tax_i \tag{3.11}$$

where p_i is the average air or HSR fare, AEC_i is the average access and egress cost to departure and arrival travel facilities of alternative i, and Tax_i is the amount of possible environmental tax on transport mode i.

To understand strategic company behavior in terms of fare and frequency responses following supply variations, we assume a company will operate a route (i.e., a travel alternative from passenger point of view) in the market under consideration if it can generate nonnegative profits. The generic expressions of the (air or HSR) operator's profits generated operating alternative i is:

$$\pi_i = (p_i - c_i) \cdot N_i - k_i \cdot f_i - K_i \tag{3.12}$$

where p_i, as mentioned above, is the average fare charged on alternative i, c_i is the marginal cost per passenger, k_i is the marginal cost per flight/train, K_i is the fixed cost, and N_i is the number of passenger traveling with alternative i. Considering the integrated passenger choice and generation model presented above, N_i can be expressed as:

$$N_i = Q \cdot P_{i|Travel} = \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot LoS^{\theta} \cdot P_{i|Travel} \tag{3.13}$$

The profit function (Equation 3.12) can therefore be rearranged as follows:

$$\pi_i = (p_i - c_i) \cdot \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot LoS^{\theta} \cdot P_{i|Travel} - k_i \cdot f_i - K_i \tag{3.14}$$

Albeit airlines are free to simultaneously operate different route serving the same market, we assume they maximize profits at route level. Such an assumption allows us to disentangle our model from considerations based on market coverage and opening and closure of the single route. To derive at least in the first instance the optimal frequency and fare, we assume that the airlines and the HSR operator, in order to maximize profits, determine their fare and frequency simultaneously and independently, given the fares and frequencies of their competitors and the characteristics of transport modes.[10] We acknowledge the strength of these assumptions (i.e., simultaneous and independent choice of frequency and fare) that in the common practice are likely to be violated due to the endogeneity between service frequency and fare (service frequency impacts on determining of the fare level, and *vice versa*). Anyway, we believe that such assumptions provide a local-best solution in terms of frequency and fare, especially when facing marginal supply-side changes compared to existing market structure, while ensuring the simplicity of the structured theoretical approach and a straightforward analytical solving.

Considering Equation 3.14, maximizing profits of company *i* with respect to frequency yields:

$$\frac{\partial \pi_i}{\partial f_i} = (p_i - c_i) \cdot \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot \frac{\partial LoS^{\theta}}{\partial f_i} \cdot P_{i|Travel} + (p_i - c_i) \cdot \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot LoS^{\theta} \cdot \frac{\partial P_{i|Travel}}{\partial f_i} - k_i = 0$$

$$\Leftrightarrow f_i = \frac{(p_i - c_i) \cdot \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot LoS^{\theta} \cdot P_{i|Travel} \cdot (\beta + \varepsilon \cdot HSR) \cdot \left[1 + P_{i|Travel} \cdot (\theta - 1)\right]}{k_i} \tag{3.15}$$

While, maximizing profits of company *i* with respect to the fare yields:

$$\frac{\partial \pi_i}{\partial p_i} = \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot LoS^{\theta} \cdot P_{i|Travel} + (p_i - c_i) \cdot \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot \frac{\partial LoS^{\theta}}{\partial p_i} \cdot P_{i|Travel} + (p_i - c_i) \cdot \omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot LoS^{\theta} \cdot \frac{\partial P_{i|Travel}}{\partial p_i} = 0 \tag{3.16}$$

$$\Leftrightarrow (p_i - c_i) = \frac{-1}{\delta \cdot \left[1 + P_{i|Travel} \cdot (\theta - 1)\right]}$$

Equation 3.16 gives the best fare response function for company *i*, while Equation 3.15 the best frequency response. Considering the independence and simultaneity of the decisions, fare in Equation 3.15 to be optimal should satisfy Equation 3.16. Substituting the optimal fare in Equation 3.15 yields:

$$f_i = \frac{-\omega \cdot Pop^{\rho} \cdot GDP^{\tau} \cdot LoS^{\theta} \cdot P_{i|Travel}(\beta + \varepsilon \cdot HSR)}{\delta \cdot k_i} \tag{3.17}$$

[10] The characteristics of transport modes such as travel time are considered exogenous to operators, especially in the short run. Airports performance and infrastructure characteristics are indeed considered parameters not exclusively under the control of the company.

Similar best fare and frequency response function can be derived for airlines and HSR operator operating alternative $j \neq i, j \epsilon I$. The equilibrium, if any, is located at the intersection of the best response functions.

As mentioned above, this formulation represents a first attempt to identify company strategic responses in a multimodal context and is far from being exhaustive. Future research efforts based on this theoretical formulation include the analysis of the properties of the equilibrium with the ultimate goal of complementing the evaluations carried out in the following Chapters of this thesis. Such an assessment would be focused on understanding the impacts and effectiveness of policy initiatives considering the behavior of airlines and HSR operators as well as the strategic responses induced by such measures.

3.3 Social welfare maximization problem

Modeling modal shift dynamics and demand induction, as well as understanding operators' strategic reactions yield valuable suggestions for policymakers in defining and structuring a wide range of socially optimal policies. In this sub-Section, for illustrative purposes, we describe how the socially optimal taxation level on the single transport modes (as initiative to incentivize the less polluting travel alternative) can be derived jointly considering the models described above.

In a competitive environment, the regulator aims to maximize social welfare. Typically, consumer surplus and operator profits are the two main components included in the social welfare estimation. However, the increasing pressures regarding sustainability and emission reduction flowed over the past few years call for the inclusion of the cost of negative externalities generated by each transport mode in regulator's assessment.[11] One possible solution to achieve this goal is to levy an environmental tax to the most polluting transport mode (or their passengers) ensuring that the price of transport modes reflects their environmental impact, ultimately incentivizing passengers for adopting sustainable behaviors.

With the aim of identifying the optimal amount of possible environmental tax in the multimodal setting described above, we define the social welfare as:

$$SW = CS + OP - EC \tag{3.18}$$

where CS is the consumer surplus, OP are the operator profits, and EC are the environmental costs. The first two components obviously increase social welfare, while the latter has a negative impact, representing the environmental and health cost of polluting emissions. Considering the integrated passenger choice model and the profit formulations (see previous sub-Sections), the SW expression can be reformulated as:

$$SW = LoS \cdot Q + \sum_{i \in I} \pi_i - \sum_{i \in I} f_i \cdot \chi_i \cdot \psi \tag{3.19}$$

where $LoS \cdot Q$ is the customer surplus computed according to Small and Rosen (1981) specifications for nested logit structure, $\sum_{i \in I} \pi_i$ is the sum of airline and HSR operator profits as

[11] In support of this thesis, several are the policies and initiatives promoted at different levels (national, continental, and worldwide) aimed at discouraging the use of air travel, both directly (charging a passenger tax) and indirectly requiring airlines to compensate for their emissions or purchase emission allowances. For a complete overview of these initiatives please refer to Section 2.2.

detailed in the previous sub-Section, and $\sum_{i \in I} f_i \cdot \chi_i \cdot \psi$ are the environmental costs. The latter is computed considering the frequency of the connection, the per-flight (or per-train) emission rate for company i, χ_i, and the monetary value of an emission unit, ψ. Due to the *greenness* of HSR mode compared to air transport,[12] it can be assumed $\chi_{HSR} \ll \chi_{Air}$.

The optimal taxation level ensuing the maximization of social welfare in the light of profit maximizing behavior of companies and passenger choices, Tax_i^*, can be derived maximizing the SW given companies' response functions.

$$
\begin{gathered}
Max \quad LoS \cdot Q + \sum_{i \in I} \pi_i + \sum_{i \in I} f_i \cdot \chi_i \cdot \psi \\
s.t. \quad \frac{\partial \pi_i}{\partial p_i} = 0 \;\; \forall\, i \, \in I \\
\frac{\partial \pi_i}{\partial f_i} = 0 \;\; \forall\, i \, \in I
\end{gathered}
\tag{3.20}
$$

Similarly to the identification of the optimal frequency and fare presented above, the theoretical approach just described to derive the social-optimal amount of an environmental tax is far from being exhaustive. However, it provides a useful example of further interesting potentialities of the joint use of the integrated model and the formulation of company profits that may be exploited in future research with the final goal to support and guide policymaker decisions.

[12] Different studies documented the lower GHG emission of the HSR compared to air transport on a per-seat basis (Givoni and Banister, 2006; Janic, 2011; Jiang et al., 2021; Robertson, 2016).

Chapter 4 – Replacing short-medium haul intra-European flights with high-speed rail: impact on CO_2 emissions and regional accessibility

4.1 Introduction

As already discussed in previous Sections, over the recent years, environmental sustainability has gained increasing importance in the EC's agenda with the design and enforcement of initiatives aimed at achieving the ambitious target of a 90% reduction in transportation GHGs by 2050 compared to 1990 levels (EC, 2019). Several of these initiatives have concerned the air transport industry. Commercial aviation is responsible for about 14% of all GHG emissions from transport at a European level (EEA, 2019). In 2020, the pandemic totally changed the expected growth scenario (Gudmundsson et al., 2021), highlighting the importance of pursuing aviation-related environmental targets in the years to come.

Among the plethora of environmental policy measures undertaken to mitigate the negative externalities of air transport (e.g., the introduction of CO_2 emission from aviation in the EU emission trading scheme) a crucial initiative involves a modal shift toward greener modalities of transport such as high-speed rail (HSR), rail, buses, and coaches (Borken-Kleefeld et al., 2013; Dalkic et al., 2017; Givoni and Dobruszkes, 2013; Zhang et al., 2005). The EC proposed the conversion to rail of the majority of medium-distance passenger transport by 2050, tripling the length of the existing HSR network by 2030 (EC, 2011).

Today, the urgent need for airlines' state aid and recovery packages due to the recent COVID-19 crisis has provided an unprecedented opportunity for policymakers to create a turning point in the reduction of aviation environmental impact. Several initiatives have been recently undertaken in different European countries: French lawmakers have moved to ban short-haul internal flights where train alternatives exist in a bid to reduce carbon emissions. This measure,[13] proposed by the Citizens' Convention for Climate following the Air France bailout

[13] The initiative to abolish domestic short-haul flights is part of a broader legislative bill proposed by the French Citizens' Convention for Climate aimed at reducing climate change. The bill, which passed its first reading in the French National Assembly on April 12, 2021, will end routes for which the same journey could be made by train in under two-and-a-half hours. Currently, flights with a majority of connecting passengers will not be affected by the policy, however, the same legislative package calls for the extension of the measure to feeder flights to be considered within one year of the law's approval. The French government had faced calls to introduce even stricter

agreement, entails the closure of air services operated on domestic routes served by an alternative rail connection within 150 minutes. Another initiative concerns the environmental clauses included by the Austrian government into the state aid package aimed at supporting Austrian Airlines in 2020. Specifically, the agreement requires Austrian Airlines to halve emissions from domestic flights by 2030 by ending domestic routes already served by an HSR connection in less than 180 minutes. The growing pressure on aviation emissions reduction and the increasing number of policy initiatives should urge policymakers to design appropriate packages and measures aimed at encouraging a sustainable modal shift strategy.

This research contributes to the current zero-carbon transition debate and air-HSR literature by (i) evaluating the extent to which intra-European air routes are also operated by other competitive transport modes and (ii) identifying which short-medium haul air routes could potentially be subject to a cancellation policy. Eventually, the paper estimates the overall reduction in offered seats and CO_2 emissions following the cancellation of routes. We analyze intra-European medium and short-haul routes with more than 50,000 offered seats in 2019—about 1700 routes and 377 million (43.1% of total intra-European) offered seats—and examine which routes (and, consequently, number of flights and offered seats) could be banned in light of the recent strengthening role of the HSR and the presence of other competitive land-based transportation modes such as conventional trains and long-distance buses. This work aims to provide a better understanding of how the above-mentioned potential substitution patterns characterizing intra-European routes would impact the accessibility of both European peripheral and central areas. By developing impact indices for different territories, we found that positive (reduction in CO_2 emission) and negative (increase in travel time [ITT] for passengers) effects of replacing short-medium haul flights with alternative transport modes are not evenly distributed among European regions with different *ex-ante* accessibility level. Finally, we compare the different degrees of route substitutability by adopting the passengers' perspective, considering, in addition to travel time (TT), other relevant dimensions, such as fares or service quality (approach based on the generalized travel cost). The analysis paves the way for formulating policy insights and quantifying the environmental benefits of replacing current air transport services on short-medium haul routes. Several critical issues concerning successful policy implementation (such as the need for capacity increases in HSR and possible market concentration) that need to be discussed and addressed by policymakers will be raised.

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rules: Citizens' Convention on Climate indeed had proposed to apply the ban of air journeys where train journeys of less than four hours exist.

The remainder of this Chapter is organized as follows. Section 4.2 frames the present work within the previous streams of research on air transport and its substitutability with alternative transport modes. Section 4.3 specifies the sample of considered routes as well as the data sources and methodology employed. Section 4.4 describes the degree of technical substitutability between air transportation and alternative modes of transport. Specifically, we outline the impacts of possible air route cancellation both at a macro-European and at a micro-regional level. Section 4.5 discusses the results and develops policy suggestions with a specific focus on challenges that policymakers need to address to enable the successful implementation of the analyzed policy. Finally, Section 4.6 briefly recaps the findings, outlines the limitations, and depicts potential paths for future research.

4.2 Related literature

The global pressure to reduce aviation carbon emissions is today wide.[14] On the one hand, this environmental issue is expected to become even more substantial in the near future given the poor effectiveness of the enforced regulatory approaches to limit air transport climate emissions (e.g., EU Emission Trading Scheme) (Larsson et al., 2019; Vespermann and Wald, 2011). On the other hand, the negative effects of COVID-19 not only make climate targets harder to achieve, but also aggravate the current problems (Abate et al., 2020; Amankwah-Amoah, 2020). The interaction between air and alternative transport modes in short-haul medium markets has attracted much attention, as passengers have similar total travel time (TT), making alternative transport modes highly competitive and, simultaneously, generally environmentally preferable (Dobruszkes, 2011; Givoni and Dobruszkes, 2013; Zhang et al., 2005).

Previous studies extensively investigated the implications of coexisting alternative transport modes serving the same market, mainly focusing on the role played by HSR —the best candidate to substitute air transportation in short-medium haul markets (Rothengatter, 2011). Both theoretical and empirical models addressed the topic of the effect of the introduction of a parallel HSR service on air transport service (Castillo-Manzano et al., 2015; Cheng et al., 2015; Dobruszkes et al., 2014; Givoni and Dobruszkes, 2013). Furthermore, several analyses highlighted service attributes affecting the outcome of air-HSR competition (Albalate et al., 2015; Castillo-Manzano et al., 2015; Dobruszkes, 2011; Jiménez and Betancor, 2012).

The market structure of competing or collaborating transport modes (HSR and air) has been widely analyzed even through the lens of environmental outcomes (as better described in Section 2.1). Several studies have estimated the environmental benefits of opening new HSR lines (new corridors) or upgrading the existing ones (increased operating speed) (D'Alfonso et al., 2016; Li and Loo, 2017; Wang et al., 2019; Zanin et al., 2012). Various studies argue that lower local air pollution levels and GHG emissions make HSR preferable to air transport in most circumstances (Givoni and Banister, 2006; Janic, 2011; Miyoshi and Givoni, 2013). Nevertheless, it has been documented how the introduction of new HSR services does not necessarily lead to overall environmental advantages. This result derives both from the demand stimulation effect and the high emissions deriving from HSR infrastructure construction and maintenance phases. Ultimately, due to the novelty of the debate and the lack of wide-scope

[14] For a complete description of current policies aimed at reducing emissions from aviation as well as a comprehensive overview of literature studies on the topic, please refer to Chapter 2.

empirical studies investigating the topic, mixed and inconclusive evidence emerges when assessing the conditions under which each of the two modes could be preferable.

Although air transport has proven to be a major contributor to GHG emissions, its widespread over the recent decades has brought important benefits in terms of regional accessibility. Especially for remote and peripheral areas characterized by sparse populations and relatively undeveloped land-based transport systems, the presence of airports and air transport services ensures sufficient accessibility (Halpern and Bråthen, 2011). As far as HSR is concerned, several studies find that its presence enhances regional and city accessibility (Monzón et al., 2013; Ortega et al., 2012; Preston, 2012). However, there is mixed evidence of the effect of HSR on accessibility imbalance between regions (Xu et al., 2018; Chen and Haynes, 2017, 2015; Qin, 2017). This discordant evidence can be traced back to the different geographical scales adopted in the analysis (Gutiérrez, 2001).

So far, the literature focused more on short and long-term consequences on air transportation of new competitive equilibria emerging from the introduction of HSR connections and the consequent environmental implications, rather than on the impacts following a possible complete and enforced replacement of air routes, where alternative connections operated by alternative transport modes offer passengers similar TT. This paper aims to evaluate the impact of a possible policy of banning intra-European short-medium haul routes in cases in which they can be substituted by preserving or, at most, causing a limited deterioration in the passengers' travel conditions. The contribution of the paper to the literature is threefold. First, it integrates the stream of studies focused on the impacts of air transportation and pollutant emission resulting from the air-HSR competition by examining the direct effects in terms of potential CO_2 savings owing to a complete withdrawal of air routes that can be substituted without a significant detrimental effect on passengers' travel conditions. Second, it evaluates the alleged policy focusing on the effects in terms of regional accessibility. Lastly, it provides discussion points and key policy implications for the proper future implementation of such a policy.

4.3 Data and Methods

4.3.1 Research design

Our research focuses on intra-European routes, defined as those connecting European Economic Area members within the European border control-free travel area (Schengen area). Intra-European aviation includes 28 countries, constituting one of the largest air markets in the world, accounting for around 6 million flights (21.2% of which are domestic) and more than 875 million offered seats in 2019. These flights are estimated to have produced over 66 million CO_2 tons in the same year. To evaluate the impact of possible cancellations of routes that are currently operated by air and also effectively served by alternative transport modes, we focus on short-medium haul flights (of less than 800 km). Flights on this type of route represent a potential replacement especially given their high level of competition with alternative transport modes such as HSR.[15] Moreover, because of the higher level of emission per ton kilometer than other types of flights,[16] these flights are also distinguished by their greater potential for environmental savings (Grimme and Jung, 2018).

In line with the first legislative measures prohibiting air routes,[17] we initially analyze air routes' technical substitutability through TT, which best represents the degree of alternative infrastructure provision on the individual route (e.g., the presence of high-speed lines allows much shorter TTs than other conventional alternatives). Moreover, despite alternative transport modes being environmentally preferable to air transport, differences in TTs play a major role in identifying potential competitive substitutes. TT is widely recognized as a key competitive factor in and determinant of air-HSR competition and modal choice, respectively (Dobruszkes, 2011; Dobruszkes et al., 2014; Xia and Zhang, 2016; Yang and Zhang, 2012). Although this perspective represents the schemes of policymakers concerning the identification of routes that are potentially technically substitutable, it is lacking in modeling passenger preferences that take into account other dimensions, such as fares or service quality. Thus, we subsequently analyze the degree of route substitutability by evaluating the passenger generalized travel cost

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[15] Several studies have found HSR to be the main competitor of air transport on medium-haul routes, mainly between 300 and 800km (Button, 2012; Givoni and Banister, 2006; Hu, HaoHu, H., Wang, J., Jin, F., Ding, N., 2015. Evolution of regional transport dominance in China 1910–2012. J. Geogr. Sci. 25 et al., 2015; Rothengatter, 2011). For short-haul flights, even other land-based transport modes, such as traditional trains and long-distance buses, are considered suitable alternatives and contribute to operating greener trips (Baumeister, 2019).

[16] This is not only because the energy-consuming phases of take-off and climb are distributed along a shorter flight length but also because of the lower load factor.

[17] Both French and Austrian governments have prohibited airline connections covering distances that could be travelled within a certain TT by alternative connections (this threshold was set at 2.5 and 3 hours, respectively).

(GTC), intended to assess the overall performance of the different alternatives, both in terms of TT and fares. This last analysis contributes to integrate our core analysis; however, there is a major drawback to the use of GTC as a measure to evaluate the replacement of the air routes. The prohibition of air connections by governments will cause a profound change in the current competitive landscape that is likely to lead to substantial increases in market concentration. This may result in increased fares for alternative transport and reduced service levels. Apart from requiring the introduction of appropriate monitory mechanisms by policymakers, discussed in sub-Section 4.5, it may change the GTCs for passengers in difficult-to-predict ways. Note that a price model to estimate changes in the fare component of the GTC might solve this shortcoming. However, the evaluation of the substitution between air travel and modal alternatives based on passenger TTs appears more robust, at least in the short-term, as TTs mainly depend on technical characteristics of the alternatives (HSR infrastructure), and less on competitive conditions. This ultimately provides a quantification of the potential for air route substitution to alternative transport modes considering the existing infrastructure rather than the level of the alternative services offered. For this reason, the analysis does not focus on frequencies and current capacity of the alternative connections, which nevertheless play a significant role in the discussions presented in sub-Section 4.5.

4.3.2 Data collection

In this Section, we describe the data used to evaluate the degree of technical substitutability of short-medium haul air routes. A comprehensive data set for intra-European air routes and possible alternative connections was assembled from two main data sources.

Information on intra-European air routes such as frequency, offered seats, and origin and destination passenger flows in 2019 was collected from the Official Airline Guide (OAG) database.[18] We collected information on European short-medium haul flights (less than 800 km) with at least 50,000 offered seats in 2019.

TTs and the number of transfers and fares for alternative transport modes (HSR, traditional trains, long-distance buses, or a combination of those) as well as one-way airfares were collected from the multimodal search engine Rome2Rio,[19] which provides different alternatives for travelling from an origin to a destination. Each alternative is described by the total TT, the

[18] Other empirical papers (e.g., Redondi et al., 2021) employed OAG database as the data source for flight schedules (OAG Schedule Analyser) and passenger flows (OAG Traffic Analyser).

[19] Other empirical papers (e.g., Birolini et al., 2019; Llorca et al., 2018) employed Rome2Rio [www.rome2rio.com] as the data source for public transport alternatives.

travel and transfer time by segment (defined as a part of the journey carried out using a single vehicle), and the average fare for each segment.[20] Times collected from Rome2Rio are door-to-door travel times, which over the past years have been widely under-represented in literature (Zhao and Yu, 2018). They constitute the overall TT for trips from an origin to a destination and comprise components such as access time, departure waiting time, on-board time, transfer time, and egress time.[21] For each alternative proposed by Rome2Rio, the main mode of travel was identified (the mode by which the segment with the greatest distance was travelled) and consequently the access and egress times were defined, respectively, as the part of the journey before the main segment and after the main mode. Consistent with the assumptions of many studies on air connectivity and accessibility at the European level (Burghouwt and Redondi, 2013), in case of trips with air as the main mode, we assume a departure waiting time of 60 minutes for check-in, boarding, and security activities. Otherwise, in case of journeys using alternative transport modes, given the current lack of specific checks on access to stations and security controls, we assume a departure waiting time of 15 minutes (the amount of time in advance a passenger goes to the station to ensure catching the train-bus).[22] Figure 4.1 exemplifies our approach for the multimodal journeys between the city centers of Bordeaux and Paris with air and HSR as the main mode.

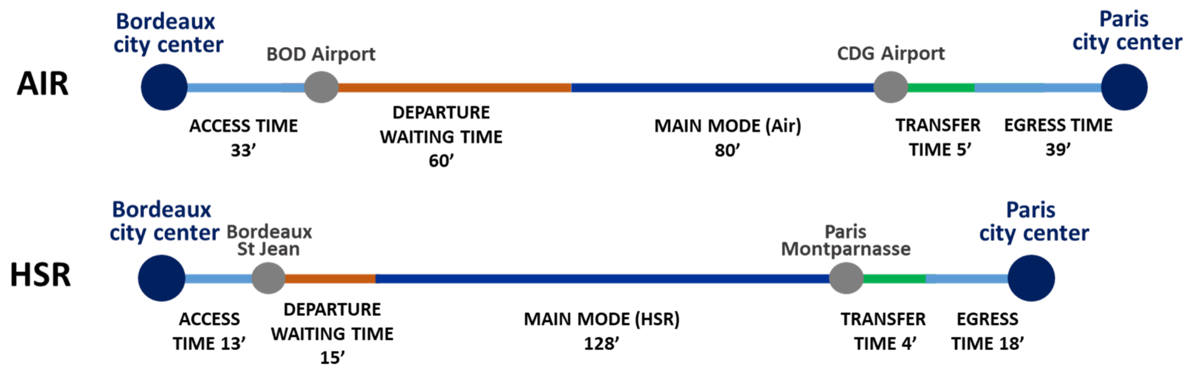

Figure 4.1: Different components of multimodal trip between Bordeaux and Paris (alternatives with air and HSR as main mode).

[20] The average price collected from Rome2Rio provides an estimate of the average price quoted for each segment of the trip. Price differentiation by travel purpose is not available.

[21] Access time represents the time a traveler needs to get to the main-mode traveling facilities (e.g., airports and train stations) from the starting point of the journey; departure waiting time represents the amount of time spent at the airport or station for check-in, boarding, and security activities; time onboard is the time a traveler spends on the main mode; transfer time refers to the time taken between the various vehicles making up the journey; egress time represents the time a traveler spends getting from the arrival facility to the final destination.

[22] In the event of a future raise in boarding and security controls for HSR to levels comparable to those for air travel, the degree of substitutability of air routes will inevitably be reduced.

Table 4.1 reports the main descriptive statistics for the sample analyzed as well as the characteristics of the air journey and the alternative connection carried out with alternative transport modes. The sample analyzed comprises 1,689 routes accounting for almost 2.8 million flights and 377 million offered seats (47% and 43.1% of intra-European flights and offered seats in 2019, respectively). Almost half of the analyzed routes are domestic (48.9%). More than one in five intra-European short-haul routes have an HSR connection as the best alternative to air transport in terms of TT. Although this value may seem small, it should be commented in light of the still poor capillarity of the HSR network across the European continent (especially in some countries). Overall, conventional rail and HSR are the best alternatives to air transport in almost 8 out of 10 cases. The air alternative shows a significantly shorter average distance traveled than the other land-based alternatives (533 vs 702 km). It can also be noted that air transport guarantees significantly shorter in-vehicle times than alternative connections due to both lower traveled distance and higher average speed. This value is partially compensated in the higher incidence of out-of-vehicle time in air transport mainly due to check-in, boarding, and security activities. The average fares of air and alternative connections are similar (€122 and €132, respectively) but the latter exhibits higher volatility.

		Air journey	**Alternative connection**
Analyzed routes	1,698		
Departure/arrival cities	246		
% routes in which HSR[1] is the best alternative to air transport			22.0%
% routes in which conventional train[2] is the best alternative to air transport			56.4%
Average distance (km)		533.1 *(182.8)*	701.8 *(328.7)*
Average in-vehicle time (time onboard plus access and egress times, minutes)		118.7 *(24.6)*	434.1 *(253.9)*
Average out-of-vehicle time (sum of departure waiting time and transfer times, minutes)		77.3 (*15.9*)	59.9 *(49.1)*
Average fare (€)		121.6 *(49.1)*	131.8 *(96.0)*

[1] The main segment of the alternative trip is carried out by train with an average speed higher than 175 km per hour.
[2] The main segment of the alternative trip is carried out by train with an average speed lower than 175 km per hour.

Table 4.1: Descriptive statistics relating to the sample analyzed and the alternatives compared considering trips between city centers. Average values and standard deviation (into brackets).

4.3.3 Methodology

It is widely recognized that on a single air route between two airports (A and B), different types of passengers can concurrently coexist. First, point-to-point passengers simply take a non-stop flight between cities in the catchment area of A and B. Second, "beyond" passengers who start their journey from A (generally from the city center), aim to take a connecting flight from B after the flight from A to B. Next, "behind" passengers constitute the portion of traffic between A and B that originates behind A and connects in airport A on route A to B (the city center of B is generally the final destination). Ultimately, "bridge" passengers connect from another flight at A to another flight after B.

Given this premise, to evaluate the changes in TT and GTC representative of all these air passengers' categories due to possible cancellation of the air route, we collect TTs and fares with different and complementary approaches. First, we take the perspective of point-to-point passengers considering the possible journeys connecting city pairs (city center approach) because this type of passenger is interested in direct transportation service between two places. Second, we consider the perspective of the different types of connecting passengers ("beyond", "behind", and "bridge"). For such passengers, completing the journey by utilizing several transport modes (intermodal trip) with accompanying luggage is particularly critical. However, the recent introduction of the integrated HSR-air option—efficiently coordinating HSR and airlines with measures such as integrated luggage handling services and on-site HSR station at the airport—enables an interconnecting passenger to perform intermodal trips more easily (Brida et al., 2017; Kroes and Savelberg, 2019). Specifically, concerning "beyond" ("behind") passengers, as the arrival (departure) airport represents only an intermediate step in their overall journey, we collect journey alternative parameters considering travel from the departure airport (city center) and arrival city center (airport). "Bridge" passengers represent, on average, less than 1% of the total passengers on the route sample analyzed; hence, they were considered negligible for our analysis.

TTs and fares were collected considering both trips between departure and arrival city centers and between departure airport (city center) and arrival city center (airport).[23] This allowed us

[23] For locating city centers, the multimodal search engine Rome2Rio employs a geocoder technology aimed at identifying the precise latitude/longitude coordinates of textual place names. Generally, the location identified corresponds to major transit hubs located in the city center. In this respect, the city centroid-based approach, not accounting for the actual distribution of the population in the metropolitan area, might favor alternative transport modes over air journeys. It is worth noting, however, how over the analyzed sample Rome2Rio centroids well represent the fulcrum of population agglomeration in each metropolitan area (average distance less than 2.8 km)

to quantify the ITT and increase in generalized travel cost (IGTC) resulting from the abolition of each air route and type of passenger, by comparing the TT and fares by air with the most convenient alternative in terms of TT (operated as the main mode with HSR, traditional train, or long-distance buses).

With regard to TT, according to several studies that found transfer and departure waiting times much more burdensome than on-board TT, we weighed these components using a time multiplier. We assumed this value to be equal to 1.76, namely the inter-urban trip time multiplier estimated by Wardman et al. (2016) meta-model for wait time and interchange wait. The weighted perceived TT for each alternative i and passenger type j is thus obtained from the following formula:

$$TT_{ij} = IVT_{ij} + \mu \cdot OVT_{ij} \quad (4.1)$$

where IVT, OVT, and μ are the in-vehicle time (time onboard plus access and egress times), the out-of-vehicle time (sum of departure waiting time and transfer times), and the out-of-vehicle time multiplier, respectively. By comparing the TT thus weighted between air travel and the most convenient alternative connection in terms of TT, we compute the percentage ITT resulting from replacing the air route for each type of passenger. Finally, to summarize the degree of substitutability of each air route, we calculate the weighted increase in travel time (WITT) to switch from air to the most convenient alternative in terms of TT. The WITT is defined as:

$$WITT = \alpha \cdot ITT_{Point-to-point} + \beta \cdot ITT_{Behind} + \gamma \cdot ITT_{Beyond} \quad (4.2)$$

where α, β and γ are the share of point-to-point, “behind,” and “beyond” passengers, respectively, on the single route estimated using the OAG Traffic Analyzer.

The attractiveness of each travel alternative is even evaluated by estimating the associated GTCs. The GTC for each alternative and type of passenger is defined by adding two components:

$$GTC_{ij} = DC_{ij} + VoTT \cdot TT_{ij} \quad (4.3)$$

legitimizing the use of a centroid-based approach. Airports locations identified by Rome2Rio correspond to those provided by the OAG database.

The first component summarizes the monetary costs incurred by passenger type j to travel the alternative i. It comprises three main components: airfare if the alternative involves an air segment (collected by Rome2Rio), land-based public transport fares (collected by Rome2Rio), and estimated driving costs.[24] The latter represents the cost associated with TT, obtained by multiplying the weighted perceived TT with a value of TT. The official values of time recommended by the major national authorities for the evaluation of transport projects and policies reviewed in Wardman et al. (2016) were considered. Due to lack of data availability regarding the share of business and commuting travelers on the specific route, we consider the average value for all users. This value was assumed to be equal to 22.21 € per hour.[25] Moreover, to evaluate the robustness of the results, a sensitivity analysis was conducted using the average time value estimated in national valuations for commuting and business passengers. They were assumed to be equal to 15.15 € and 41.18 € per hour, respectively.[11] To summarize the degree of substitutability of each air route in terms of GTC, we calculated the weighted percentage of increase in generalized travel cost (WIGTC) to switch from air to the most convenient alternative in terms of TT, defined as follows:

$$WIGTC = \alpha \cdot ITT_{Point-to-point} + \beta \cdot ITT_{Behind} + \gamma \cdot ITT_{Beyond} \tag{4.4}$$

In the empirical analysis, first, we estimated the impact on air transport of route ban policy based on an examination of the TT performance of existing alternatives (characterized by WITT less than or equal to a certain threshold), taking the perspective of policymakers interested in identifying the impacts of such a policy, which are identified at an aggregate level (number of flights, offered seats and, potential CO_2 savings) and at the domestic market or airline level. We also analyzed the potential impacts on the accessibility level of different European regions following the possible air route banning policy.

Second, we provided some insights on the passenger perspective evaluating route substitutability considering the WIGTC. This aims to identify the impacts on the GTC borne by the passenger as a result of the envisaged abolition of air routes.

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[24] Because Rome2Rio provides cost estimates for car segments considering case-by-case taxi, private car, or shared vehicle, driving costs were calculated by multiplying distance by the average car costs per kilometer, including fuel, maintenance, insurance, and depreciation. Similar to Lieshout et al. (2016), we assume these costs to be 0.20 €/km on average.

[25] Since values of time summarized in Wardman et al. (2016) were expressed in 2010 prices, they were converted into 2019 values using the average European inflation rate provided by Eurostat (Harmonized index of consumer prices): https://ec.europa.eu/eurostat/web/hicp

4.3.4 Emission estimation

The estimation of aviation emissions is a widely discussed topic. In recent years, although different aviation emission models have been developed, they are often characterized by estimates that differ significantly from each other (Kurniawan and Khardi, 2011). In this study, pollutant emissions, as well as the consequent reduction of pollution in case of the ban of air routes, were estimated using a tool developed by the European Environment Agency (EEA).[26] The tool estimates the direct polluting emission and fuel consumption for different types of aircraft and route lengths, considering the landing and take-off (LTO) and the climb, cruise, and descend (CCD) phases based on actual flight movement. Hence, details on the origin (departure) and destination (arrival) airports and aircraft type are required to use this approach. The methodology takes into account that fuel burn is related to flight distance while recognizing that fuel burn can be comparably higher on relatively short distances than on longer routes. This is because aircraft use a higher amount of fuel per distance for the LTO cycle compared to the cruise phase. Although it is possible to estimate the consumption and emissions on each route from data on the individual aircraft models, with the aim of decoupling our analysis from airlines' fleet assignment decisions (a route may result more polluting simply because it is currently served by older or less efficient aircraft), we chose to calculate emissions by using the average emission levels of the two most employed aircraft models used for intra-European flights (Airbus A318 and Boeing 737-100 operating more than 58% of flights and 77% of ASKs on our route data sample). Moreover, due to fragmentation and inefficiencies of European airspace (European Parliament, 2015), for each route, we considered a flight distance 5% longer than the great-circle distance between origin and destination airports.

[26] Within the tiered methodology developed by the EEA to estimate aircraft pollutant emissions, we apply the Tier 3 approach, which is described in "EMEP/EEA air pollutant emission inventory guidebook 2019: Technical guidance to prepare national emission inventories." EEA Technical Report (Issue 13/2019) — https://www.eea.europa.eu/publications/emep-eea-guidebook-2019

4.4 Empirical analysis

4.4.1 Travel times

Macro-European level

The first part of the empirical analysis aims to evaluate the degree of substitutability between air transportation and alternative modes of transport, mainly HSR. We focused on the impact of possible cancellations of intra-European short-medium haul routes operated by air but also served by alternative transport modes in terms of the number of flights and offered seats potentially subject to the ban. We analyzed the contribution of this cancellation to the air transport environmental challenge by reducing CO_2 emissions.

Figure 4.2 illustrates the degree of substitutability of intra-European routes as a share of total intra-European flights and in absolute terms. Figure 4.2(A) reports the share of routes, flights, offered seats, and potential CO_2 savings for each WITT level considered as the threshold to define a route potentially subject to the ban. Figure 4.2(B) depicts the number of offered seats and millions of CO_2 tons potentially replaceable for each WITT level. The degree of substitutability increases with the ITT threshold. Almost 26.5 million offered seats (3.02% of offered seats on intra-European routes in 2019) were found to be replaceable with alternative trips without a significant WITT for passengers. This would lead to a reduction in aviation CO_2 emission of around 1.3 million tons (around 2% of overall annual emissions from intra-European flights). Considering a WITT threshold of 20% and 50%, these values increase to around 63 and more 125 million offered seats and 3.13 and 6.2 million tons of CO_2 savings, respectively.

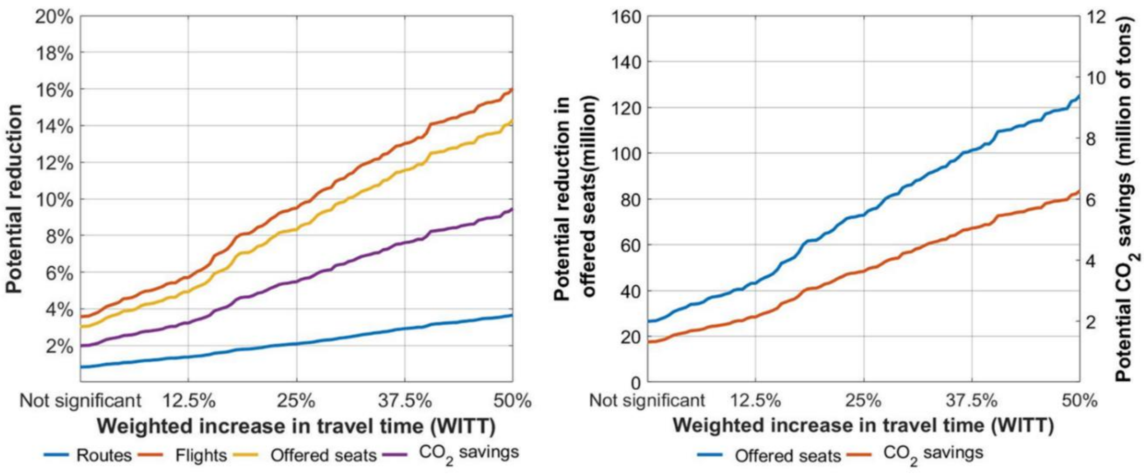

Figure 4.2: Share of intra-European routes, number of flights, offered seats, and potential CO_2 savings (A) and offered seats that potentially could be dropped and potential CO_2 savings (B) for each WITT level considered as the threshold to define the route substitutable. Year 2019.

Table 4.2 reports the top 10 substitutable routes (considering a WITT threshold of 20%)[27] in terms of offered seats. The cancellation of the Madrid (MAD) – Barcelona (BCN) route, suspending around 16,000 flights per year accounting for more than 3 million offered seats against a WITT for passenger close to zero, would guarantee savings around 120,500 tons of CO_2 emissions per year. This cancellation alone would stimulate an estimated 3.9% reduction in CO_2 emissions from the Spanish domestic market. The second potentially cancellable route in terms of seats offered is the Paris-Orly (ORY) – Toulouse (TLS) route accounting for about 2.9 million offered seats and potential savings of more than 136,000 tons of CO_2 emissions per year (approximately 6.4% of emissions from French domestic aviation). The top 10 substitutable routes, 8 of which include domestic flights, account for more than 18 million offered seats with potential savings of over 751,000 CO_2 tons (2.1% and 1.1% of intra-European offered seats and CO_2 emissions, respectively).

	Frequency – Annual flights	**Offered seats (million)**	**Reference market**	**WITT**	**Potential CO_2 savings***	**Alternative HSR connection**
MAD-BCN	15,956	3.10	ES-ES	Not significant	3.89%	Yes
ORY-TLS	16,358	2.91	FR-FR	17.9%	6.40%	Yes
FRA-MUC	9,990	1.90	DE-DE	18.3%	3.44%	No
TXL-DUS	11,068	1.70	DE-DE	15.7%	4.89%	Yes
ATH-SKG	9,155	1.58	GR-GR	16.9%	9.23%	No
LHR-CDG	9,404	1.51	GB-FR	Not significant	6.10%	Yes
AMS-CDG	8,466	1.47	NL-FR	15.2%	18.94%	Yes
LIS-OPO	10,657	1.36	PT-PT	10.8%	12.65%	No
LIN-FCO	9,986	1.35	IT-IT	4.6%	3.30%	Yes
GOT-ARN	7,649	1.25	SE-SE	4.6%	6.97%	No

* Potential CO_2 savings as a percentage of reference market emissions (total domestic market emissions if the route is domestic, total international market emissions if the route is international).

Table 4.2: Top 10 substitutable routes (considering a WITT threshold of 20%) in terms of offered seats. Year 2019.

[27] Considering a threshold of 20% WITT would seem reasonable in the light of the environmental clauses introduced by the French and Austrian governments in the recent bailout agreements. Indeed, both legislative initiatives have set thresholds in terms of the time of the alternative connection via HSR to define the route as substitutable (this threshold was set at 2.5 and 3 hours, respectively). Both these two values aim at ensuring the substitutability of the route preserving the TT for the passenger and at the most causing a slight increase in the TT.

Figure 4.3 analyzes the degree of substitutability of air routes that have alternative connections where the main leg is carried out by HSR.[28] Almost 25% of offered seats in competition with HSR results to be potentially replaceable by HSR without any ITT for passengers. This figure increases from 41.8% to 54.2% as the WITT threshold increases (from 25% to 50%). Although these values are significantly higher than those of routes with alternative connections operated by conventional transport modes, there is ample room for further improvement in the substitutability of routes where HSR is already in operation. This improvement can be pursued especially through better integration of HSR within the various modal networks. Moreover, of the airline seats potentially considered to be subject to ban without any ITT for passengers, the majority (53.7%) includes alternative trips carried out by HSR. This measure decreases (from 33.2% to 25.0%) as the WITT threshold increases (from 25% to 50%). The only exception is the increased share of offered seats replaceable by HSR connections for WITT values between 17% and 21%. The routes characterized by this range of time increases include those served by HSR that are particularly dense, such as Paris – Toulouse and Lyon – Toulouse. Alternative trips made, at least partially, with HSR guarantee routes substitutability inducing a lower ITT,

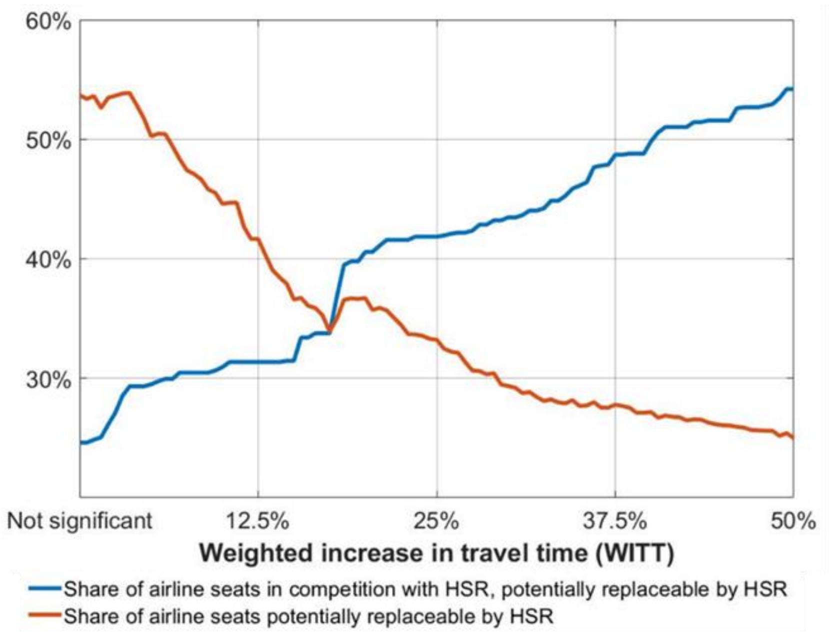

Figure 4.3: Share of airline seats in competition with HSR, potentially replaceable by HSR, and share of airline seats potentially replaceable by HSR.

[28] The main segment of the alternative journey is covered by train with an average speed higher than 175 km per hour.

whereas journeys using conventional means of transport (with lower average travel speeds) ensure substitutability of routes but with a significantly higher detrimental effect on passengers.

The overall picture of substitutability at the European level reveals different trends analyzing the degree of substitutability by country. Most substitutable routes are domestic, while HSR's presence at the international level mainly benefits the substitutability of air routes between France, the United Kingdom, Belgium, and the Netherlands (see Figure 4.4).[29] Figure 4.5 depicts the trend in the share of potentially substitutable offered seats as the WITT threshold increases for the five largest European domestic markets. France has a degree of substitutability of domestic routes, significantly higher than the other major European markets, especially for low WITT threshold. More than 20% of domestic offered seats (nearly 6.7 million per year) could be replaced without any significant ITT for passengers. Almost 27.4% of French domestic offered seats can be replaced against a WITT of less than 15%, and this figure rises to more than 50% for an ITT of more than 45%. The other major European markets share similar levels of substitutability considering low WITT thresholds. Conversely, Germany and the United Kingdom assume a more relevant role as the WITT threshold increases: the former reaching and exceeding the French value for WITT threshold greater than 30%, with the latter distancing itself from the patterns of Mediterranean countries (Spain and Italy). The potential CO_2 savings follow roughly the same pattern.

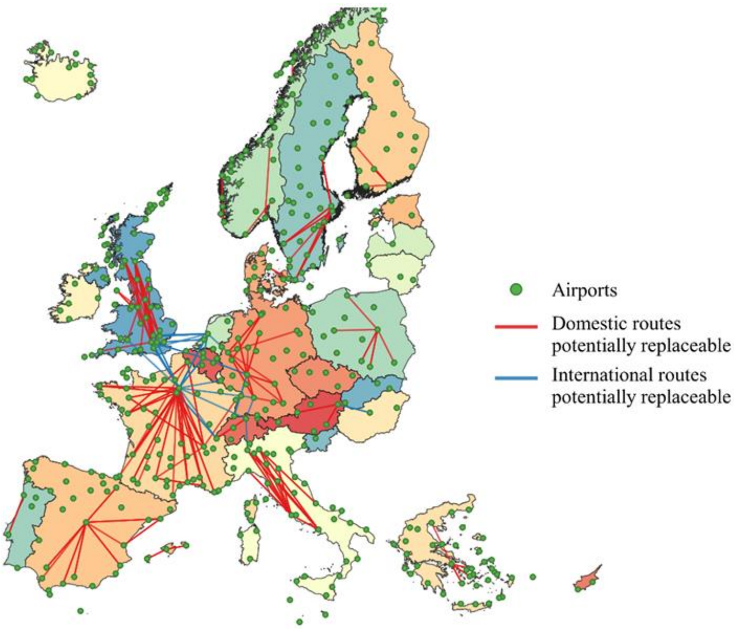

Figure 4.4: Domestic and international routes that are considered potentially replaceable using a WITT threshold to define route substitutability equal to 20%.

[29] Note that some overseas air routes between the Balearic Islands results replaceable by ferry connections. This is mainly due to the longer departure waiting time of the air alternative.

Focusing on Figure 4.5, it is interesting to draw a comparison between the impacts in terms of offered seats potentially subject to the ban at the national level and the characteristics of air routes operated and the infrastructure endowment of each country (the extension of HSR network). About the average length of domestic air routes in operation, Spain, due to the large share of domestic traffic to and from the islands, dominates at the European level with an average length of almost 900 kilometers. France and Italy follow, with air routes of similar average lengths (around 630 km). Germany and United Kingdom follow further behind with average lengths of 410 and 360 kilometers, respectively. In terms of in-operation HSR lines Spain and France dominate with 3,300 and 2,734 kilometers, respectively, followed by Germany and Italy with 1,571 and 921 kilometers. Conversely, the United Kingdom plays a marginal role with only 113 kilometers classified as HSR. It is noteworthy that this country is characterized by an extensive and capillary traditional railway network. A widespread and efficient high-speed network seems to guarantee the possibility to end many air routes with limited detrimental effects in terms of TT on passengers. A clear example of this is France, where many routes may be scrapped and replaced with alternative connections in the face of limited ITT. However, this does not always hold. In this respect, it is emblematic the difference in terms of substitutability of air routes between Spain and France in the face of similar HSR network extensions. This can undoubtedly be attributed to the large share of Spanish domestic traffic to and from the islands which by nature are more difficult to be replaced effectively. On the other hand, short average air route lengths allow high degrees of substitutability by non-high-speed alternative connections, as with the case of Germany. The reduced length of in-operation domestic air routes allows Germany to exhibit a high degree of substitutability, especially while facing greater increases in passenger TT (alternative means of transport obviously have a lower average speed).

Finally, considering the type of airlines most impacted by the possible cancellation of flights considered as substitutable (Figure 4.6), we outline around 5.8 and 19.3 million seats offered by low-cost carriers (LCCs) and full-service carriers (FSCs), respectively, that can be replaced by other means of transport without inducing any significant ITT for passengers. These values increase almost linearly with the WITT considered as the threshold for defining the route substitutable. One would expect LCCs to be less exposed to route substitution than FSCs, as airports served by LCCs are generally located further away from city centers and more rarely connected to city center by direct train services or HSR connections. Indeed, the curve of potentially impacted LCCs' seats shows a less steep slope than that of FSCs. A more in-depth

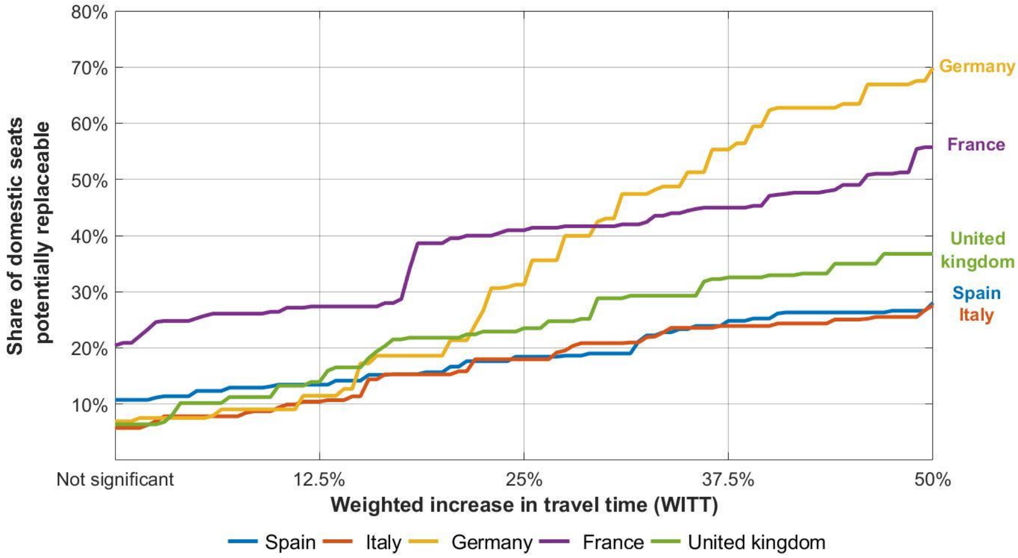

Figure 4.5: Share of domestic seats potentially replaceable for different WITT thresholds, top 5 European domestic markets.

analysis of potentially replaceable offered seats shows that Air France plays a dominant role: 19.1% of seats offered could be replaced without significant ITT, whilst 36.6% and 49.5% of seats offered could be replaced with a WITT threshold of 20% and 50%, respectively. Alitalia and Iberia follow in terms of percentage impact, registering significantly higher impacts than the low-cost Ryanair, easyJet, Eurowings, and Vueling. Lufthansa exhibits significant impacts only for WITT above 20%. Potential CO_2 savings follow approximately the same pattern as that shown for offered seats.

Table 4.3 summarizes the potential impacts and benefits of a policy of banning air routes that can be substituted without a significant WITT for passengers.

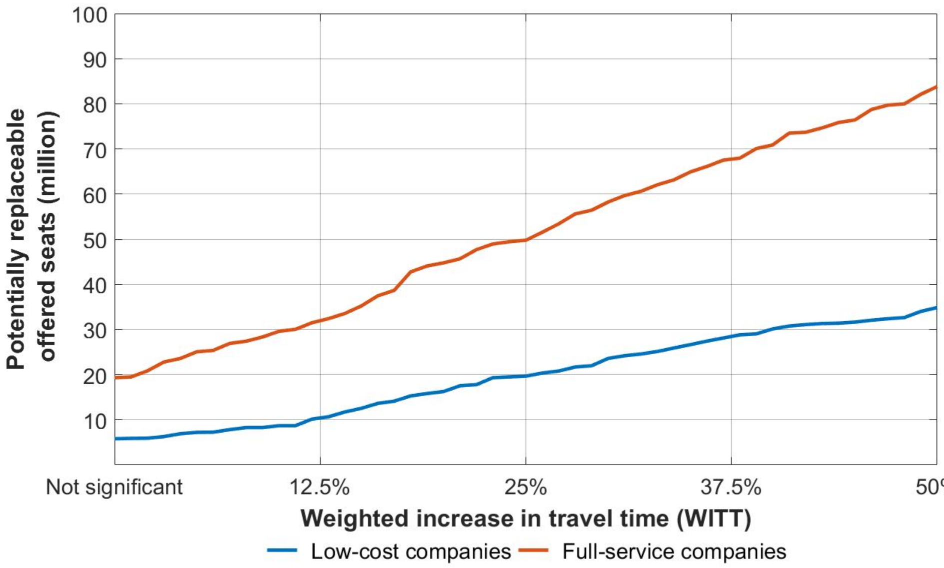

Figure 4.6: Offered seats (million) that potentially could be dropped for each WITT level considered as the threshold to define the route substitutable and type of airline.

Potential impacts and benefits	
Routes	104 *(0.82%)*
Annual flights	211,786 *(3.57%)*
Offered seats (million)	26.48 *(3.02%)*
Potential CO_2 savings (million tons)	1.31 *(1.98%)*
Share of offered seats potentially replaceable by HSR connections	53.7%
LCCs' offered seats (million)	5.81
FCSs' offered seats (million)	19.34

Table 4.3: Potential impacts and benefits of a policy of banning air routes that can be substituted with no ITT, absolute values and shares of intra-European total. Year 2019.

Impacts on regional accessibility

In this Section, we study how the effects of a policy based on the cancellation of short-medium haul flights are distributed regionally to identify whether it excessively penalizes some areas and exacerbates or reduces existing differences in accessibility.

To outline different impacts of the cancellation of short-medium haul intra-European flights, European regions had to be classified based on their *ex-ante* accessibility level. We adopt a classification based on a potential multimodal accessibility index elaborated within the ESPON project TRACC.[30] This index reflects the relative competitive position of each European region toward European destinations. The measure assumes that the attraction of a destination increases with size and declines with distance, TT, or cost. Therefore, both size (population) and distance are considered. The multimodal index is calculated by jointly considering accessibility by road, rail, and air.

As shown in Figure 4.7, European regions could be divided according to their accessibility level in five categories: very peripheral, peripheral, intermediate, central, and very central region. The traditional core-periphery pattern clearly appears with higher accessibility levels in Belgium and neighboring regions of Germany due to the favorable geographical location and the greater extension of the infrastructure network. High-level road infrastructure serves more or less all regions, whereas HSR serves mainly hubs and corridors. Thus, the highest accessibility is visible along major corridors (French corridors towards the Atlantic and the Mediterranean Sea and the Italian North-South link from Milan to Naples). Regions that are not

[30] TRACC (TRansport ACCessibility at regional/local scale and patterns in Europe) is an applied research project conducted within the framework of the ESPON 2013 Programme, partly financed by the European Regional Development Fund: https://www.espon.eu/tracc

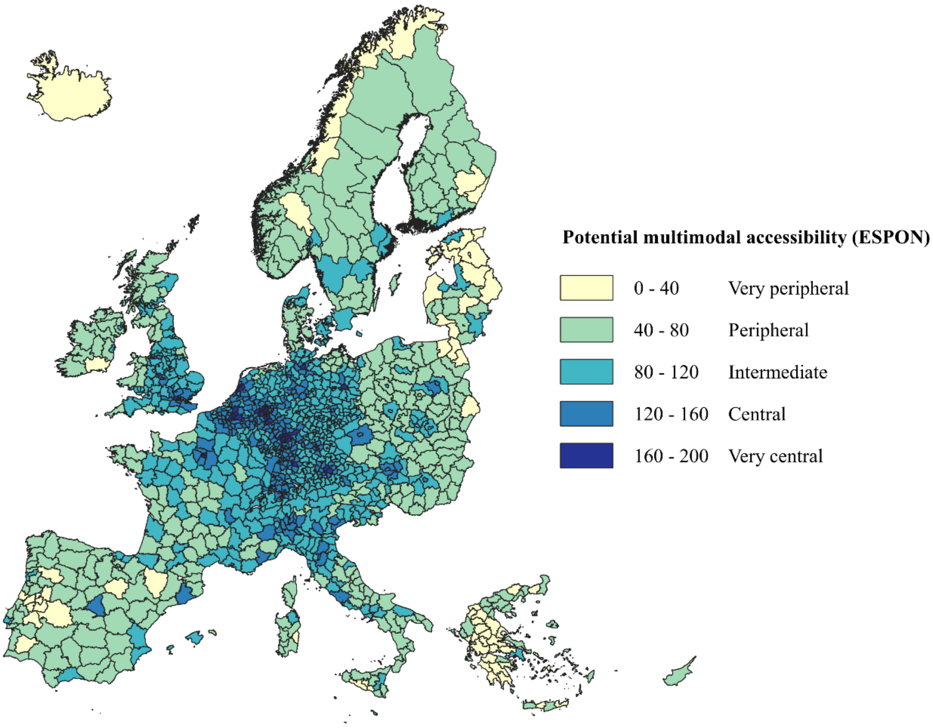

Figure 4.7: Classification of European zones according to the potential multimodal accessibility index. Source: Author's own elaboration on data from ESPON TRACC project.

served by good air connection might be compensated by other transport links for road and rail and *vice versa*.

Comparing Figure 4.4 and Figure 4.7, most routes potentially replaceable appear to be concentrated in central or intermediate areas. To perform a more in-depth analysis, we define two indices specifically aimed at highlighting the impacts in terms of substitutability faced by each area to evaluate the effect on regional accessibility arising from such a policy.

The first index, calculated for each region with at least one scheduled flight departing or arriving in 2019, is the percentage of offered seats potentially subject to cancellation in case an air route banning policy is implemented (considering a WITT threshold equal to 20%). This provides information on the degree of substitutability of flights arriving or departing in a region. Table 4.4 shows the average values of this index for the different accessibility levels of a region (as defined above) and the number of analyzed regions for the different impact levels. Cities and regions according to the percentage of offered seats potentially eligible for removal are classified as those with:

- No impact: 0%;
- Low impact: 0%–5%;
- Medium impact: 5%–15%;

	Average of the share of potentially replaceable offered seats	Share of offered seats potentially replaceable					
		No impact 0%	**Low impact** 0%-5%	**Medium impact** 5%-15%	**High impact** 15%-30%	**Extreme impact** >30%	**Total**
Very peripheral	4.65%	72 *(87.8%)*	1 *(1.2%)*	2 *(2.4%)*	2 *(2.4%)*	5 *(6.1%)*	82
Peripheral	3.47%	180 *(87.8%)*	1 *(0.5%)*	8 *(3.9%)*	8 *(3.9%)*	8 *(3.9%)*	205
Intermediate	6.30%	68 *(65.4%)*	9 *(8.7%)*	11 *(10.6%)*	10 *(9.6%)*	6 *(5.8%)*	104
Central	5.07%	18 *(39.1%)*	10 *(21.7%)*	14 *(30.4%)*	4 *(8.7%)*	-	46
Very central	8.73%	-	2 *(18.2%)*	8 *(72.7%)*	1 *(9.1%)*	-	11
Total	4.63%	338	23	43	25	19	448

Table 4.4: Number of regions/cities by accessibility level and share of offered seats potentially eligible for banning (WITT threshold equal to 20%).

- High impact: 15%–30%;
- Extreme impact: >30%.

The average of the share of offered seats potentially subject to ban reveals that, on the one hand, moving from very peripheral to intermediate areas, the number of replaceable seats increases from 4.65% to 6.30%, passing through the 3.47% of peripheral regions. On the other hand, passing from regions with middle levels of accessibility to very central areas, the average of the share of offered seats ranges from the high impact registered in intermediate areas to a lower 5.07% in central areas and a more accentuated 8.73% in very central areas.

The share of the region with zero impact decreases as its accessibility increases. The vast majority of peripheral and very peripheral regions (87.8%) are not affected at all (no routes are potentially subject to the ban). This pattern is reversed for central and very central regions. Indeed, more than 60% of the former and all the latter offer at least one seat potentially subject to the ban. This can be attributed to the high level of infrastructure in regions with greater accessibility. In other words, as the level of *ex-ante* accessibility increases, there are more efficient alternative connections in the region that provide a higher level of substitutability. Considering the areas impacted by air route substitution (regions with an index greater than zero), fairly homogeneous impacts are observed in intermediate areas. Notwithstanding low and medium impacts that characterize the very peripheral and peripheral regions, a cluster of extremely impacted zones consisting of 5 and 8 zones respectively emerges, attributable to regions where a relevant route in terms of offered seats (if not the only route operated) is potentially subject to prohibition. This eventuality is further investigated through the introduction of an index specifically aimed at assessing the impact on passengers of air route cancellations (the average ITT). Contrarily, central and very central regions, albeit more impacted, show a milder share of potentially impacted offered seats. None of these regions are extremely impacted because those with high accessibility have higher levels of offered seats and, although the number of impacted seats is higher, it is spread among many unaffected routes.

The second index jointly considers the number of offered seats that could potentially be cancelled and the ITT that passengers would experience by travelling these routes using alternative transport modes. We define this measure as the average percentage ITT per offered seat arriving or departing from a specific region (considering both offered seats subject and non-subject to replacement). Regions with no routes potentially subject to cancellation, with a WITT threshold of 20%, will show an average ITT per passenger equal to zero as well as regions with substitutable routes but for which the alternative trip guarantees TTs comparable to those by air (no significant ITT). Areas will experience high values of this measure as the number of impacted offered seats increases and the passengers' WITT increases. According to this index (Table 4.5), cities/regions could be divided into those with:

- No impact (no routes eligible for removal) or no significant ITT (the alternative trip guarantees TTs comparable to those by air);
- Low impact: <1%;
- Medium impact: 1%–2.5%;
- High impact: 2.5%–5%;
- Extreme impact: >5%.

	Average impact on TT per offered seat	**Impact on TT per offered seat**					
		No impact or no significant ITT	**Low impact** <1%	**Medium impact** 1%-2.5%	**High impact** 2.5%-5%	**Extreme impact** >5%	**Total**
Very peripheral	0.08%	79 *(96.3%)*	1 *(1.2%)*	1 *(1.2%)*	1 *(1.2%)*	-	82
Peripheral	0.27%	184 *(89.8%)*	7 *(3.4%)*	5 *(2.4%)*	7 *(3.4%)*	2 *(1%)*	205
Intermediate	0.32%	74 *(71.2%)*	8 *(7.7%)*	19 *(18.3%)*	1 *(1%)*	2 *(1.9%)*	104
Central	0.34%	21 *(45.7%)*	3 *(6.5%)*	21 *(45.7%)*	1 *(2.2%)*	-	46
Very central	0.70%	-	2 *(18.2%)*	9 *(81.8%)*	-	-	11
Total	0.26%	358	21	55	10	4	448

Table 4.5: Number of regions/cities by accessibility level and percentage increase in TT per offered seat (WITT threshold equal to 20%).

The average impact on TT per offered seat depicts the air route cancellation impacts regionally. The higher the *ex-ante* level of accessibility, the greater the expected impact in terms of TT per offered seat. This trend is driven by the large number of offered seats that can be replaced in central and very central areas due to the better alternative connections, especially HSR. Higher infrastructural level guarantees efficient alternative connections in terms of TT in case of air route cancellation. Most of the very peripheral and peripheral areas (96.3% and 89.8%, respectively) have no routes potentially subject to a ban or, in case of routes potentially cancellable, they are effectively served by alternative connections (no significant ITT for passengers). Moreover, only a marginal part (1.2% and 4.4%, respectively) of these regions suffers high or extreme impact values. Intermediate regions show an intermediate pattern between peripheral and central regions.

Overall, the analysis of the regional impact outlines a clear trend: central and very central areas are the most impacted in terms of the share of offered seats, however, they experience medium to low increases in TT in case of substitution. These findings can be attributed to the infrastructural endowment of these areas, allowing air routes substitution and guaranteeing competitive alternative trips. Regions with lower accessibility levels are mostly preserved by route substitution and only a marginal part of these areas register a significant impact in terms of increase in passengers TT.

4.4.2 Generalized travel cost

In this Section, we seek to model passenger preferences that consider, in addition to TTs, other dimensions, such as fares and time costs. For this purpose, we evaluate the substitutability of routes based on the weighted (between all passenger categories) increase in the generalized travel cost that passengers would bear if the air route is removed and they used alternative connections. It is necessary to specify how this analysis strongly depends on the current competitive environment and how the results may be substantially affected by the alleged route ban policy and the resulting changes from a competitive and pricing perspective.

Because it is not possible to accurately estimate the proportion of commuting and business passengers traveling on each route, the increase in GTC resulting from the possible ban of each air route was carried out considering an average value of time. Subsequently, given the significantly different values of time for these categories of passengers reported in the literature, a sensitivity analysis was conducted, considering values of time of commuting and business passengers as extreme scenarios on a continuum.

Figure 4.8 shows the share of short-medium-haul offered seats potentially subject to cancellation for each threshold of WIGTC. At first glance, it clearly appears that by considering GTC instead of TT alone as a criterion for defining route substitutability, the impacts of a cancellation policy would be higher for a given threshold. This is primarily because alternative connections exhibit, on average, limited increases (and even decreases) in travel fares, while TTs generally increase, thus resulting in limited GTC increases and a higher degree of substitutability. However, this result would change if the increasing market concentration induced the providers of the alternative means of transport (HSR companies) to increase prices, as we will discuss in the next Section. This trend appears clearly when breaking down the different components of the GTC increase (time cost and fares) and investigating how they contribute to form the overall value of the GTC increase. Figure 4.9 represents this breakdown by route length bands. As expected, the higher route length, the higher the average GTC increase when substituting air routes. The trend in average GTC increase is driven by the increase in time cost as distance increases (alternative connections progressively lose competitiveness over air transport in terms of TT as route length increases). On the other hand, the GTC fare-related component results, on average, negative for routes of less than 400 km, thus partially dampening the increase in GTC induced by the time-cost component. However, this convenience in terms of fares, mainly due to higher per kilometer airfares compared to those of alternative modes of transportation, fades for longer flights. This can be traced back to airfares that increase less than proportionally with flight distance.

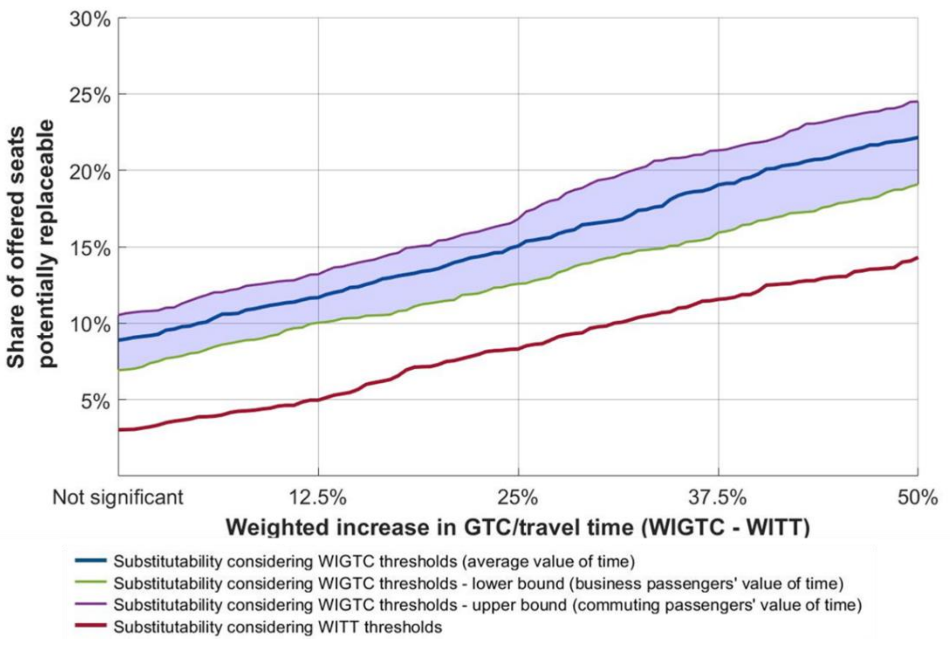

Figure 4.8: Share of potentially cancellable intra-European offered seats per WIGTC/WITT level considered as the threshold to consider the route eligible to be banned.

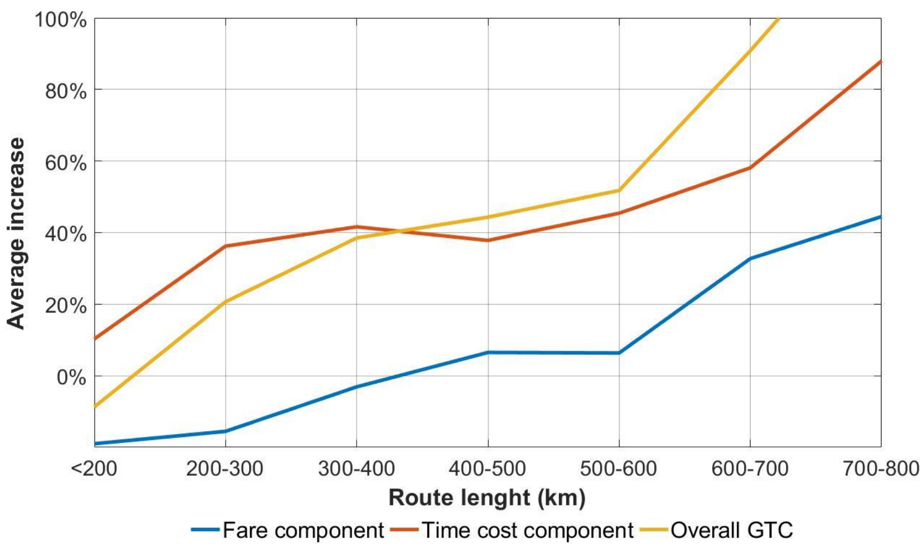

Figure 4.9: Breakdown of the weighted (with respect to offered seats) average GTC increase into a fare-related component and a time-cost component by route length band.

Different trends emerge when analyzing the degree of substitutability based on the WIGTC considering, instead of the average value of time, the distinctive value of time for commuting and business passengers respectively (Figure 4.8). The former, characterized by low monetary values of time, are more inclined to accept significant ITT, resulting in a significantly higher degree of route substitutability. Concurrently, by considering the value of time typical for business passengers, the analysis reveals a lower degree of substitutability, which, however, remains higher than that expressed when considering the WITT constraint (the first part of our analysis).

The two measures of substitutability (WITT and WIGTC) exhibit a high correlation coefficient (0.871). This is confirmed even by stratifying with respect to the route length and size (offered seats). The correlation between the two measures of substitutability ranges between 0.807 and 0.908 as the route distance band varies, and between 0.819 and 0.894 as the number of offered seats varies. This results in similar outcomes and suggestions when the two analyses (based on TT and GTC) are conducted. However, we maintain that WITT is a more robust measure to estimate the impact for passengers of the substitution between air services and alternative transport means because it depends less on ex-post competitive conditions, while focusing on the level and quality of infrastructure provision for the alternative transport means.

At this point, it is worth seeking to provide an initial comparison between the benefits of the air cancellation policy (reduction in CO_2 emissions) with associated costs burden by the passengers (increase in GTC). Although calculations performed depend on a number of assumptions (including, without any doubt, the value of time as well as the economic evaluation of emissions), it provides an initial rough and interesting comparison of the benefits and costs of the policy. The benefits are the expected reduction of the CO_2 emissions. These have been monetized using the quoted price on the European emissions market (EU ETS) of a CO_2 ton, assumed to be a good proxy for the social cost of carbon emissions.[31] This price amounts on June 2021 to €55. To ensure the robustness of the results, in addition to the average value, we consider a price range for CO_2 emissions with a lower limit of €35 and an upper limit of €75.[32] On the other hand, policy costs have been quantified based on the net GTC increase that passengers of the different types (point-to-point and interconnecting) would face as a result of the end of air routes. Specifically, the estimate is based on the number of passengers of each type provided by the OAG Traffic Analyzer and on the GTCs computed as described in Section 4.3.3.

Figure 4.10 reports the evolution of the benefits and costs of the cancellation policy as the WIGTC considered as a threshold varies. It is possible to observe that for WIGTC below 15%, the total costs of the policy borne by passengers are lower than the value of the benefits. Conversely, for values above 15%, the costs exceed the benefits. Varying the monetization of CO_2 emissions, the WIGTC cost-benefit offset point ranges from 13% to 19%. The average

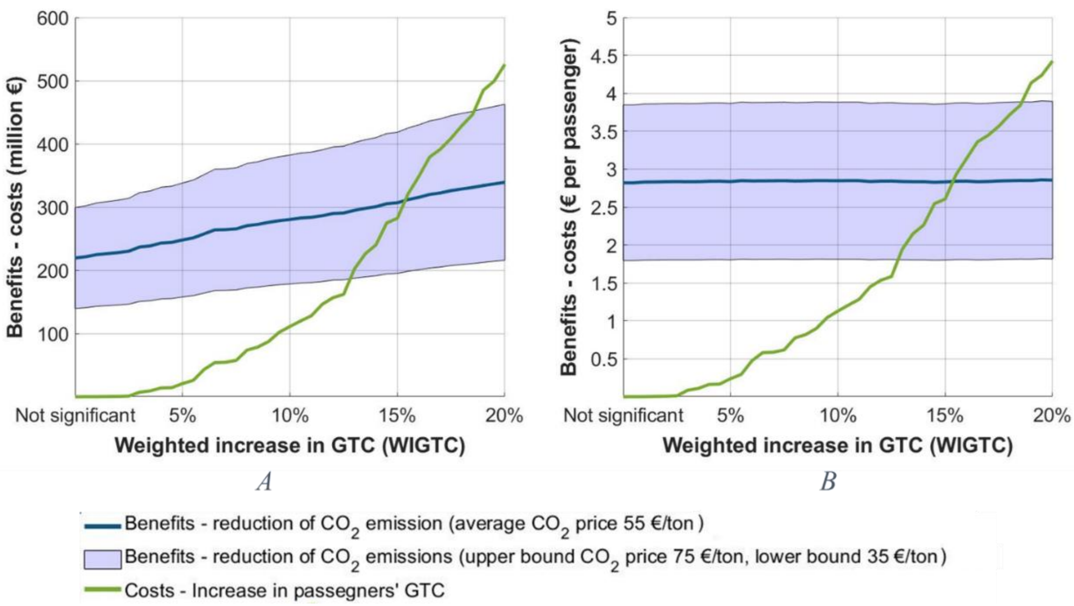

Figure 4.10: Benefits and costs of the analyzed policy for different WIGTC thresholds: total (A) and per passenger values (B).

[31] The social cost of carbon (SCC) is the marginal cost borne by the whole society due the impacts caused by emitting one extra ton of carbon dioxide.

[32] Note that the latest studies calculate costs of more than US$135 per ton of CO_2 would be needed to drive carbon emissions to stay below the 1.5 °C limit.(IPCC, 2018).

(per passenger) value of CO_2 emissions savings remains stable as the WIGTC changes and ranges between 1.8 and 3.9 euros (with a mean value of €2.85). In contrast, the average cost per passenger increases as the WIGTC increases. Looking at the figure, it is also useful to note that the higher benefits compared to the low costs observed for low WIGTC could however be partially used to encourage investment in alternative transport infrastructures and increase their capacity.

Finally, it is worth pointing out that our analysis does not consider other significant variables for passengers, such as the quality of service, which is particularly important for business passengers. In this regard, it is noteworthy that, at least land connections served by HSR, have so far reached levels of comfort that are comparable, if not superior, to those achieved by air (possibility of working onboard with Wi-Fi connection, dedicated carriages, bar and restaurant service). In addition, the costs (such as overnight costs) incurred by passengers if the removal of the air route no longer allowed for daily round trips was not considered.

4.5 Discussion and policy implication

In this Section, we analyze and discuss the main implications and critical issues concerning the implementation of policies to ban short-medium haul air flights for environmental purposes.

The policies recently adopted by national governments and policymakers to reduce aviation emissions constitute the driving force behind a clear trend toward the reduction of short-medium haul air routes. Until a few years ago, there was an extensive debate on whether the growing competition faced by aviation from increasingly competitive means, such as HSR, would lead to the total replacement of short-medium-haul air routes. Nowadays, it appears clearer that the abolition of routes where an effective alternative exists is likely to be forthcoming, at least in some EU Countries.

The reduction of short-medium haul flights might mark the end of a more than 30-year presence (in some cases, dominance) of air transport. Since intra-European aviation deregulation, air travel has not only attracted passengers who previously travelled by alternative transport modes but also enabled new categories of users to travel. This has been partially changed by the recent widespread deployment of HSR networks, which have already contributed to a reduction in demand for air transport on certain routes. Nonetheless, the legal abolition of short-medium haul routes represents an even more critical decision that raises several questions and issues concerning both the effective implementation of the policy and possible side effects.

These questions concern five main areas: presence and organization of alternative transport modes, competitive landscape, impacts on passengers and regional accessibility, evolution of the air transport industry, and coexistence with other measures towards sustainability.

Concerning the first issue, it is noteworthy that the primary regulatory initiatives promoted by policymakers assess air route substitutability setting a threshold in terms of TT of the alternative connection. To prevent excessive detrimental effects for passengers and reductions in accessibility to peripheral regions, it is essential to carefully identify air routes that could be subject to blockades. To this end, the evaluation of alternative connection TT is an adequate proxy for the current level of infrastructure provision and able to identify routes served, for instance, by HSR links. This assessment, however, needs to be supported by a more in-depth preliminary analysis of the capacity available on alternative transport modes that should be able to accommodate the diverted demand following the closure of the air routes. Coordination between policymakers and railway companies (or alternative transport service providers) is therefore crucial to preliminarily evaluate the capacity of the current rolling stock as well as ensure adequate planning of modal shift allowing companies to implement appropriate organizational measures (e.g., revision of scheduling and timetables) and investments (e.g., hiring or increasing vehicle fleet). Furthermore, policymakers together with railways infrastructure managers need to identify to what extent the shift to rail option can be accommodated on the current high-speed rail infrastructure considering congestion issues and the compresence of conventional rail services in some segments of the infrastructure. For the same reasons, a gradual and progressive introduction of the policy with specific transitional periods is required. Over a longer period, the process of reducing short-medium haul air routes will also require adequate planning and implementation of improvements to the high-speed transport network by policymakers and governments both at the European and national levels. Thus, the implementation of the envisaged development of a pan-European network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports, and railroad terminals within the Trans-European Transport Network (TEN-T) project is essential. Specifically, the removal of bottlenecks and the creation of multimodal links with direct connections between the HSR networks and airports appears to be crucial.

Equally significant is the issue of competition, which at least in its multimodal component will be reduced following the withdrawal of air travel on routes subject to cancellation. The prohibition of air travel will inevitably result in market concentration, which might lead to higher fares and reduced quality. Thus, policymakers should implement appropriate initiatives to reduce the possibility of abuse of market power, such as stricter regulations (e.g., the introduction of price monitoring mechanisms and agreements to prevent fare increases) or the promotion of competition within railway and alternative modes industry. Regarding the latter, the introduction of on-track or multi-service competition through several railway companies competing on the same network (following a model similar to that applied with Trenitalia and NTV on the Italian HSR network) seems, in the first instance, positive. However, it is still necessary to carefully monitor the level of competition between companies to avoid the establishment of a collusive oligopoly.

Other key issues related to the ban of short-medium haul air routes are the effects on passengers and regional accessibility. These topics are broad and relevant and necessitate discussion beyond what is covered in the empirical Section of this paper. Regarding the former, it is reasonable to expect, at least in the short-term, impacts in terms of both TT and cost and service quality. If the quantification of the former is feasible by analyzing alternative TTs, the *a priori* evaluation of the latter is more difficult, given the profound change in the competitive landscape that will occur when air routes are withdrawn. This assessment requires the formulation of specific hypotheses and forecasts regarding the evolution of the competitive environment, such as the number of competitors, the competitive pressure, and the effect on fares for each specific market.

Moreover, contrary to the extensive documentation following the introduction of high-speed services on some routes (Givoni and Dobruszkes, 2013), the loss of part of the demand (air passengers who decide not to travel anymore) due to the reduction in supply and the worsening of travel conditions (dissuaded demand) is foreseeable, at least in the short-term. This and the ITT for passengers is a key element of this policy aimed at reducing aviation emissions. Policymakers are indeed required to find the right balance between environmental benefits and safeguarding the welfare of passengers (both in terms of time and costs) and, more generally, passengers' need to travel. This paradigm will have to be pivotal in assessing and calibrating route-blocking measures, adopting them only where such removal will not excessively aggravate the accessibility and integration of a region within the European and global context. It may constitute a central element in assessing and calibrating future route-blocking measures, adopting them only where such removal will not excessively aggravate passenger travel conditions as well as the accessibility and integration of a region within the European and world stage.

The issue of sustainability of airlines' business in the face of the cancellation of some routes and the evaluation of secondary effects such as impacts on airlines' strategies and network evolution represent other relevant topics that will need to be addressed to fully understand the impacts of this policy. Regarding the former, the introduction of specific compensatory mechanisms and subsidies to limit the carrier economic and financial losses should be considered. The latter refers, among others, to the increase in pollutant emission due to the replacement of slots liberated by the cancellation of short-haul flights with long-haul ones at some airports. A possible solution to this phenomenon, already highlighted in previous studies (Socorro and Viecens, 2013), could be a detailed and specific analysis of policy impact on single airports and the consequent definition of limits for the introduction of new flights.

A final point of discussion concerns how the encouragement of modal shift to HSR relates to other policies and opportunities aimed at the sustainability of short- to medium-haul air connections. Among them, besides generic measures internalizing emission costs (i.e., EU ETS) and the use of SAFs, electric-powered aircraft has the most promising prospects to revolutionize the aviation industry and contribute to achieving its climate goals. Electric aircraft will drastically reduce atmospheric emissions (zero CO_2 during operation) and will be quieter (by about 36%) than conventional aircraft (Schefer et al., 2020). With over 300 aviation electrification projects active worldwide, the first 50 to 100-seat regional aircraft are announced for entry into service by 2035 (IATA, 2021). However, despite the promising prospects, the first-generation electric aircraft is expected to face a major challenge of low battery density, which results in shorter ranges and lower seat capacities than their conventional fossil-fuel counterparts. As such, at least for the short- and medium-term, electric aircraft is a viable option only for medium- and short-range thin markets, such as regional routes serving remote regions. On the opposite, due to low capacity, aircraft electrification is not a real option for dense medium-haul commercial markets in the near future. These routes (particularly dense and within 800 km) are the connections along which HSR investments have the most promising opportunities to gain relevant passenger flows thus ensuring their environmental sustainability even from a life-cycle perspective. With this regard, electric aircraft and modal shift initiatives towards HSR are complementary actions in decarbonizing short- and medium- haul air markets.

4.6 Conclusion

The deregulation of intra-European aviation kick-started a nearly 30-year season of tremendous growth in air transportation stimulated by lower fares and improved connectivity. Decreases in travel costs resulted in both market generation (enabling new users to travel) and shifting from other transport modes to air transport. Indeed, with liberalization, air transport became more convenient compared to traveling by cars, buses, or trains.

Nowadays, the issue of sustainability of growth in the air transport industry and the pressure to reduce the environmental impact of aviation is pushing policymakers in the opposite direction, namely, toward ending short-medium haul air flights and replacing them with alternative transport modes. This attempt, evidenced by ongoing policy initiatives, has been considerably strengthened by the significant increase in the performance of these kinds of transport arising from the widespread deployment of HSR networks over the last years.

This research represents the first attempt to evaluate the impact of possible policy initiatives to ban short-to-medium-haul intra-European flight routes concurrently served by alternative modes of transport. The accurate assessment of the degree of technical substitutability between air and alternative modes of transport, mainly HSR, allows us to conduct a thorough evaluation of the resulting impact at a macro-European and a micro-regional level.

At a macro-European level, the benefits (emission savings) and impacts on the air transport industry (decrease in offered seats for certain airlines and at certain airports), are not equally distributed across Europe. Around 63 million (7.2% of intra-European) offered seats could be replaceable with alternative trips causing a maximum increase in weighted passenger TT equal to 20%. Discontinuing these routes is estimated to reduce intra-European aviation CO_2 emission by 4.72% (approximately 3.13 million tons per year). Impacts are mainly concentrated on domestic routes and where alternative connections are possible, at least partially, by HSR. The French domestic market, because of the considerable extension of the French HSR network and the presence of numerous air connections to Paris-Orly (ORY) airport, is the most impacted domestic market in terms of the number of routes, flights, and offered seats. It also leads in terms of potential CO_2 savings, standing out as the best candidate for the adoption of such a policy (as evidenced by recent legislative initiatives). The French market is followed by Germany, the United Kingdom, Spain, and Italy in terms of impact. Besides, FSCs are more affected than are LCCs by route removal policies, probably due to their greater presence at major airports better served and integrated into the modal network.

Overall, albeit with uneven results, such a policy would make it possible to achieve, at least partially, the targets set in some bailout agreements concluded in the wake of the recent COVID-19 pandemic. Moreover, it would mark a step toward the meeting of medium-long-term targets in terms of GHG emission reduction set by the EC.

Turning to the analysis of impacts at regional level, we investigate how the impacts both in terms of offered seats potentially dropped and increased connection times are distributed across European regions based on their *ex-ante* level of accessibility. Specifically, we outline how the implication of such a policy burdens mainly central areas with a high *ex-ante* level of accessibility. Already disadvantaged peripheral areas would only be marginally affected by such a policy. The replacement of short-medium haul flights would thus preserve already disadvantaged regions by placing the burden of reducing emissions from aviation mainly on areas already efficiently served by alternative transport modes.

Despite the effects previously highlighted, a policy based on the cancellation of short-medium haul flights may also lead to relevant side effects. Although an accurate investigation of these elements is beyond the scope of this paper, our analysis raises several critical questions and issues that policymakers will need to answer in the coming years to effectively and successfully implement such a policy. Topics range from the reduction of competitive pressure (between different transport modes) to the increase in pollutant emission due to the introduction of new long-haul flights at some airports that witnessed the cancellation of short-medium haul flights. Other key elements that need to be considered are the enhancement of intermodal cooperation and coordination, the effects on passengers, the demand—such as changes in travel conditions (level of service and fares), and the reduction of demand due to a reduction in supply. An additional pivotal aspect that requires the coordination between policymakers, railways operators, and railway infrastructure managers is the evaluation of to what extent the shift to rail triggered by the ban of air connections can be accommodated on the current infrastructure with the existing rolling stock. Lastly, as outlined in Chapter 2 of this thesis, it is worth mentioning how investments in new HSR lines or upgrades of the existing ones require significant economic investments and turn to be effective from a total life cycle emissions perspective only in case of high diverted demand. Thus, investments in the HSR network should focus on dense markets where a significant number of passengers diverted could be achieved. On the opposite, thin markets connecting remote regions do not justify the huge investments to build HSR infrastructure and can complete their process toward zero emissions thanks to new technologies such as electric-powered aircraft. These will be key points of discussion in the coming years and will have to be properly addressed by policymakers to maximize the benefits while minimizing the side effects.

Finally, it is worth outlining for the benefit of future research some limitations of our study. First, because we focus on evaluating the impacts and consequences of a possible policy of cancellations of short-medium-haul air routes, our work could be further developed by focusing on understanding the competitive impacts and evolutions resulting from the termination of the air alternative. Second, although in the analyzed sample the centroid-based approach well represents the actual population distribution within the metropolitan area of each city, using a granular approach accounting for the actual population distribution could allow a more accurate assessment of air route substitutability. Third, while evaluating impacts on air transport and pollutant emissions, we do not evaluate the propagative effects of the cancellation of the air routes such as induced demand on alternatives routes, the need for an increase in the frequency and capacity of alternative public transport connections, and the prospective need for major infrastructure investments on the alternative transport network (and consequent indirect CO_2 emissions due to infrastructure construction). In this regard, our study represents the first attempt to assess the order of magnitude of possible impacts within the aviation sector stimulated by this type of policy that needs to be complemented and improved in future research to obtain a clearer picture of benefits and drawbacks arising from its implementation.

Chapter 5 – Diverted and induced demand: evidence from the London-Paris passenger market

5.1 Introduction

As discussed in previous Chapters, nowadays, competition between HSR and air transport is becoming fiercer. Indeed, over the last two decades, HSR systems have developed steadily worldwide with an increase of in-operation HSR lines of more than 50,000 km (UIC, 2021). The competition between transportation modes is particularly intense for short-medium haul routes where HSR is more competitive relative to air transport due to several factors, including average speed, faster check-in/out times, punctuality, higher frequencies, and closeness to the city centers (Xia and Zhang, 2016; A. Zhang et al., 2019). The introduction of HSR in such a type of route has led to significant changes in air operators' business strategies (Albalate et al., 2015). Indeed, they have had to cope with a significant decrease in market shares, frequencies, passenger volumes, and fares (Castillo-Manzano et al., 2015; Cheng et al., 2015; Wan et al., 2016). Implications of the introduction of HSR are not limited to those on air transport supply, but covers also on the demand side. Specifically, in addition to having a demand diversion effect (i.e., attracting passengers who previously traveled by other modes), it contributes to stimulating total demand, resulting in induced demand.

In the years to come, it can be foreseen that further intensification of competition between HSR and air transportation will take place. This is likely to be most evident in the European scene as a consequence of the ongoing EU climate policies and initiatives extensively described in Section 2.2. On the one hand, the EC placed railway transportation at the forefront of its transportation policy by focusing on both infrastructure development and stimulation of competition within the industry. On the other hand, to build a sustainable future, the EU has undergone a series of policies aimed at achieving the ambitious target of a 90% reduction in transportation GHG emissions by 2050 compared to 1990 levels (EC, 2019). These objectives entail converting the majority of medium-distance passenger transport to rail and internalizing the external costs of transport at the latest by 2050 ensuring that those who use transport will bear the full costs. All in all, either the prospects for the HSR network development and the need to reduce the transportation emissions raise HSR as destined to compete more and more with air transport in short- and medium-haul markets.

These changes on the horizon make it urgent to thoroughly understand the competitive dynamics between air transportation and HSR as well as consumer preferences towards either transport mode. Even more crucial is to estimate the impact on demand resulting from changes in supply attributes in a multimodal context. However, while most existing studies have focused on the evaluation of the short-term impact on air transportation following the introduction of an HSR connection as well as the determinants of passengers' mode substitution and ex-post assessment of induced demand, very few studies have strived to explicitly investigate induced/reduced demand effects due to supply variations in a multimodal context.

In such a context, the paper contributes to the strand of literature focused on diverted and induced demand by applying the integrated model formalized in Chapter 3 to the multimodal passenger market between the cities of London and Paris. The London-Paris passenger market was one of the first markets to highlight inter-modal competition between HSR and air transport. Indeed, since the Channel Tunnel opened in 1994, the connections between the two multi-airport cities located nearly 350 km away are operated not only by several air carriers but even by the high-speed service Eurostar. Applying the proposed methodological setting to this market allows us to describe the competitive dynamics across different transport modes understanding passengers' preferences concerning different supply attributes and providing some sketches about different propensities of passengers towards different modes. Furthermore, because of London-Paris passenger market was also analyzed in an earlier study by Behrens and Pels (2012) focused on intermodal competition in the period 2003-2009, we are able to take a longitudinal perspective. Specifically, we compare our evidence for the period 2009-2019 with that reported in the previous study, capturing any changes in passenger preferences over time. Considering instead the trip generation part of the integrated modeling approach, we understand how both socio-economic characteristics and supply attributes contribute to capturing a higher or lower portion of potential travel demand. Such a model is then applied to estimate changes in travel demand resulting from different scenarios concerning, for instance, changes in the attributes of single transport modes or the market composition (entry or exit of an alternative). Eventually, we provide interesting insights in terms of compensation mechanisms that HSR providers could implement in the case of a possible ban on short-medium-haul flights to guarantee the same level of service for passengers.

The remainder of this paper is organized as follows. Section 5.2 frames the previous streams of research on competition between HSR and air transport and induced demand. Section 5.3 formalizes the passenger utility function adopted and specifies the data sources and the methodology of aggregation of the data, while Section 5.4 discusses the empirical results. Finally, Section 5.5 provides a conclusion outlining the main findings and limitations of the work and points out directions for future research.

5.2 Related literature

Over the last two decades, the significant expansion of the worldwide HSR network from less than 6,000 to more than 56,000 km has highly increased the number of medium-distance passenger markets subject to intermodal competition (UIC, 2021). This trend has prompted the scientific literature to extensively focus on understanding the mechanisms of competition between different transport modes as well as the effects (substitution and induction) on final demand of the introduction of a new HSR connection. In the following, we present a short description of these aspects with specific references to the London-Paris market, for a more complete overview please refer to Chapter 2.

Previous studies have pointed out strong competition between HSR and air transport in short-medium-haul markets (Givoni and Banister, 2006; González-Savignat, 2004). Specifically, HSR has been recognized as the dominant transport mode for travel distances between 300 and 800 km with the attractiveness and market share gradually decreasing as travel distances and travel times increase (Dobruszkes, 2011; Román et al., 2007; Rothengatter, 2011). Various empirical assessments confirmed that frequency and offered seats, as well as HSR average speed and travel time are crucial factors affecting the final outcome of air-HSR competition (Albalate et al., 2015; Castillo-Manzano et al., 2015; Dobruszkes, 2011; Jiménez and Betancor, 2012). Specifically, speed, travel time and comfort are the primary driver for choosing HSR (Cascetta et al., 2011; Coto-Millán et al., 2007). Among the different analyzed markets, the London-Paris passenger market plays a leading role. Indeed, it was one of the first markets in Europe to be subject to intermodal competition between aviation and HSR since the opening of the Channel Tunnel in 1994. By using cross-sectional data over the period 2003-2009, Behrens and Pels (2012) have investigated how the introduction of HSR in this market affects passenger preferences and consequently market shares of travel alternatives. The authors have shown fairly constant customers' preferences over the analyzed period identifying frequency, total travel time, and fare as the primary determinants of passengers' choice. Lastly, the heterogeneous behavior of leisure and business passengers regarding these dimensions has been identified. Overall, travel time has been recognized in the scientific literature as the main factor in determining the level of mode substitution towards HSR. Nevertheless, it is clear that on-board travel time alone is not a sufficient proxy for HSR's ability to attract passengers from other modes. Indeed, both access and egress time, and waiting time at departure play a key role in passengers' choice between different transport modes.

Diverted demand toward HSR from other rail services and transportation modes such as air and road constitutes only a portion of the overall demand for a new high-speed service. As a matter of fact, the introduction of a new HSR service also leads to an increase in travel demand due to improved travel conditions (induced demand). The determinants of induced demand derive from the microeconomic theory, according to which any reduction in the cost of goods (in this case, the transportation service) results in an increase in demand (Noland, 2001; Yao and Morikawa, 2005). The concept of induced demand encompasses a wide range of both short and long-term effects (Gorham, 2009). The former includes changes in trip-making patterns with variations in trip destination, travel departure times, and trip frequency. The latter, instead, refers to long-term decisions, such as relocation of the residence and economic activities, as well as changes in vehicle ownership and in the regional development patterns. Over the years, both ex-ante and ex-post assessments of the demand for HSR have been developed to quantify the relative weight of diverted and induced demand. For instance, Givoni and Dobruszkes (2013) in a review of ex-post studies after the introduction of HSR have quantified induced demand in the range of 10–20%, while the diverted demand from other transport modes on the order of 90–80%. However, a wide heterogeneity in the evidence is highlighted. This can be traced back both to the disparate time frames after the introduction of HSR adopted in the different studies and to diverse boundaries of the concept of induced demand considered. Demand induction (or reduction) as well as demand diversion is not limited to cases where a new transportation mode is introduced but takes place even as a result of any changes in attributes of existing travel alternatives, including fares, frequencies, and travel times.

Albeit the importance of estimating the magnitude of HSR diverted and induced demand when evaluating transportation projects and impacts of policy regulations, so far, only a few studies have focused on explicitly modeling these patterns in a multimodal context, leading therefore policymakers to not consider these aspects when undertaking regulation initiatives (D. Zhang et al., 2019). In this context, this paper aims to apply the integrated methodological framework proposed in Chapter 3 to analyze passenger preferences and induced demand in the multimodal passenger market between London and Paris. Accordingly, the main contribution of the paper to the literature is to integrate the stream of studies focused on passenger modal preferences in a context where HSR and air transportation compete, estimating the impacts on the overall travel demand induced by changes in the attributes of available alternatives. The findings of supply-demand interaction are then applied to provide evidence about the compensatory mechanism that HSR providers may have to implement in case of a complete withdrawal of short-medium haul air routes to ensure passengers similar travel conditions.

5.3 Empirical setting

This research focuses on the London-Paris passenger market. Specifically, our attention is paid to passengers traveling between the Greater London Area[33] and Paris over the period 2009-2019. As clarified in previous Sections, the London-Paris market represents a unique case study as it was one of the first markets to highlight inter-modal competition between HSR and air transport. Connections between the two multi-airport cities located nearly 350 km away are indeed offered not only by a multiplicity of air routes operated both by full-service and low-cost carriers but even by the HSR connection via Eurostar since the Channel Tunnel opening in 1994.

To analyze the dynamics of demand induction and diversions as well as passenger modal choice in this market, we apply the integrated nested logit model formulated in Chapter 3. Specifically, to apply the methodological framework, we deem different sub-markets within the overall passenger market between London and Paris. On the London side, by breaking down the Greater London Area into 21 zones according to International Territorial Levels (ITL) classification[34] level 3, we analyze the passenger flows from and to each ITL London area. As far as Paris is concerned, due to the lack of specific information about the passengers' departure zone or final destination, we assume that the origin/destination of passengers using Paris HSR station and airports is located within the Paris Urban Area.[35] Therefore, in this Chapter, a sub-market represents the passengers flow between a single London zone and Paris Urban Area.

The following sub-Sections describe the deterministic utility function adopted as well as the data used to estimate the proposed nested logit formulation.

5.3.1 Deterministic utility formulation

To practically estimate the two-level aggregate nested logit model, the passenger deterministic utility function needs to be specified. In the current Chapter, the deterministic utility function of a passenger traveling with alternative *i* in sub-market *m* and period *t*, $V_{i,mt}$, is defined as:

[33] The Greater London Area is an administrative area around the city of London covering 1572 km^2 with nearly 9 million estimated inhabitants in 2019 — https://www.ons.gov.uk
[34] The International Territorial Levels (ITL) classification is a geographical nomenclature subdividing the UK territory into regions at three different levels (1, 2, and 3 respectively, moving from larger to smaller territorial units). The classification reflects the pre-existing Nomenclature of territorial units for statistics (NUTS) developed by the European Union. — https://www.ons.gov.uk
[35] The Paris Urban Area is a French urban continuity area centered on the municipality of Paris. Covering about 2800 km^2 and accounting for more than 11 million inhabitants, it is the largest urban area in France and the European Union.

$$V_{i,mt} = \alpha \cdot ln(freq_{i,t}) + \beta \cdot PPM_{i,t} + \gamma \cdot taveltime_{i,mt} + \tau \cdot fare_{i,mt} \quad (5.1)$$

Adopting the representation detailed in Equation 5.1, the choice of an alternative is modeled based on average weekly frequency, average on-time arrival (PPM), total travel time, and fare. Average on-time arrival represents the so-called Public Performance Measure (PPM), a common indicator employed in aviation and rail transport to determine the percentage of on-time arrival (defined as flights or trains arriving less than 15 minutes compared to the scheduled time). This term was included because several studies pointed out the importance of incorporating the travel time reliability in model specification (Hensher and Li, 2012; Li et al., 2010). Total travel time is the sum of four components: on-board travel time, departure waiting time,[36] access and egress time, and finally expected delay. Fare is the average price paid by a passenger traveling with alternative *i* in period *t*. Due to the expected diminishing returns in service utility from adding an additional connection, average weekly frequency has been included in the indirect utility formulation using the logarithmic form (Hansen, 1990).

As already mentioned, because of the well-recognized different behaviors of leisure and business passengers, the integrated model was estimated separately for leisure and business passengers.

5.3.2 Data collection

To estimate the two-level aggregate nested logit model, historical data on both passenger flows and characteristics of available transport modes on the market at hand were collected.

Information on passenger flows between London and Paris was collected from the International Passenger Survey (IPS). The IPS is a continuous survey carried out by the Office for National Statistics (ONS) providing detailed information on the numbers and types of passengers traveling to and from the United Kingdom by air, sea, or the Channel tunnel. The IPS consists of about 250,000 anonymous face-to-face interviews per year. More than 95% of passengers entering and leaving the UK are eligible for random sampling in the survey. The interview questionnaire collects both respondents' socio-demographic characteristics and information on the travel arrangements used. While the former includes information such as age, gender, and

[36] Departure waiting time represents the amount of time in advance from scheduled departure time passengers are advised to arrive at the airport or station for check-in, boarding, and security activities.

country of residence, the latter consists of information about the departure and arrival airport or station, trip purpose, and carrier. Unfortunately, no information about education or income is collected. Based on the information gathered, the interviews are divided according to the respondent's residence (i.e., UK or overseas resident) and to the direction of the flow (i.e., departing or arriving in the UK). Some additional information such as the fare paid and the town visited during the stay in the UK for overseas passengers is required only to passengers who have completed their journey (i.e., departing overseas resident and UK resident arriving in the UK). Lastly, to produce reliable estimates of passenger traffic passed through a port or route in each sampling period, each observation is associated with a weight indicating the number of passengers for which that observation is representative.

To the aim of our study, we selected from the entire IPS dataset in the period from 2009 to 2019 the observations of passengers traveling from the Greater London Area to Paris airports or railway stations, and *vice versa*. Moreover, to leverage the entire informative set (namely, know the fare paid and the town visited during the stay), we further selected only passengers' categories that have completed their journey. Finally, we excluded observations concerning air passengers claiming to travel through London and/or Paris airports for an interconnecting flight. The sample assembled according to these specifications is composed of 9655 leisure and 3570 business observations. Considering the weight associated with each observation, the sample consists of around 13 leisure and 4.6 business million passengers. On average, passengers travelling to the London Greater Area account for around 39.1% of leisure and 44.1% of business passengers traveling via London airports and stations. Table 5.1 reports the number of observations per year, alternative, and type of passengers. Overall, both leisure and business markets are largely dominated by Eurostar with a market share of almost 89%. FSCs' market share is about 10% for business passengers while it is lower (6.6%) for leisure ones. Finally, LCCs hold a marginal market share for business (1.6%) and a more significant one for leisure passengers (4.2%). Table 5.1 provides aggregate statistics regarding socio-demographic characteristics of the sample. Considering gender, there are more females among leisure travelers (54.3%), while males represent the majority of passengers traveling for business purposes (60.6%). About 47% of leisure travels is made by young people (below 35 years), while only 6.5% by people older than 65. Passengers in their thirties, forties, and fifties represent most business travelers.

Supply characteristics of available aviation and HSR connections between London and Paris in the period 2009-2019 were collected from several secondary sources. The average weekly frequency, as well as on-board travel time, were gathered from the OAG Schedule Analyzer database for the air alternative, while HSR’s ones from official timetables published by Eurostar. The departure waiting time (i.e., time in advance with which passengers are advised to arrive at the airport/station with respect to the scheduled time) was collected from the carrier's website. Air France and British Airways indicate 60 minutes, easyJet and Vueling 40 minutes, and Eurostar 30 minutes. On-time punctuality data was provided by the Civil Aviation

	Leisure								
	QQS-CDG-EUR	LCY-ORY-AF	LCY-ORY-BA	LGW-CDG-U2	LGW-CDG-VY	LHR-CDG-AF	LHR-CDG-BA	LHR-ORY-BA	LTN-CDG-U2
2009	983 (91)	4 (0.4)				19 (2.2)	46 (2.9)		61 (3.5)
2010	788 (90.7)	5 (0.8)				69 (3.9)	38 (2.8)		43 (1.8)
2011	759 (90.5)	7 (1)				49 (3.1)	26 (2.2)	4 (0.3)	65 (2.8)
2012	796 (91.6)	6 (0.8)				43 (2.7)	21 (1.8)	6 (0.5)	52 (2.7)
2013	694 (90)	2 (0.3)				63 (5)	38 (2.5)	6 (0.4)	41 (1.8)
2014	829 (87.5)	5 (1.5)		7 (0.9)		68 (5)	32 (1.9)	9 (0.5)	66 (2.8)
2015	896 (90.2)	7 (1.3)		10 (1)		39 (3)	35 (2)	15 (0.8)	34 (1.7)
2016	688 (87.4)	8 (1.6)		14 (2.7)	2 (0.2)	29 (2.6)	38 (2.8)	13 (1.1)	17 (1.6)
2017	703 (86.6)			19 (4.7)	5 (1.3)	29 (2)	23 (2.3)	7 (0.7)	18 (2.5)
2018	541 (89)		2 (0.5)	15 (3.3)	7 (1.1)	20 (1.5)	24 (2.6)		18 (2)
2019	568 (89.2)		2 (0.6)	5 (3)	6 (1.1)	21 (1.9)	19 (2.4)		8 (1.8)

For all the tables: CDG: Paris Charles de Gaulle; LCY: London City; LGW: London Gatwick; LTN: London Luton; ORY: Paris Orly; QQS: London St Pancras; XPG: Paris Gare du Nord; AF: Air France; BA: British Airways; EUR: Eurostar; U2: easyJet; VY: Vueling Airlines.

	Business								
	QQS-CDG-EUR	LCY-ORY-AF	LCY-ORY-BA	LGW-CDG-U2	LGW-CDG-VY	LHR-CDG-AF	LHR-CDG-BA	LHR-ORY-BA	LTN-CDG-U2
2009	288 (85.3)	9 (3.5)				10 (4)	24 (4.7)		14 (2.5)
2010	283 (87.4)	5 (2)				34 (5)	25 (4.9)		7 (0.7)
2011	246 (83.5)	8 (3.5)				28 (5.6)	25 (5.5)	3 (1.1)	8 (0.8)
2012	307 (89.1)	7 (2.6)				16 (2.3)	21 (4.4)	3 (0.7)	6 (0.9)
2013	281 (87.6)	9 (4.2)				18 (2.9)	22 (3.4)	6 (1)	9 (0.9)
2014	354 (89.6)	5 (2.6)		1 (0.6)		22 (3.1)	20 (2.6)	6 (0.7)	7 (0.8)
2015	355 (93.5)	2 (0.8)				7 (1.5)	12 (2.1)	9 (1.5)	4 (0.6)
2016	312 (90.6)			1 (0.6)		20 (3.7)	13 (2.5)	9 (1.7)	5 (0.8)
2017	218 (89.7)			3 (2.1)	1 (0.6)	19 (3.6)	13 (2.9)	3 (1)	
2018	159 (87)		5 (4)	3 (2.4)		17 (3)	11 (3.1)		2 (0.5)
2019	196 (85.5)		4 (3.4)		1 (1.1)	11 (2.7)	15 (6.1)		3 (1.2)

Table 5.1: Observations per year, alternative, and type of passengers (market share computed considering IPS weights in brackets).

Authority[37] and the Eurostar press release,[38] respectively. In the case of air routes, in addition to on-time punctuality data, data relating to average delays (in minutes) were also collected. Average fare per passenger type and alternative were computed starting from the IPS questionnaire response.[39]

	Leisure			Business		
	Air	HSR	**Total**	Air	HSR	**Total**
Gender						
Male	48.9%	45.3%	45.7%	73.5%	58.9%	60.6%
Female	51.1%	54.7%	54.3%	26.5%	41.1%	39.4%
Age class						
< 25	31.2%	16.4%	18.0%	4.3%	6.1%	5.9%
25-34	36.8%	27.4%	28.5%	26.4%	24.8%	25.0%
35-44	14.9%	23.6%	22.7%	32.5%	33.4%	33.3%
45-54	10.5%	16.6%	15.9%	25.5%	22.4%	22.8%
55-64	4.5%	8.9%	8.4%	10.0%	11.5%	11.3%

Table 5.2: Share of passengers by gender and age class for different transport modes and passenger type.

Lastly, access and egress times from HSR stations and airports were collected using the multimodal search engine Rome2Rio[40] which provides several alternatives for travelling from an origin to a destination. In detail, on the London side, we computed the population-weighted access/egress time by car to reach each HSR station and airport in London from each potential departure/arrival zone (i.e., each of the 21 ITL zone in London). As far as Paris is concerned, given the absence of information about the passengers' departure zone or final destination, we considered the population-weighted average access/exit time by car from the single HSR station and airport to Paris Urban Area. Access and egress time for each sub-market, namely origin/destination zone in London and chosen route is the sum of access and egress time in London and Paris. All supply characteristics were collected on a quarterly basis, apart from Eurostar on-time punctuality data that is provided only yearly.

Table 5.3 reports the average weekly frequency, average on-time arrival, and average scheduled main mode travel time (i.e., sum of on-board travel time and departure waiting time) per alternative and year. Overall, the London-Paris market was highly dynamic. For each analyzed

[37] Civil Aviation Authority (CAA) UK flight punctuality data — https://www.caa.co.uk/punctuality

[38] Eurostar press office — https://mediacentre.eurostar.com

[39] Following an approach similar to Behrens and Pels (2012), we exclude indicated fares lower than 10 or higher than 1000 British pounds. Moreover, to obtain a more accurate estimate and since the indicated fare is an alternative specific characteristic not dependent on origin/destination zone, the average fare has been calculated from indicated fares in IPS even by drawing on observations of passengers not bound for or originating in the Greater London Area.

[40] Rome2Rio — www.rome2rio.com

period (i.e., quarter), the passengers faced a choice set containing at least five and a maximum of eight alternatives. However, apart from the HSR connection, only three air connections (i.e., those on the LHR-CDG route operated by the FSCs British Airways and Air France and that operated by easyJet from LTN) have continuously linked London and Paris throughout the analyzed period. These connections also showed the highest and most stable weekly frequencies. Two new connections offered by LCCs easyJet and Vueling have been operational since 2014 and 2015, respectively. The alternative to ORY from London City airport operated by Air France exited the market in 2017. Shortly after, this last connection has been reactivated by British Airways. Finally, Eurostar offered a significantly higher frequency (slightly declining since 2017) compared to the single airline alternatives.

The main mode travel times, including on-board travel time and departure waiting time, were quite stable over the years. Eurostar connection features a significantly longer on-board travel time than air travel, nevertheless this is partially offset by the shorter departure waiting time. Air connections exhibited similar on-board travel times and differ mainly due to the diverse departure waiting times. Furthermore, Eurostar benefits from much shorter access/egress times as railway stations are located closer to city centers than airports.

	Average weekly frequency								
	QQS-CDG-EUR	LCY-ORY-AF	LCY-ORY-BA	LGW-CDG-U2	LGW-CDG-VY	LHR-CDG-AF	LHR-CDG-BA	LHR-ORY-BA	LTN-CDG-U2
2009	116	25				56	59		25
2010	112	29				59	57		19
2011	112	32				55	53	18	18
2012	110	31				51	48	27	18
2013	113	30				50	46	27	18
2014	116	35		14		53	45	27	18
2015	116	27		14		51	45	27	19
2016	112	22		18	11	49	46	26	19
2017	102	21	16	19	11	46	45	24	20
2018	105		17	19	13	46	48		19
2019	107		17	19	18	42	48		19

	Average main mode travel time								
	QQS-CDG-EUR	LCY-ORY-AF	LCY-ORY-BA	LGW-CDG-U2	LGW-CDG-VY	LHR-CDG-AF	LHR-CDG-BA	LHR-ORY-BA	LTN-CDG-U2
2009	174	143				134	138		119
2010	171	149				136	137		119
2011	170	150				134	136	140	119
2012	172	153				133	135	140	120
2013	169	152				135	134	138	120
2014	170	148		115		135	135	136	119
2015	170	143		115		135	135	138	119
2016	170	144		115	112	136	138	143	119
2017	170	144	138	117	115	136	139	144	121
2018	171		137	117	113	137	137		122
2019	170		130	118	113	140	137		122

	Average on-time arrival in % (PPM)								
	QQS-CDG-EUR	LCY-ORY-AF	LCY-ORY-BA	LGW-CDG-U2	LGW-CDG-VY	LHR-CDG-AF	LHR-CDG-BA	LHR-ORY-BA	LTN-CDG-U2
2009	95	89				77	84		77
2010	87	83				73	76		61
2011	93	89				76	82	83	78
2012	92	90				78	80	80	83
2013	90	84				78	74	77	85
2014	92	78		70		83	77	77	79
2015	88	71		68		82	74	75	70
2016	89	62		62	73	78	80	81	68
2017	90	68	86	60	77	77	82	85	67
2018	81		78	69	73	71	78		69
2019	92		71	66	70	80	79		70

Table 5.3: Average weekly frequency, average on-time arrival performance, and average scheduled main mode travel time (sum of on-board travel time and departure waiting time) per alternative and year.

Lastly, Figure 5.1(A) and 5.1(B) show the average fare paid by respondents per year, carrier type and, passenger type. For both categories of travelers, the Eurostar fare was generally lower than that of FSCs, but higher than the low-cost one. As regards FSC, prices for leisure travelers were more volatile than the business fare, which appeared stable except for the period 2012-2013. In addition, a close match between British Airways and Air France fares for the connection between LHR and CDG is observed. The lowest fare, over the whole period and for both categories of passengers, was that offered by easyJet from LTN airport.

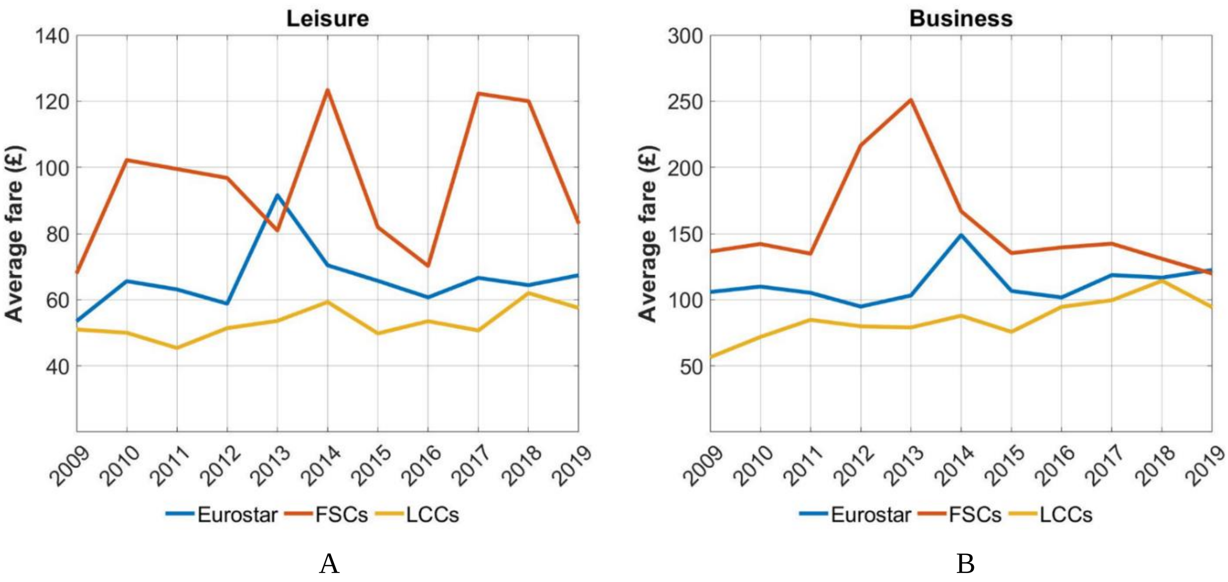

Figure 5.1: Average fare paid by respondents per year, carrier type, and passenger type.

5.3.3 Data aggregation and model setting

Data gathered for both passenger flows and supply characteristics were appropriately assembled to estimate the integrated demand generation and distribution model. As stated above, the overall London-Paris market was divided into various sub-markets, intended as passengers' flows originated in (directed to) the single ITL zone of the Greater London Area and directed to (originated in) Paris Urban Area. For each sub-market, passenger type, and period, we aggregated the selected IPS observations considering the weight (i.e., number of passengers for which that observation is representative) indicated by the UK ONS. In doing so, we obtained an estimate of passenger flows traveling using each alternative. Passenger flows were aggregated considering a quarterly granularity over the period 2009-2019. This choice resulted in the availability of 44 periods of analysis for each sub-market and passenger type. The market share of the single alternative was then derived from the total flow of passengers of a given type in each sub-market and time period.

Consistent with the deterministic utility formulation adopted (Equation 5.1), weekly frequency, average on-time arrival (PPM), fare, and travel time are the specific alternative attributes considered in the travel distribution model. While the formers directly derive from supply characteristics data described in the previous sub-Section, the latter is the sum of four main components: scheduled on-board travel time, departure waiting time, access and egress time, and finally expected delay. This last component was calculated as the product of the average delay in minutes and the percentage of delayed trains/flights (i.e., 1-PPM).[41]

The trip distribution model is then estimated as described in Section 3.1.2 by regressing the difference between the log of market shares of alternative pairs on the difference in their attributes. To avoid systematically excluding observations of sub-markets where only one alternative was sampled by IPS survey in a quarter (and therefore systematically underestimating the market share of these alternatives), we artificially generated alternative-pairs by comparing these observations with another alternative randomly picked among those available (i.e., belonging to the choice set) in the period under consideration.[42] The utility functions for leisure and business passengers estimated in the trip distribution model allowed the LoS measure to be calculated for each sub-market, period, and passenger type. This measure integrates the utilities provided by the individual alternatives within passenger's choice set and represents the composite measure of the travel impedance in a specific market and time period.

Passenger flows traveling using single alternatives were then aggregated by period, market, and passenger type and were entered into the trip generation model along with information about the LoS.[43] Specifically, the parameters of the Cobb-Douglass travel demand function were estimated for each passenger type by regressing the total passenger flow in each quarter and sub-market on the geometric mean of the populations and per capita GDP of the zone of origin and destination (i.e., socio-economic characteristics) as well as the measure of travel impedance

[41] Since Eurostar does not make public the average delay data, coherently with Behrens and Pels (2012) we assume as a proxy of the average delay of Eurostar the official rail delay boundary of 10 minutes.

[42] In this case, to practically estimate the model we assumed a market share of 99% for the alternative sampled and a market share of 1% for the alternative randomly selected. A sensitivity analysis on this assumption has been carried out and does not significantly affect the estimates of trip distribution model.

[43] Since we leverage only on passengers' categories that have completed their journey (i.e., arriving UK passengers and departing foreigners) to estimate the trip distribution model, in this phase passenger flows have been appropriately recalibrated to be representative of the total market flows.

(i.e., LoS). While the latter was directly obtained from the trip distribution model, the former were explicitly collected. In detail, population and GDP per capita for each ITL zone of the Greater London Area were gathered by the UK Office for National Statistics (ONS).[44] Values of population for the Paris Urban Area were extrapolated from the Gridded Population of the World produced by the Socioeconomic Data and Applications Center (SEDAC) at Columbia University. Paris Urban Area GDP per capita values were instead retrieved from INSEE[45] statistics.

In addition to the quarter dummies to model the seasonal effect throughout the year, a dummy variable related to Brexit was included in the demand function to capture any changes in the travel demand pattern resulting from the United Kingdom's exit from the EU.[46] Indeed, the literature suggests that specific events can significantly influence travel choices (Arentze and Timmermans, 2009). The UK's referendum decision to leave the EU has substantially increased financial and political uncertainty in the country, as well as the cost of travel abroad due to the sharp decline in the British pound (Collinson and Jones, 2016; McConnell et al., 2017). Since all these factors have a strong effect on international travel patterns and tourism (Michael Hall, 2010), an impact on travel intention to and from the UK can therefore be expected (Pappas, 2019). Lastly, additional dummies were specified to properly model passenger flows of certain zones of London whose population or GDP values markedly differ from the others.

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[44] Regional Gross Domestic Product by Region, ONS — https://www.ons.gov.uk/economy/grossdomesticproductgdp

[45] Institut national de la statistique et des études économiques — https://www.insee.fr/en/accueil

[46] An additional dummy variable related to Brexit was specified for the period 2018-2019. In this period, representatives of the UK and the EU negotiated the terms for the planned withdrawal of the UK from the EU. These negotiations arose following the official notification of the European Union (Notification of Withdrawal) Act 2017 to the European Council President on 29 March 2017. During the negotiations, growing fears of a no-deal exit (also referred to as hard Brexit) were raised in public opinion.

5.4 Empirical results

5.4.1 Trip distribution model

Table 5.4 shows the estimated coefficients and robust standard errors of the trip distribution model. The model was estimated separately for business and leisure passengers. Furthermore, to highlight potential heterogeneity in passenger modal preferences, in addition to the base model, a model estimated only on differences of air alternatives' market shares was structured. This second approach, differently to the base model described in Chapter 3, explicitly models in the "Travel" branch only the air alternatives, considering HSR mode in the "Not travel or alternative transport modes" branch. This choice allowed us to provide a more accurate proxy for passengers' sensitivity to the attributes of the air alternatives, thus highlighting different propensities of passengers towards air or HSR mode in a multimodal context.

	Base model				**Air model**			
	Leisure		**Business**		**Leisure**		**Business**	
	Coeff.	**Robust SE**	**Coeff.**	**Robust SE**	**Coeff.**	**Robust SE**	**Coeff.**	**Robust SE**
Ln (Weekly Frequency)	1.924***	0.0715	2.198***	0.0914	0.693***	0.246	1.473***	0.337
PPM	0.0166***	0.0060	0.0397***	0.0080	-0.0109	0.0131	0.0002	0.0244
Travel time (min)	-0.0047	0.0043	-0.0113*	0.0058	-0.048***	0.012	-0.060***	0.018
Fare (£)	-0.017***	0.0015	-0.0072***	0.0009	-0.014***	0.0042	0.0007	0.0036
Observations	1143		807		578		258	
R^2	0.710		0.757		0.050		0.131	

***p<0.01, **p<0.05, *p<0.1

Table 5.4: Estimation results for the trip distribution model.

As regards the base model, all estimated coefficients are significant for both trip purposes, except for the travel time coefficient in the leisure passenger model. The estimated coefficients are consistent with those reported in previous transport mode choice studies. In detail, business passengers are more sensitive to average weekly frequency and travel time than leisure passengers. On the opposite, leisure passengers exhibit a higher sensitivity to the average fare. Concerning the public performance measure (PPM), our model returns statistically significant and positive coefficients for both types of passengers. In magnitude, the sensitivity found for leisure passengers is lower than for business ones. This result is consistent with the higher value of time and thus the higher importance of transport modes' reliability for the latter type of passengers.

Overall, the estimated coefficient for travel time and fare results either in sign and magnitude comparable to those reported by Behrens and Pels (2012) for the same market in the period 2003-2009. Therefore, this finding highlights substantial stability in passengers' preferences regarding these attributes over time. A separate discussion should be made for the comparison of the estimated coefficients for the average weekly frequency and on-time arrival performance. As regards the former, the coefficients in our model are higher in magnitude. This can be traced back to an increase in passengers' sensitivity to the frequency of connections offered by the single carrier. However, it should be noted that this difference could also derive from the presence in Behrens and Pels' model of alternative specific constants that partially internalize the effect of frequency. On the other hand, about on-time arrival punctuality, the model calibrated on the period 2003-2009 provided positive and, contrary to our estimates, higher coefficients for leisure passengers than those for business ones. Yet, it should be noted that the coefficient estimated for business passengers was not significant.

Additional and more stimulating insights arise when comparing the coefficients of the base model with those estimated considering only differences in air market shares. Indeed, the second model provides an estimate of the attitudes of each passenger type about the attributes of air alternatives. Any differences between these estimates and the previous one (i.e., base model) can be accordingly interpreted as the presence of heterogeneity in passengers' preferences regarding the attributes of the different transport modes (air and HSR). Overall, both types of passengers favor frequencies of the HSR alternative over those of the air alternatives. On the other hand, the total travel time by HSR is much less burdensome than that of air transportation. This evidence can be attributed to the higher level of comfort on-board HSR (comfort and space on-board to work or unwind, with free Wi-Fi on-board) and the absence of strict safety protocols which in the case of air travel burden the passenger. Moreover, the HSR alternative allows luggage to be brought on-board saving passengers the burden of retrieving it on arrival. Once again, both in terms of frequency and total travel time, business passengers are more sensitive than leisure passengers. As regards the fare, no substantial differences emerge between the two models. Finally, the coefficient for the PPM in the air model is not statistically significant for either business or leisure passengers. This evidence, although unexpected, can be traced back to the progressive loss of representativeness of this measure over the recent years. Indeed, it has been documented how, in some cases, airlines have progressively extended their scheduled times above route technical travel times (allocating block buffer times) intending to improve on-time performance and avoid delays (Forbes et al., 2019). Over the last 15 years, in the London-Paris market airlines lengthen their scheduled travel times on average by 6 min, while actual flight times could be assumed unchanged. The longer schedule times translated into a 6% improvement in on-time performance. Therefore, it is possible that the punctuality index is less reliable than before and consequently has lost its importance in air passengers' choice.

5.4.2 Trip generation model

After estimating the coefficients for the trip distribution model, we can focus on the trip generation model. Estimated coefficients and robust standard errors for the total travel demand model are reported in Table 5.5.

	Leisure		**Business**	
	Coeff.	**Robust SE**	**Coeff.**	**Robust SE**
Population	1.281***	0.192	0.574**	0.225
Per-capita GDP	2.814***	0.142	2.404***	0.157
LoS	0.181*	0.104	0.333**	0.131
Constant	-40.52***	3.403	-28.53***	4.264
Quarter II	0.338***	0.056	-0.078	0.064
Quarter III	0.304***	0.059	-0.089	0.066
Quarter IV	0.148**	0.060	0.096	0.064
Brexit	-0.121*	0.063	0.111	0.070
Zone TLI31	-0.172	0.188	-0.481**	0.207
Zone TLI32	-1.675***	0.175	-1.462***	0.193
Zone TLI42	-1.423***	0.122	-1.633***	0.148
Zone TLI74	-1.068***	0.099	-0.931***	0.107
Observations	883		701	
R^2	0.652		0.603	
MAPE	14.3%		15.8%	

***p<0.01, **p<0.05, *p<0.1

Table 5.5: Estimation results for the trip generation model.

Overall, both models exhibit good fitting capacity. In detail, leisure and business total demand models are characterized by a mean absolute percentage error (MAPE) on the estimates of quarterly passenger flows of 14.3% and 15.8%, respectively. In both models, the population, GDP, and LoS parameters of the traveler demand function are statistically significant. As conventionally recognized, travel demand for both types of travelers is positively sensitive to socio-economic characteristics of the origin and destination zones. Specifically, the population parameter is higher for leisure passengers than for business passengers. A similar pattern emerges when analyzing the GDP parameter. While the first result is consistent with expectations, the second at first glance appears to be counterintuitive. However, this evidence should be analyzed by looking at the specific market under consideration. Indeed, the zones of London with the highest value of GDP per capita are those located in the city center and which, due to the numerous attractions, are also the most attractive for tourists. More interesting are the estimates for the LoS parameter. This coefficient results positive and significant in both models, thus recognizing travel demand sensitive to changes in supply. Moreover, the estimated contribution of LoS on trip generation is higher for business than leisure passengers. This outcome testifies their greater sensitivity to variations in the overall measure of travel impedance, *ceteris paribus*. Considering the constant term and quarter dummies, a statistically significant seasonal trend emerges throughout the year for leisure flows. In detail, these are higher during the spring and summer seasons and gradually decrease during fall and winter months. Business passenger flows do not exhibit any statistically significant seasonal pattern. Furthermore, by analyzing the Brexit dummy, it can be observed that after the official announcement of the UK exit from the EU and during the negotiations, no significant impacts on business flows were outlined. Contrariwise, Brexit has a negative and statistically significant effect on leisure passenger flows. Overall, the UK's withdrawal decision from the EU caused stagnation and decline in tourist flows, thus confirming the findings of the studies by Arentze and Timmermans (2009) and Pappas (2019). Starting from the estimated intercity travel demand function, we extrapolate the sensitivity of demand to supply characteristics. Specifically, we investigate the impacts in terms of induced or dissuaded demand resulting from changes in the different supply attributes. To this aim, taking 2019 supply characteristics and passenger flows as baseline,[47] we consider different scenarios of supply attributes variations. Estimated impacts on leisure, business, and overall passenger demand in the different scenarios are reported in Table 5.6.

Scenario	**Leisure**		**Business**		**Overall**	
	Δ Passengers	**Δ %**	**Δ Passengers**	**Δ %**	**Δ Passengers**	**Δ %**
Introduction of an additional daily Eurostar connection	48,903	1.7%	45,792	3.8%	94,696	2.3%
Reduction of Eurostar travel time by 10 minutes	18,685	0.6%	36,987	3.1%	55,673	1.3%
Cancellation of the air route LHR-CDG-AF	-64,129	-2.2%	-40,526	-3.4%	-104,655	-2.5%
Cancellation of all the air connections	-158,263	-5.4%	-86,024	-7.2%	-244,287	-5.9%

Table 5.6: Estimates of induced and reduced demand following different supply characteristic changes.

[47] The identification of a reference context is necessary because induced demand can never be directly estimated, but rather only inferred from a reference scenario (Gorham, 2009).

Assuming a one-trip increase in the daily frequency of HSR connection operated by Eurostar (thus going from an average daily frequency of 15 trains to 16), our model estimates a demand stimulation of more than 94,500 passengers per year. Induced demand is higher for business passengers who proved to be more sensitive to the LoS in our model, other things being equal. Overall, the increase in the frequency of the Eurostar connection would lead to a 1.7% and 3.8% increase in leisure and business flows to/from the Greater London Area, respectively. A second scenario analyzed is a 10-minute reduction in on-board travel time of Eurostar as a result of possible infrastructural investments on HSR line (passing from the current 140 to around 130 minutes). In this scenario, induced demand would account for about 1.3% of the current demand, representing in absolute terms 55,500 more passengers traveling annually. Even in this case, the increase for business passengers would be greater than for leisure ones.

5.4.3 Impacts of air routes withdrawal

In addition to scenarios based on the increase in HSR frequencies and decrease in travel times, it is possible to investigate the impacts on the total demand resulting from the complete cancellation of a single air route or even of all air routes between London and Paris. While the first scenario is representative of demand changes following the entry/exit of a route in the market (as occurred several times during the period under analysis), the second, deliberately more extreme, aims to evidence the impact of the possible abolition of short-medium-haul flights for environmental purposes where alternative connections operated by alternative transport modes exist. Indeed, due to the growing pressure to reduce aviation emissions, several initiatives in this direction have been recently undertaken in different European countries, such as France and Austria. As regards the impact of the withdrawal of a single air route, we assumed the closure of the route between London Heathrow and Paris Charles de Gaulle operated by British Airway. This route, together with its counterpart operated by Air France, is the main air connection between London and Paris either in terms of frequency and number of passengers. The abolition of this route would lead to an overall reduction in demand of around 105,000 passengers per year (approximately 2.5% of current ridership). Although greater in absolute terms for leisure passengers, in relative terms the impact would be greater for business passengers whose flows would be reduced by 3.4%. The abolition of all air routes between London and Paris as a result of a policy to reduce aviation emissions would have a much greater impact on travel demand. About 6% of passengers (in absolute terms almost 240,000 passengers per year) currently traveling between the two cities would cease to travel. Specifically, the removal of air connections, leading to a drop in the LoS of 27% and 21% for leisure and business passengers, would result in a reduction in traffic volumes of 5.4% and nearly 7.2%, respectively.

In such a context, it is highly interesting to deepen how HSR service providers could compensate for the lack of air alternatives to guarantee passengers the same LoS. Indeed, in the case of a possible ban on short-medium-haul flights, it is envisaged and desirable that regulators should require the remaining service providers (such as HSR) to implement appropriate organizational measures (e.g., revision of scheduling and timetables) and investments (e.g., hiring or increasing vehicle fleet) (Avogadro et al., 2021). Table 5.7 shows the average changes in HSR service characteristics required to guarantee the same LoS for passengers in case of a complete cancellation of the air alternatives.

	Leisure		**Business**	
	Δ	**Δ %**	**Δ**	**Δ %**
Increase in weekly frequency	+19	+17.2%	+12	+10.8%
Decrease in on-board travel time (min)	-65	-46.2%	-20	-14.1%
Decrease in fares (£)	-18	-26.5%	-31	-25.5%

Table 5.7: Changes in the HSR supply characteristics required to maintain the LoS in case of a complete cancellation of the air alternatives.

Overall, our model reveals that, regardless of the attribute on which the HSR service provider focus to increase its LoS, more effort is needed to compensate for the reduction in LoS for leisure passengers than for business ones. Indeed, as detailed in the trip distribution model, leisure passengers associate less value with increased frequencies and decreased travel times than business ones. On average, stemming the removal of air routes would require increasing the weekly frequency of Eurostar by 19 trains for leisure passengers and only 12 for business ones. The introduction of 19 additional trains would lead to an increase in the number of weekly offered seats by Eurostar in each direction between 14,402 and 17,138.[48] This additional capacity would be more than adequate to accommodate passengers currently traveling by air that would be diverted to HSR (estimated at around 3900 passengers per week and direction). However, it should be noted that we have to take into account even the proportion of travelers that use London airports and are originated/directed from/to zones of the UK other than the Greater London Area. Assuming that the extra-frequencies would be adequate to guarantee

[48] This estimate is based on the capacity of the rolling stock currently used by Eurostar, i.e. the British Rail Class 373 (Eurostar e300) and the British Rail Class 373 (Eurostar 320) with a capacity of 758 and 902 seats, respectively.

comparable LoS even for these travelers, the overall diverted demand due to flight cancellations can be quantified in 11,200 passengers. Therefore, the additional capacity would be sufficient to accommodate all diverted passengers from air transportation. Reducing HSR travel time to compensate the lower LoS due to the withdrawal of air routes does not seem sustainable if implemented alone. It would be feasible only combined with an increase in HSR frequencies. Indeed, to guarantee the LoS for leisure passengers, it would be necessary to almost halve HSR on-board travel time. On the contrary, for business passengers, it would be possible to maintain the previously offered LoS with a reduction of about 20 minutes in HSR on-board travel time.

Lastly, a downward revision of fares does not seem a viable option. On the contrary, the reduction in competition (at least in its multimodal component) following the withdrawal of air travel will inevitably result in market concentration, which might lead to the side-effect of higher fares. In this respect, the regulatory and antitrust authorities will be called upon to implement appropriate initiatives to reduce the possibility of misuse of market power, such as stricter regulations (e.g., the introduction of price monitoring mechanisms and agreements to prevent fare increases) or the promotion of competition within railway industry (e.g., promoting on-track or multi-service competition). Notwithstanding, a further increase in HSR frequencies (or reduction in travel times), compared to that described above, may be necessary whether the fare increase resulting from the market concentration cannot be sufficiently contained. Indeed, as one might expect, the higher the increase in HSR fares, the stronger compensation mechanisms required to avoid passengers a experiencing reduction in LoS. For instance, a 10% increase in HSR fares following air routes closure would require an additional increase in HSR frequencies (i.e., in addition to that required in case of no impact on HSR fare) of 7.2% and 4.5% (in absolute terms equal to 24.4% and 15.3%) to guarantee comparable LoS to leisure and business passengers respectively. These values would increase to 14.8% and 9.2% (32% and 20% in absolute terms) in case of a fare increase by 20%.

Overall, it appears that in the case of cancellation of the air alternatives, HSR providers can primarily leverage on increase frequencies to compensate for the reduction in LoS. Specifically, by comparing the additional HSR frequencies required to the number of canceled flights, we observe for the London-Paris market a substitution rate of 0.12, namely about every 9 flights dropped it is required the introduction of an additional HSR ride to compensate the LoS for passengers. This measure, further validated, may constitute the basis for future research aimed at assessing the compensatory mechanisms required after a possible enforced ban of flights at a pan-European level. Compensation mechanisms based on increase frequencies structured by

HSR service providers can also be supported by infrastructural investments aimed at reducing travel times. Lastly, since in case of upward adjustments of HSR fares resulting from market concentration stronger compensatory actions will be required to compensate service level for passengers, it is worth emphasizing the leading role that the regulatory and antitrust authorities will play during the transition process following the cancellation of air routes.

5.5 Conclusions

Over the last years, the widespread of HSR at a worldwide level, as well as the huge investments planned to expand the HSR network raised intermodal competition to the forefront of scholars' and practitioners' debates. In addition, the issue of sustainable growth of the air transport industry and the pressure to reduce the environmental impact of aviation is pushing policymakers to end short-medium haul air flights and convert air passengers to alternative transport modes, mainly HSR. In such a context, the integrated model aimed at jointly modeling trip distribution and generation in an multimodal context presented in Chapter 3 was applied to the London-Paris passenger market using a large cross-sectional dataset of revealed preferences collected over the period between 2009 and 2019. The integrated formulation allowed us to understand the key dimensions by which travelers evaluate transport modes and how supply attributes variations concur to influence the total travel demand, increasing or decreasing the current ridership. Concurrently, by making demand generation sensitive to a composite measure of the quality of the different transport modes, we were able to investigate the compensatory mechanisms that HSR service providers should implement in the case of a ban of air connections.

Our analysis confirms the importance of supply attributes, such as travel times, fares, punctuality, and frequencies on passenger choice. Specifically, our research returns a higher sensitivity of leisure passengers to fares. Contrariwise, a higher value is associated with frequency, travel time, and punctuality by business travelers. Consistent with past studies, the value of time is higher for business than leisure passengers. Furthermore, by developing a sub-model intended to understand the attitudes of air passengers towards the different attributes, we found heterogeneity in the evaluations of airline and HSR frequencies and travel times. In particular, travel time on-board the HSR results much less burdensome for travelers than that on-board the aircraft. This evidence could be traced back to the higher comfort on-board HSR (more space to work and free Wi-Fi on-board) and to the absence of specific security checks (no restrictions on items allowed on-board).

The results of the trip generation model indicate that both leisure and business travel flows are positively related to the mutual socio-economic characteristic of the origin and destination zones. Besides, we observed a positive and significant contribution of the LoS on the travel demand of both leisure and business passengers, thus identifying supply-demand interaction. We also noticed the uncertainty surrounding the UK's exit negotiations from the EU has negatively impacted inbound and outbound tourist flows. More interesting, we investigated how supply variation of both air and HSR alternatives induce or reduce the overall demand between London and Paris. As far as the HSR is concerned, we found that the introduction of a new daily connection increases total flows by 2.3%, whereas infrastructural investments aimed at improving travel times of the HSR line result in just over 55,500 extra trips per year (1.3%). On the other hand, a reduction of over 2.5% is reported whether the LHR-CDG route operated by British Airways exits the market. The suspension of all air services between London and Paris indeed would cause a much relevant impact, reducing current ridership by about 6%. In the last case, in addition to estimating the impact in terms of reduced demand, we analyzed the compensation mechanisms that might be required from the HSR provider to ensure the maintenance of the LoS and thus mitigate the detrimental effects on passengers resulting from the closure of air routes. We showed that the HSR service providers can mainly leverage increased frequencies to guarantee quality connections after the closure of air routes. Specifically, we estimated a substitution rate of 0.12. This means that to compensate for the loss in passengers' LoS it would be necessary to introduce an additional HSR ride about each 9 air flights dropped. Furthermore, we observed that for the London-Pairs passenger market this revision of scheduling would be more than adequate to accommodate passengers diverted from air transport. Lastly, we outlined how the compensatory mechanisms required are much more intense whether, following the removal of air routes, the antitrust and regulatory authorities fail to mitigate the possible fare increase resulting from the market concentration, thus highlighting the leading role played by these authorities in the process of ensuring competition following a possible cancellation of air routes.

Finally, it is worth mentioning some of the limitations of the current approach that pave the way for future works. First, this is a first attempt to assess the heterogeneity of traveler preferences. Therefore, the interesting differences in passengers' attitudes towards air or HSR mode depicted could be deepened and further examined in a future empirical assessment. Second, the parameters of both trip generation and distribution models are estimated based on data specific to the London-Paris passenger market. Accordingly, the representativeness of our results needs to be validated even for other multimodal markets. Evidence on induced demand and compensatory mechanisms may then be applied to other multimodal markets at a pan-European level to identify a more accurate estimation of the impacts and the compensatory mechanisms required in case of a possible policy of enforced modal shift from air transport to HSR or other initiatives to promote air-to-rail mode substitution.

Chapter 6 – Policy impacts on the propensity to travel by HSR in the Amsterdam – London market

6.1 Introduction

A key aspect of the European Union's transport related policy towards reductions of GHG emissions is the promotion of the shift of the majority of (short-medium haul) air passengers to rail, as well as the increase of competition within the railway industry itself (for further details see Section 2.2). The ‘Fit for 55’ package, proposed by EU to reduce emissions of GHGs, includes a tax on jet fuel. The EC’s 2020 Sustainable and Smart Mobility Strategy specifically mentions a modal shift, aiming to double high-speed rail (HSR) traffic in Europe by 2030. The EC, as well as individual countries, called for a limit on short-haul flights (EC, 2020b). France and Austria introduced bans on domestic flights if train alternatives are available.[49] Similar policies have been considered by Germany and Spain. Analogous developments are seen in China, where government aims to introduce HSR services for 80% of Chinese cities with 1 million inhabitants or over (Li et al., 2019).

A relatively recent addition to the European HSR network is the Eurostar-connection between Amsterdam and London. This service is in operation since April 4, 2018, starting with two trains per day. The return trip would require a stop at Brussels for border controls, a direct trip from Amsterdam (Rotterdam) to London would take place when juxtaposed controls would be established in the Netherlands in 2020. A daily service of 5 trains was planned, but due to COVID, there are 3 daily trains from London to Amsterdam. According to Eurostar’s website, London to Amsterdam takes 3 hours and 52 minutes, and Amsterdam to London takes 4 hours and 9 minutes (indirect services take longer). Eurostar (2022) reports 80% less GHG emissions, compared to an equivalent short-haul flight, on the London-Amsterdam route. While we do not go into the details of this claim, a substantial decrease in GHG emissions would be possible if passengers would substitute to HSR on this route (and the claim is correct). The market share achieved by the Eurostar alternative between London and Amsterdam in the first years of

[49] In France domestic flights are banned since 2021 if rail alternatives of 2.5 hours or shorter are available. In Austria domestic flights are banned since 2020, if an alternative rail connection within 180 min exists (Oxera, 2022).

operation is quite limited, when compared to the aviation alternative as a whole.[50] There may be various reasons, such as travelers' unfamiliarity with the new alternative, the relatively high fares for the Eurostar alternative, or the fact that the frequency of service (of the aviation alternative) in the London-Amsterdam market is already high. Givoni and Rietveld (2009) find that the marginal benefit of an additional (air) service in the Amsterdam-London market is close to zero. If the HSR service does not generate additional traffic, an increase in market share of the HSR alternative must come at the expense of the aviation alternative. If the HSR alternative is promoted because GHG emissions are lower, important questions therefore concern the best leverages to act on to enhance the HSR market share. For example, which are the impacts of a possible air ticket tax, HSR price reduction, or increase in HSR frequencies?

This contribution adds to the body of literature on rail-air substitution by answering these questions for the London-Amsterdam market. This is a mature market, with relatively high frequency and low marginal utility of frequency (Givoni and Rietveld, 2009). Stimulating the HSR alternative potentially has strong effects on the aviation alternative and GHG emissions. From the literature we know that (new) services offered by low-cost airlines lead to an increase in tourism demand (Álvarez-Díaz et al., 2019). Local authorities accommodated, or even stimulated such growth through the subsidization of airport development or even airlines (Álvarez-Díaz et al., 2019). And even though the aforementioned stimulation of airport development had different reasons (increasing tourism spending following from increased passenger flows, rather than stimulating a greener alternative), the outcome of the stimulation of HSR in the London-Amsterdam market may have similar outcomes: if generalized travel cost for the HSR alternative is lowered, overall demand in the market may increase. Such an increase may be unwanted if it also means more GHG emissions. Therefore, this paper studies tools to increase market share of the HSR alternative on the London-Amsterdam market, as policy to stimulate substitution from air to rail to decrease GHG emissions, taking into account that such policy may increase overall demand.

To accomplish this, we adopt the two-level aggregate nested logit model formulated in Chapter 3, able to jointly study trip generation and distribution in a single framework. Using this model, we determine the potential of various policies to stimulate air-to-rail substitution. Furthermore,

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[50] According to data from the International Passenger Survey (IPS) carried out by the UK Office of National Statistics (ONS), the average market share of Eurostar connection for passengers traveling between the Southern part of the UK and Amsterdam is equal to 8.5%. This value increases to 11.5% considering only passengers departing from the Greater London Area.

we consider the effect on passenger welfare of implementing different policy initiatives. Both an environmental tax on air tickets and the reduction of the HSR fare have been found to be ineffective in encouraging modal shift, if not adequately accompanied by improvements in HSR service (in terms of frequency and travel time). Furthermore, we pinpointed how any continuation of the current congestion at Amsterdam and London airports, with the resulting inconveniences and queues, would significantly impact air transport demand and give impetus to the diversion to HSR.

The remainder of this Chapter is organized as follows: Section 6.2 frames the present work within the previous streams of research. Section 6.3 formalizes the formulation of the deterministic passenger utility adopted in the Chapter and describes the data sample collected and the data aggregation process used to calibrate the model. Section 6.4 deploys the results obtained from the estimation of the empirical model. Section 6.5 simulates the effects of different incentive mechanisms of HSR modes by evaluating their effectiveness and policy implications. Lastly, Section 6.6 concludes the work by outlining pathways for future research.

6.2 Related literature

The literature on the interaction between HSR and aviation as well as on the environmental effects of substitution to HSR is quite substantial and has been extensively discussed in Section 2.1. The short review presented in this Section focuses on aspects relevant to the market at hand (London-Amsterdam).

6.2.1 HSR and aviation

On some European routes the introduction of a HSR connection has, over the recent decades, considerably reduced air ridership (e.g., London-Paris, Paris-Lyon, Rome-Milan, Madrid-Barcelona routes). Givoni and Dobruszkes (2013) report that HSR market share generally decreases with HSR on-board travel time. HSR can capture more than 50% of the market in markets with HSR travel times of up to about 3.5 hours. Studied markets with HSR travel times of around 4 hours report market shares between 45% and 56%. Specifically, the Tokyo–Hiroshima route (894 km) exhibited in 2009 a HSR market share of 56% (Clever and Hansen, 2008), while both Paris–Marseilles (782 km) and Paris–Amsterdam (547 km) routes, observed in 2000 and 2004, respectively, report HSR market share of 45% (Campos and Gagnepain, 2009; Steer Davies Gleave, 2006). Based on these observations alone, the HSR alternative in the London-Amsterdam market, with a travel time of 3 hours and 52 minutes might be able to gain a substantial market share. This conclusion is supported by Kroes and Savelberg (2019), who find that Amsterdam-London route has the largest potential for substitution among short distance routes served by Amsterdam Schiphol airport, accounting alone for more than three-quarters of the predicted substitution. However, Dobruszkes et al. (2014) outline that the impact of HSR entry on airline services decreases between 2 and 2.5 hours of travel time on HSR. Furthermore, Dobruszkes et al. (2014) point out the effect of airline hubbing strategies, which require a large number of flights. Finally, for the European case, Behrens and Pels (2012) find that HSR is clearly a viable alternative for both leisure and business travelers in the London–Paris market. Specifically, Behrens and Pels (2012) find that longer HSR travel times may be offset by frequency and fares in both the business and leisure market segments.

To summarize the discussion so far, the literature is not clear on the potential of the HSR alternative between London and Amsterdam. According to some studies, the HSR travel time falls within the range in which a significant market share may be expected, using fare and frequency as policy variables, if necessary. Other studies point out the negative effect of travel time. Furthermore, the fact that both London and Amsterdam are served by hubs, leading to relatively high frequencies of the air alternative, may have a negative effect on the potential of HSR. This is particularly relevant when the HSR does not serve directly the airport itself resulting in an air-rail option that is still far from seamless for passengers, also due to the absence of integrated ticketing and coordinated baggage handling.

Over recent years, several studies have focused on the Chinese case because of the huge investments in HSR infrastructure. Li et al. (2019), investigating the determinants of the strong decline in the number of air passengers on Chinese routes with HSR services, attribute the cause to the daily frequency of service. Conversely, Zhang et al. (2017) found that HSR travel time is a more important determinant of the strong negative impact of HSR on air transport than the frequency of service. The variable with the strongest effect on air travel demand according to Zhang et al. (2017) is the price difference between airfare and HSR.

To conclude this part of the literature review, we note that HSR travel time, frequency of service, and fare are found to be important determinants of aviation demand. Not all studies come to the same conclusion, showing that an analysis at the market level is necessary to determine if HSR is a viable alternative when introduced in a market. Given that the frequency of service of the aviation alternative between London and Amsterdam is already very high (Givoni and Rietveld, 2009), an increase in total frequency in this market may have little influence on total demand. However, since the frequency of service of the HSR alternative is comparatively low, an increase in the frequency of service of this particular alternative may lead to a shift from air to rail, like in the other cases mentioned above.

6.2.2 Induced demand and trip generation

As discussed in Chapter 2, air to HSR substitution is often promoted in an attempt to reduce GHG emissions. One of the main statements to justify such a policy refers to the *greenness* of HSR compared to air transport on a per-seat basis (see e.g. Jiang et al., 2021). However, notwithstanding HSR’s *greenness* (per seat), the introduction of HSR services does not necessarily lead to environmental advantages. Indeed, if the introduction of an HSR alternative on a route means that generalized travel cost decreases, the overall demand may increase. Modal shift to HSR may lower CO_2 emissions, but if additional growth in demand is accommodated using the available aviation capacity, overall CO_2 emissions may not decline, thus leading to a negative net environmental effect. In other words, a trade-off between the substitution effect and the traffic generation effect takes place (D’Alfonso et al., 2016, 2015). This entails that the evaluation of the effectiveness of policies promoting modal shift for environmental purposes cannot disregard modeling and considering traffic generation effects (Chen et al., 2021).

Within transportation literature, potential bilateral transport flows between an origin and destination (i.e., traffic generation) have been typically modeled via a gravity-based approach (Wojahn, 2001; Zhang and Zhang, 2016), in which travel demand is assumed to be positively proportional to the mutual attraction factors and inversely proportional to impeding factors. The former generally include socio-economic characteristics such as GDP and population, while the latter refer to the generalized cost of travel or distance between the origin and the destination, ultimately representing the ease or difficulty of traveling between regions. Since such variables do not capture multilateral resistance[51] between two locations, Zhang and Zhang (2016) explicitly control for multilateral effects and find that the magnitudes and signs of most parameters are hardly influenced, concluding that in the Chinese case, multilateral effects are not important. Zhang and Zhang (2016) refer to Behar and Nelson (2014), who argued that for isolated bilateral changes in trade frictions, the multilateral effects are small for most cases and, accordingly, can be ignored. In the case of the London-Amsterdam market the effects may not be isolated since both cities accommodate a hub, which offers connections to the rest of the world. But since no data is available for rail connecting traffic, in the current paper it is not possible to consider the effect of multilateral resistance. However, by restricting the analysis to point-to-point passengers only, we reasonably exclude the necessity to model this type of effect.

[51] It is not only the bilateral resistance that influences flows between two locations, but also multilateral resistance to other countries that influences flows between two locations.

6.3 Empirical setting

To analyze the determinants of passenger choice in the market between Amsterdam and London as well as simulate the effects of regulatory policies on passenger distribution and the overall travel demand, we apply the innovative two-level aggregate nested logit model thoroughly described in Chapter 3. The integrated model jointly describes passengers' itinerary choice and demand generation in a single framework. Such a model, once calibrated on historical data of the multimodal Amsterdam-London market, allows us to develop possible regulatory scenarios and estimate their effects both in terms of traffic distribution and changes (induction, or conversely, reduction) of the overall traffic level. Ultimately, it enables the assessment of the effectiveness of such policy initiatives. In the following, we first formalize the passenger utility function, then we describe the data collection and aggregation process necessary to estimate the integrated model for the market under consideration.

6.3.1 Deterministic utility formulation

In the current Chapter, the deterministic utility function of a passenger traveling with alternative *i* in sub-market *m* and period *t*, $V_{i,mt}$, is defined as:

$$V_{i,mt} = \alpha_i + \beta \cdot ln(freq_{i,mt}) + \gamma \cdot traveltime_{i,mt} + \delta \cdot travelcost_{i,mt} + \varepsilon \cdot HSR \cdot ln(freq_{i,mt}) \qquad (6.1)$$

where $freq_{i,mt}$ is the frequency of alternative *i* in sub-market *m* and period *t*. Frequency is included in logarithmic form two reasons (Hansen, 1990). First, to account for the expected decreasing marginal utility of frequency. Second, since a route alternative can be considered as an aggregation of individual flights/trains, the logarithmic form is the most suitable for a characteristic that captures the size of an aggregated alternative (Ben-Akiva and Lerman, 1985). $traveltime_{i,mt}$ is the travel time of alternative *i* in sub-market *m* and period *t*, and includes on-board travel time, departure waiting time,[52] expected delay, and finally access and egress time to reach departure HSR station or airport (arrival zone) from the departure zone (arrival station or airport). $travelcost_{i,mt}$ is the travel cost of alternative *i* in sub-market *m* and period *t*, and includes the average fare of the single alternative and estimated access and egress driving costs. $HSR \cdot ln(freq_{i,mt})$ is an interaction term between frequency and HSR mode, thus modelling the additional utility of HSR frequency compared to the average value of the utility associated to the generic frequency parameter. Lastly, α_i are mode- and airline-specific constants.

[52] Minimum time passengers are advised to arrive in advance at the airport/station with respect to the scheduled time for security checks and check-in activities.

6.3.2 Data collection

To estimate the proposed two-level aggregate nested logit model on the Amsterdam-London market, data on both passenger flows and characteristics of transport modes are required.

Similarly to Chapter 5, data on passenger flows were collected from the International Passenger Survey (IPS), a continuous survey conducted by the Office for National Statistics (ONS) providing detailed information on the numbers and types of passengers entering and leaving the UK. The information used for the purposes of the current analysis includes the respondent's demographic characteristics (gender and age) and details of the travel arrangements, the departure and arrival travel facility, and the fare paid. Unfortunately, no information about education or income is collected. The passenger flows estimated through field interviews are then adjusted using a weighting procedure by the ONS to yield reliable estimates of passenger traffic for each airport-railway station and route for each sampling period. To the aim of the study, from the entire IPS dataset in the period 2015-2019, the observations of passengers traveling from Amsterdam travel facilities to London airports or railway stations, and *vice versa*, were selected.[53] Moreover, air passengers claiming to travel through London and/or Amsterdam airports for an interconnecting flight have been excluded from the analysis. The sample collected according to these specifications contains 3514 leisure and 1805 business passenger interviews. Considering the weight associated with each observation, the sample is representative of around 6.4 leisure and 3.3 business million passengers. Table 6.1 reports the number of passengers per year, alternative, and type. Overall, the leisure market is dominated by low-cost carriers with a traffic share varying between 52% and 65%. Conversely, full-service airlines dominate the business passenger market with an average market share of over 67%. Lastly, the HSR connection operated by Eurostar, which entered the market only in the second quarter of 2018, holds marginal market shares for both leisure (around 10%) and business passengers (about 2.5%). Table 6.2 provides aggregate statistics regarding socio-demographic characteristics of the sample. Considering gender, there are significantly more male passenger than females for both leisure (59.6%) and business (72.5%) traveler segments. Nearly 55% of

[53] We consider London travel facilities the 5 major airports of the London airport system (namely, LCY- London City, LGW- London Gatwick, LHR- London Heathrow, LTN- London Luton, and STN- London Stansted) as well as the St Pancras HSR station in London. On the Amsterdam side, we deem the travel facilities located in the Greater Amsterdam region, i.e. AMS-Schiphol airport and the Amsterdam Centraal HSR station. Since certain trip characteristics such as fare paid and the town visited during the stay are only required for passengers during their return journey (i.e. Dutch passengers leaving the UK and British citizens entering the UK), we only focus on these observations which are, however, representative of the whole market that can reasonably be assumed to be symmetrical in the respective opposite directions.

leisure travel is made by young people (below 35 years), while passengers in their thirties, forties and fifties represents the vast majority of business travelers.

Quarterly supply characteristics were collected from secondary sources. The average fare per passenger type, alternative, and period were computed starting from the primary IPS source. The average weekly frequency, as well as on-board travel time, were gathered from the OAG Schedule Analyzer database for the air alternatives, and from official timetables published by Eurostar for the HSR connection. The departure waiting time (i.e., minimum time passengers are advised to arrive at the airport/station with respect to the scheduled time for security checks and check-in activities) was identified from the indications provided on the carrier's website and on the airport website. Specifically, it was set to 60 minutes for CityJet, to 40 minutes for easyJet and Vueling, and finally equal to 30 minutes for Eurostar connections. British Airways and KLM indeed suggest different time depending on the departure airport. Lastly, the expected delay was computed based on the average delay and on-time punctuality statistics provided by the Civil Aviation Authority[54] and Eurostar.[55] Table 6.3 reports the average weekly frequency per alternative and year. Overall, the air market between Amsterdam and London appears very dense with about 230 flights per week operated by full-service carriers, and 120 by low-cost carriers, for a total amount of about 50 daily flights (approximately 7750 offered seats). Air connections have been constantly operated from all five major airports in the London airport system with scheduled travel times between 65 and 80 minutes. The direct HSR connection by Eurostar between the two cities was instead launched in April 2018, with an initial frequency of 12 trains per week, increasing to 19 in 2019 (corresponding, due to the greater capacity of the train, to 900 and 1350 offered seats per day, respectively). The rail connection exhibits much longer travel times than those of air alternatives. However, this is partially compensated by the shorter departure waiting time and the higher punctuality of travel by Eurostar. As regards the average fares paid by passengers, low-cost airlines offer the lowest fares for both categories of passengers. For business passengers, the Eurostar connection prices range between the fare of low-cost companies and full-service ones, in line with the behavior observed in the London-Paris market in the same period. Conversely, HSR's fares for leisure passengers results comparable to, if not higher than (especially from 2019), those of traditional airlines, thus showing a substantially different behavior compared to the market between London and Paris.

[54] Civil Aviation Authority (CAA) UK flight punctuality data — https://www.caa.co.uk/punctuality
[55] Eurostar press office — https://mediacentre.eurostar.com

	Leisure										
	LCY-AMS-BA	LCY-AMS-KL	LCY-AMS-WX	LGW-AMS-BA	LGW-AMS-U2	LHR-AMS-BA	LHR-AMS-KL	LTN-AMS-U2	LTN-AMS-VY	QQS-ZYA-HSR	STN-AMS-U2
2015	31.5 (3%)		20.6 (2%)	90.2 (9%)	356.1 (34%)	109.3 (10%)	122.1 (12%)	170.6 (16%)			160.1 (15%)
2016	58.8 (5%)		45.1 (4%)	107.6 (9%)	416 (35%)	76.7 (6%)	126.9 (11%)	177.2 (15%)			179.1 (15%)
2017	88.8 (7%)	71.6 (6%)	16.4 (1%)	83.7 (7%)	299.3 (24%)	124.2 (10%)	111.4 (9%)	311.6 (25%)			131.4 (11%)
2018	50.9 (4%)	28.8 (2%)		73.7 (5%)	328.8 (24%)	111.6 (8%)	130.1 (10%)	252.9 (19%)	88 (7%)	96.6 (7%)	190.2 (14%)
2019	47.6 (3%)	90.3 (6%)		128.1 (8%)	402 (26%)	110 (7%)	150.3 (10%)	237.3 (15%)	65.1 (4%)	191.7 (13%)	110.4 (7%)

For all the tables: AMS: Amsterdam Schiphol; LCY: London City; LGW: London Gatwick; LHR: London Heathrow; LTN: London Luton; QQS: London St Pancras; STN: London Stansted; ZYA: Amsterdam Centraal; BA: British Airways; HSR: Eurostar HSR connection; KL: KLM Airlines; U2: easyJet; VY: Vueling Airlines; WX: CityJet.

	Business										
	LCY-AMS-BA	LCY-AMS-KL	LCY-AMS-WX	LGW-AMS-BA	LGW-AMS-U2	LHR-AMS-BA	LHR-AMS-KL	LTN-AMS-U2	LTN-AMS-VY	QQS-ZYA-HSR	STN-AMS-U2
2015	51.2 (9%)		40.5 (7%)	50.3 (9%)	74.9 (13%)	114.8 (20%)	142 (24%)	51 (9%)			58.6 (10%)
2016	78.8 (13%)		64.2 (11%)	48.6 (8%)	108.1 (18%)	114.4 (19%)	105.1 (17%)	39.3 (6%)			46.3 (8%)
2017	98.3 (15%)	56.6 (9%)	12.2 (2%)	36 (6%)	95.9 (15%)	116.6 (18%)	115.4 (18%)	84.8 (13%)			19.6 (3%)
2018	112.1 (16%)	77.6 (11%)		39.3 (6%)	106.6 (15%)	91.8 (13%)	106.3 (15%)	72.6 (10%)	7.9 (1%)	10.6 (2%)	79.4 (11%)
2019	82.6 (11%)	116.9 (16%)		32.3 (4%)	95 (13%)	126.4 (17%)	155 (21%)	88.8 (12%)	8 (1%)	22.1 (3%)	12.1 (2%)

Table 6.1: Number of passengers (in thousands) per year, alternative, and type. Market shares in brackets.

	Leisure			Business		
	Air	HSR	**Total**	Air	HSR	**Total**
Gender						
Male	60.1%	55.5%	59.6%	72.0%	89.3%	72.5%
Female	39.9%	44.5%	40.4%	28.0%	10.7%	27.5%
Age class						
< 25	21.4%	14.8%	20.7%	3.9%	8.6%	4.1%
25-34	35.4%	24.3%	34.2%	27.9%	48.8%	28.4%
35-44	17.0%	14.9%	16.8%	34.2%	15.4%	33.7%
45-54	14.1%	19.1%	14.6%	26.7%	12.8%	26.3%
55-64	7.7%	16.9%	8.7%	6.9%	14.4%	7.1%

Table 6.2: Share of passengers by gender and age class for different transport mode and passenger type. Years 2018-2019.

	LCY-AMS-BA	LCY-AMS-KL	LCY-AMS-WX	LGW-AMS-BA	LGW-AMS-U2	LHR-AMS-BA	LHR-AMS-KL	LTN-AMS-U2	LTN-AMS-VY	QQS-ZYA-HSR	STN-AMS-U2
2015	31		46	21	45	55	76	27			21
2016	31		47	21	48	56	71	32	10		22
2017	30	34	14	21	50	55	70	39	14		23
2018	30	45		21	50	56	71	41	14	12	24
2019	31	49		21	50	57	70	40	7	19	24

Table 6.3: Average weekly frequency per alternative and year.

6.3.3 Data aggregation and model setting

To practically estimate the integrated model defined in Chapter 3, defining both a time detail and a territorial aggregation level is required to accurately compute the market share of the single alternatives, as well as the overall passenger flows in each period. For the aim of this paper, we selected a quarterly granularity over the period 2015 to 2019. As regard the territorial aggregation level, within the overall passenger market between London and Amsterdam, we identified different sub-market based on the departure/arrival zone in the UK. Specifically, we consider 31 different zones in the Southern part of the UK identified according to the International Territorial Levels (ITL) classification.[56] Due to the lack of specific information about the passengers' departure

[56] The International Territorial Levels (ITL) classification is a geographical nomenclature subdividing the UK territory into regions at three different levels (1, 2, and 3 respectively, moving from larger to smaller territorial units). The classification reflects the pre-existing Nomenclature of territorial units for statistics (NUTS) developed by the EU. For the purposes of the study, larger territorial units (i.e., levels 1 and 2 ITL

zone or final destination in Amsterdam, we assumed that the origin/destination of passengers using Amsterdam HSR station and airport is located within the Greater Amsterdam area. Therefore, we identified OD-pairs from each UK zone to the Greater Amsterdam area, and vice-versa, as sub-markets. Thereby, data gathered from the IPS were appropriately assembled and aggregated considering both the time granularity adopted and the aggregation into sub-markets. This process allows us to obtain an estimate, for each period and sub-market, of the number of passengers traveling using each alternative (and thus the relative market share) as well as the overall passenger flow level.

Due to the aggregate nature of the model, the estimation of the trip distribution model is possible considering the functional form of the deterministic utility defined in Equation 6.1.[57] Specifically, the parameters of the utility function can be estimated by regressing the difference between the log market shares on the difference-in-attribute variables of two alternatives of the same sub-market and period (Berry, 1994).[58] In addition to the primary and secondary data sources described above, for each departure/arrival zone access and egress time was compiled as the population-weighted access/egress time by car using the routing service Openrouteservice[59] and then access/egress driving costs were estimated considering an average car costs per kilometer.[60] The estimated utility functions for leisure and business passengers allow computing for each sub-market and period the LoS measure. This measure integrates the utilities provided by the individual alternatives within passenger's choice set. The LoS for a specific sub-market and time period powers, together with the aggregate number of travelers, the trip generation model that can be estimated by OLS through the log-linearization of the Cobb-Douglass demand function

zones) were selected the further they are located from the Greater London Area, whose areas were instead considered according to the level 3 classification.

[57] For further details about the estimation procedure, please refer to Section 3.1.2.

[58] According to the aggregate nature of the model, all time- and market-specific effects on the utility (with the same values for all alternatives in the same sub-market and period) are systematically differentiated out. Thus, the estimates implicitly take these effects into account.

[59] Openrouteservice — https://openrouteservice.org/

[60] Access/egress driving costs were calculated by multiplying access/egress distance (computed similarly to access/egress times using Openrouteservice) by the average car costs per kilometer, including fuel, maintenance, insurance, and depreciation. Coherently with Lieshout et al. (2016), we assume these costs to be 0.17 £/km on average.

The trip generation model includes as explanatory variable socio-economic characteristics of the specific market such as the geometric mean of the populations and per capita GDP of the departure and arrival zone.[61] Time and market-specific constants have been included to capture the seasonal effect throughout the year (quarter dummies) and peculiarities of the specific departure/arrival zone in the UK. The latter effect was analyzed by dividing UK zones into homogeneous macro-zones. Specifically, we clustered zones in external (areas located further away from the analyzed travel facilities and therefore suffering a stronger competition with alternative airports), intermediate zones, and zones belonging to Outer London and Inner London.[62] We further include as explanatory variables dummies referring to the two central areas of London (i.e., TL31 and TL32).

[61] Per-capita GDP and population for each ITL zone were gathered by the UK ONS (https://www.ons.gov.uk), while values for Greater Amsterdam area were provided by Eurostat (https://ec.europa.eu/eurostat).

[62] We define as intermediate zones the ITL zones level 2 located in the South-East part of England (i.e., TLJ and TLH) that surround the Greater London Area. We consider instead external zones the ITL zones level 1 located just outside the intermediate ones (i.e., TLF, TLG, and TLK). Since we control for macro-zones and not for the individual zone, we implicitly take into account the multilateral effect of adjacent zones on demand.

6.4 Estimation results

6.4.1 Trip distribution model

Table 6.4 shows the estimated coefficients and robust standard errors of the trip distribution model.

	Leisure		**Business**	
	Coeff.	**Robust SE**	**Coeff.**	**Robust SE**
Frequency (ln)	0.186**	0.0852	0.875***	0.203
Travel time (min)	-0.0127***	0.00186	-0.0346***	0.00327
Direct cost (£)	-0.00498**	0.00202	-0.00188	0.00203
HSR	1.024***	0.349	1.868***	0.653
British Airways	(base)		(base)	
KLM	-0.171*	0.0919	-0.590***	0.155
City Jet	-0.101	0.267	-0.638**	0.258
easyJet	0.629***	0.0776	-0.343**	0.173
Vueling	0.162	0.175	-0.686	0.432
HSR x Frequency (ln)	0.343***	0.117	0.833***	0.304
Observations	1266		723	
R^2	0.179		0.220	

***p<0.01, **p<0.05, *p<0.1

Table 6.4: Estimation results for the trip distribution model.

The coefficients of frequency and travel time are significant for both trip purposes, in contrast, direct cost coefficient results significant only for leisure passengers. Overall, sensitivities towards travel characteristics are consistent with evidence reported in previous transport mode choice studies (e.g., Behrens and Pels, 2012): both higher travel time and cost negatively influence passenger utility, concurrently high frequencies increase passenger attitudes towards the single travel alternative. Furthermore, while business passengers are more sensitive to average weekly frequency and travel time, leisure passengers exhibit a higher sensitivity to monetary costs. Regarding mode-specific variable (i.e., HSR), both types of passengers show a preference for the rail mode. This can be traced back to the greater comfort onboard, the availability of internet connection, and the possibility of carrying luggage without any relevant restriction. Leisure passengers also show, other things being equal, a preference for the low-cost company easyJet, whereas business passengers for British Airways. Lastly, concerning the HSR frequency variable, both models return positive coefficients. The coefficient of this variable has to be interpreted as the extra-utility of HSR frequency compared to the average utility associated with the generic frequency parameter (i.e., weekly frequency). Thus, the positive coefficients indicate a higher marginal utility for passengers of adding an additional HSR frequency than an additional air frequency. This is firstly consistent with the saturated air market (in terms of frequencies) between London and Amsterdam. Indeed, Givoni and Rietveld (2009) found that the marginal benefit of an additional air service in this market is close to zero. On the other hand, the relatively low frequency of the HSR alternative guarantees more perspective in case of a frequency increase. Secondly, the positive coefficient can be further traced to the intrinsic (positive) aspects of the HSR connection such as the aforementioned onboard comfort and the higher (per frequency) additional capacity resulting from an additional HSR connection. Note that the aggregate frequency elasticity of HSR market share exceeds 1 in the business market, indicating that at current levels of market share, an increase in frequency leads to a more than proportional increase in demand. A conclusion may be that HSR profit maximization may be difficult at current levels of demand and market share, because a marginal increase in frequency leads to a disproportionate increase in market share, and thus opportunity to gain additional revenues. But this will be a topic for additional research, because firm strategy is not studied in the current paper.

Unfortunately, due to the lack of specific information in the dataset (e.g., income and education) as well as the aggregate nature of the model itself —requiring to compute accurate market shares and consequently preventing excessive segmentation of passengers with respect to socio-economic characteristics— it has not been possible to model the impacts of other attributes than travel purpose on modal choice. Nevertheless, in the following, we provide some evidence with respect to heterogeneities in the composition of HSR and air transport passengers with respect to the socio-demographic attributes available in our dataset (i.e., gender and age) by borrowing the concept of specificity index (SI) from Dobruszkes et al. (2022). The SI is defined as the ratio between the presence of a specific social group on board HSR compared to its presence in the whole population. If an SI is higher (lower) than 1 for one specific social group, then this group is more (less) present on HSR than in the whole population.[63] We argue that, due to the relatively recent addition of the Eurostar connection in the market between London and Amsterdam, analyzing the incidence of different social groups on board HSR passengers compared to the whole population traveling between the two cities provides an adequate proxy for social groups more prone to use HSR and for which is more likely to observe a modal shift. Considering gender, the dominance of males on board HSR ranges from almost no inequality for leisure passengers (specificity index very close to 1) to more pronounced imbalances for business passengers, whose specificity index is equal to 1.19. This confirms the evidence from Dobruszkes et al. (2022) who found for the Paris-Atlantic corridor a higher incidence of males in HSR travelers for business purposes than for leisure ones. In terms of age (Figure 6.1), younger people traveling for leisure tend to be under-represented on board HSR. In contrast, elderly people with the same travel purpose are to some extent over-visible in HSR passengers. The presence of people in their fifty or older traveling for leisure among HSR passengers is more than double of the equivalent using air connections. Overall, we observe a major propensity in modal shift toward HSR for older passengers with leisure purposes. The same pattern emerges from Bergantino and Madio (2020) which, however, do not control for heterogeneity in this pattern considering the different travel purpose. Concerning business passengers,

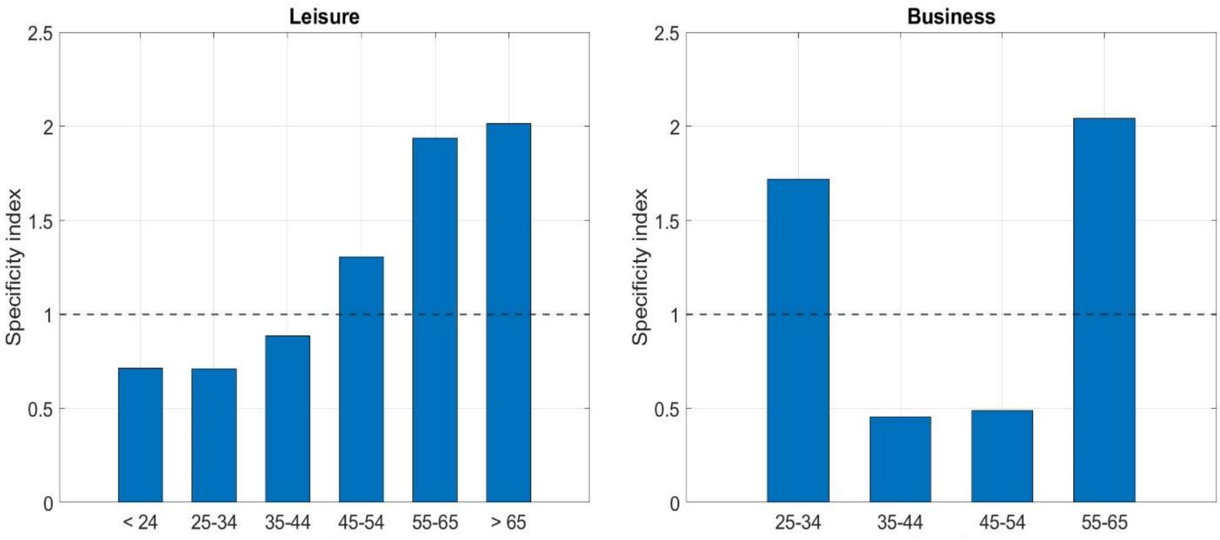

Figure 6.1: Age of HSR passengers compared to the whole population traveling between Amsterdam and London.

[63] Note that Dobruszkes et al. (2022) compute the SI by referring to the composition of the whole society (at countrywide level). In our case, we compare the presence on board the HSR with the population of travelers along the Amsterdam-London corridor (using air or HSR).

young (below 35) and old (above 55) people are over represented in HSR passengers, while medium-age people under represented. This pattern can be understood if we consider that business airfare are typically affordable or directly reimbursed by the company for those individual with a specific professional position or high seniority within company.

6.4.2Trip generation model

Estimated coefficients and robust standard errors for the total travel demand model are reported in Table 6.5. Overall, both leisure and business model exhibit good fitting capacity, with a mean absolute percentage error (MAPE) on the estimates of quarterly passenger flows between Amsterdam and London equal to 9.21% and 9.17%, respectively. All estimated coefficients result statistically significant, except for the Outer London coefficient and quarterly dummies, the latter only in the business model. Consistently with expectations, travel demand for both types of travelers results positively stimulated by socio-economic characteristics of the origin and destination zones, thus confirming demographic and economic development as a major driver in increasing mobility. The sensitivity towards per-capita GDP appears greater for business passengers than for leisure ones, thereby confirming, *ceteris paribus*, the higher attitude of business travel to economic intensive zones. Estimates for the level of service parameter result positive, significant, and consistent with utility-maximization theory in both models, thus recognizing travel demand sensitive to changes in supply. Leisure passengers exhibit higher sensitivity to variations in the overall measure of travel impedance than business passengers. In other words, leisure travel is more likely to be stimulated (or conversely, repressed) as a result of improved (worsening) supply characteristics. A seasonal travel pattern is outlined for leisure passengers with higher flows during the spring and summer seasons, decreasing during fall and winter months. Conversely, business flows do not exhibit any statistically significant seasonal trend. As regard the intrinsic travel potential of different macro zones, it appears to decrease moving away from the Greater London Area. This probably can be traced back to the effect of competition with other airports (other than those considered) and the progressive overlap of the catchment areas, parameters that gradually increase the further from the Greatest London Area. In addition, moving away from travel facilities considered, the competition with alternative transport modes increases. Lastly, intrinsic travel potentials statistically different from those of the reference macro-area emerge for the two central London areas (e.g., TL31 and TL32).

	Leisure		**Business**	
	Coeff.	**Robust SE**	**Coeff.**	**Robust SE**
Population	1.176***	0.264	1.771***	0.264
Per-capita GDP	1.104***	0.200	1.389***	0.18
LoS	0.606***	0.203	0.285***	0.0865
Quarter I	(base)		(base)	
Quarter II	0.285***	0.0843	0.0706	0.0836
Quarter III	0.236***	0.0887	-0.0505	0.0847
Quarter IV	0.0927	0.0857	0.0199	0.0885
Inner London	0.489**	0.235	0.601**	0.239
Outer London	-0.181	0.235	0.322	0.238
Intermediate zones	(base)		(base)	
External zones	-0.545**	0.259	-0.919***	0.264
Zone TL31	-0.901***	0.280	-1.116***	0.252
Zone TL32	0.436**	0.217	0.633***	0.188
Constant	-19.46***	4.444	-30.70***	4.657
Observations	560		438	
R^2	0.393		0.442	
MAPE	9.21%		9.17%	

***p<0.01, **p<0.05, *p<0.1

Table 6.5: Estimation results for the trip distribution model.

6.5 Simulation analysis and policy implications

The estimated integrated model allows us to simulate the effects of policy initiatives aimed at encouraging the use of HSR on the route between London and Amsterdam on both air-to-rail traffic diversion and passenger welfare.

Among the plethora of policies advocated over the recent years both at the national and European level, in this paper we analyze: (i) the introduction of an environmental tax on airfare aimed at discouraging air travel, (ii) the reduction of the HSR fare level achievable by, among others, increasing competition within the railway industry, (iii) increasing HSR frequency, and (iv) a reduction HSR on-board travel time. Clearly, these policies are not mutually exclusive and may be implemented simultaneously. Furthermore, in light of the recent increasing difficulties faced by airports and airlines[64] in the post-pandemic recovery period mainly due to staff shortages and strikes, we test a specific scenario in which we evaluate the effects on air-to-rail diversion following an increase in the departure waiting time at airports.

All of these simulation analyses are conducted using 2019 characteristics and passenger flows as the reference case.[65] For all the scenarios, we assumed that traffic diversion or induction patterns do not lead to airlines and HSR operator reaction with consequent changes in the relative frequency and fare level.[66] The effectiveness of the different policies initiatives is discussed both examining their potential to stimulate diversion from air to rail (in terms of number of diverted passengers and market share achieved by the HSR alternative) and their impacts on passengers' welfare. For this purpose, we use the difference in the cumulative utility of travelling passengers as a proxy for the change in their welfare (Small and Rosen, 1981). The cumulative utility for passenger type k, W_k, has been defined as:

[64] Staff shortages have been severely affecting airports and airlines across Europe as of April 2022. This situation is most critical at Amsterdam Schiphol and London Heathrow airports where passengers are facing significant queues, disruptions, and the cancellation of several flights.

[65] The identification of a reference context is necessary because diverted demand, as well as induced demand, cannot be directly estimated, but rather only inferred by comparison with a reference scenario (Gorham, 2009).

[66] We acknowledge this assumption as one of the main limitations of the current work. The identification of the optimal policy in the light of the airlines' and HSR operators' profit-maximizing behavior may certainly be the core of future research efforts.

$$W_k = LoS_k \cdot \sum_{i \in I} Q_{ik} \tag{5.7}$$

where Q_{ik} is the number of passengers of type k (business or leisure) traveling with alternative i, LoS_k is the expected maximum utility for passenger of type k, and I is the set of available travel alternatives.

The first scenario analyzed is the introduction of an environmental tax on air tickets aimed at discouraging the use of air travel. In this regard, it should be noted that in December 2020, the Dutch Senate adopted the Air Passenger Tax Act, which entered into force on 1 January 2021 introducing a new aviation levy of 7.95 € (about 6.8 £) on all passengers departing from a Dutch airport on board commercial or non-commercial flights. This tax is expected to increase to €24 (about 20.5 £) at the beginning of 2023. Simulation results for the introduction of an environmental tax are reported in Table 6.6.[67] All in all, introducing an environmental tax, in addition to the diversion effect towards the HSR alternative, would lead to a deterioration of the level of service, thus shrinking the overall demand. Assuming a taxation level of £20 (similar to that proposed by the Dutch government), air traffic would drop by 4.5% (-210,000 passengers) with a significant contraction effect even on overall market demand (-3.73%). However, only about 8% of the reduction in air passengers would be diverted to HSR (whose market share thus increases only marginally), while the remainder would cease to travel. Accordingly, the application of an environmental tax, if not adequately supported by improved HSR service, appears, at first glance, ineffective in increasing HSR market share. The increase in air fares resulting from levying an environmental will lead to an overall welfare

Amount of environmental tax (£)	**HSR market share**	**Δ% overall demand**	**Δ % HSR traffic**	**Δ % air traffic**	**Diverted demand**	**Reduced demand**	**Δ % welfare leisure passenger**	**Δ % welfare leisure passenger**
5 £	10.11%	-0.95%	0.80%	-1.15%	4,050	48,868	-3.47%	-1.09%
10 £	10.29%	-1.89%	1.60%	-2.28%	8,124	97,008	-6.82%	-2.16%
20 £	10.65%	-3.73%	3.21%	-4.50%	16,340	191,146	-13.13%	-4.27%
30 £	11.02%	-5.51%	4.84%	-6.66%	24,644	282,496	-18.98%	-6.33%
40 £	11.41%	-7.24%	6.49%	-8.76%	33,036	371,138	-24.41%	-8.34%

Table 6.6: Simulation output assuming the introduction of an environmental tax on airline tickets of different amounts.

[67] We assume full pass through of the environmental tax.

reduction, especially for leisure passengers who are more sensitive to monetary aspects. In follow-up research, this reduction needs to be balanced against potential gains in welfare due to reduced external costs following a decrease in overall demand.

An apparently similar measure to the introduction of an environmental tax on air tickets is the reduction of the HSR fare, as both leverage the relative price difference between modes. However, the latter policy, conversely to the former, causes an increase in the overall level of service, thus stimulating overall demand in the market. Looking at the estimated impacts (Table 6.7), a reduction of the Eurostar ticket by £20 would cause HSR traffic to increase by almost 41,500 passengers (+8.14%). However, only slightly more than 40% of this traffic increase (16,750 passengers) would be diverted from air to rail. The remainder would be new (stimulated) travelers. Even this measure, albeit in a more pronounced manner than the environmental tax, would therefore only lead to a marginal increase in HSR's market share. If this measure would be implemented to reduce the environmental impact of aviation by making the “cleaner alternative cheaper”, the outcome is only a marginal increase in HSR ridership, and an overall increase in demand. The combination of a reduction in the generalized travel cost and the resulting stimulation effect on the overall demand would lead to an increase in both categories of passenger welfare, albeit at the cost of additional environmental degradation, although the net-effect again is a topic for additional research. Analyzing the possible reduction in HSR fare, it should also be noted that no HSR competitor is shortly expected to enter the market under

Reduction of HSR fare (£)	**HSR market share**	**Δ% overall demand**	**Δ % HSR traffic**	**Δ % air traffic**	**Diverted demand**	**Stimulated demand**	**Δ % welfare leisure passenger**	**Δ % welfare leisure passenger**
-5 £	10.12%	0.12%	1.97%	-0.09%	4,076	5,956	0.46%	0.12%
-10 £	10.31%	0.24%	3.98%	-0.18%	8,226	12,048	0.94%	0.23%
-15 £	10.50%	0.36%	6.04%	-0.27%	12,452	18,282	1.43%	0.35%
-20 £	10.69%	0.48%	8.14%	-0.36%	16,754	24,658	1.93%	0.47%
-25 £	10.89%	0.61%	10.28%	-0.46%	21,134	31,182	2.44%	0.59%
-30 £	11.09%	0.74%	12.46%	-0.55%	25,594	37,854	2.97%	0.71%

Table 6.7: Simulation output assuming the reduction of HSR tickets by different amounts.

consideration,[68] so the only way for policymakers to promote the reduction of HSR fare would be to subsidize the HSR operator.

Much more relevant impacts arise when considering an increase in daily Eurostar frequencies (Table 6.8). The HSR operator indeed still operates three daily connections between Amsterdam and London, despite original plans to increase to five daily trains as early as 2020, later shelved due to the consequences of the COVID-19 pandemic. An increase in frequencies according to the original target, would boost HSR traffic by about 161,00 passengers (+32%), of which more than 94,000 (about 58%) would be diverted from air alternatives. These figures increase to 387,000 and 228,000 passengers in the case of an increase to 10 daily connections. As a result of the increase in HSR daily connections, HSR's market share would rise to 12.9% and 17%, respectively. Air traffic would drop by 2% and 5% against a total market that would grow, due to the stimulus effect, by 1.3% and 3.1%, respectively. The impacts in terms of passenger welfare are positive, especially considering business passengers more sensitive to the service frequency.

HSR daily frequency	HSR market share	Δ% overall demand	Δ % HSR traffic	Δ % air traffic	Diverted demand	Stimulated demand	Δ % welfare leisure passenger	Δ % welfare leisure passenger
5	12.91%	1.30%	31.61%	-2.04%	94,322	66,586	2.65%	10.92%
6	13.85%	1.71%	41.78%	-2.71%	124,966	87,728	3.38%	15.03%
7	14.71%	2.09%	51.19%	-3.32%	153,292	107,254	4.02%	19.08%
8	15.51%	2.45%	59.96%	-3.89%	179,692	125,508	4.60%	23.09%
9	16.26%	2.79%	68.20%	-4.43%	204,454	142,722	5.11%	27.07%
10	16.96%	3.10%	76.00%	-4.94%	227,794	159,066	5.59%	31.02%

Table 6.8: Simulation output assuming an increase in HSR daily frequency.

Another strategy that can be used to enhance HSR mode ridership is the reduction of travel time, which according to previous scientific studies is a key determinant of HSR-air transport competition outcomes. Considering the London-Amsterdam market, a reduction of HSR travel times can be pursued by improving organizational aspects of the

[68] Thalys, already a leader in HSR connections between Paris and Amsterdam, could have been a potential competitor for Eurostar on the London – Amsterdam route. However, the European Commission recently approved the merger between the two companies.

service (such as passport control activities) and optimizing the use of the infrastructure. In this regard, it should be noted that HSR's scheduled travel times during the first year of operation (2018) were approximately 14 minutes shorter than today, and that passport control activities introduced after Brexit currently impose a stop of Eurostar train of half an hour in Brussels. Thus, there is room for improvement. The impacts in terms of traffic diversion and the resulting increase in HSR market share under this scenario (Table 6.9) are even greater than those from the increase in HSR frequencies. A decrease of HSR

Reduction of HSR travel time (min)	HSR market share	Δ% overall demand	Δ % HSR traffic	Δ % air traffic	Diverted demand	Stimulated demand	Δ % welfare leisure passenger	Δ % welfare leisure passenger
-10	11.80%	0.91%	19.82%	-1.18%	54,222	46,686	2.50%	5.09%
-20	14.04%	2.02%	44.21%	-2.64%	121,700	103,360	5.38%	12.39%
-30	16.73%	3.37%	74.05%	-4.43%	204,526	172,408	8.68%	22.91%
-40	19.89%	5.01%	110.18%	-6.59%	304,208	256,632	12.48%	38.15%

Table 6.9: Simulation output assuming different reduction in HSR travel time.

travel time by 30 minutes would increase HSR market share by 7% compared to the 2019 levels. This increase appears particularly significant in the light of the highly concentrated air market serving the route between London and Amsterdam. Following a reduction on HSR travel time by 30 minutes, air traffic would decrease by 4.4% while HSR traffic would increase by 74% compared to 2019 levels. The increase in HSR passengers comes largely from diversion from air travel (53%) and partly from stimulated new demand. Better travel conditions and more passengers result even in the increase of the welfare measure for both business and leisure passengers.

By combining the two aforementioned measures (i.e., increase HSR frequency and reduce HSR travel time), higher results in terms of HSR market share can be obtained. Specifically, considering five trains per day in the absence of travel time changes, a market share of 13% is estimated, which would increase by almost 9% also considering a reduction in travel time of 30 minutes. By further increasing the frequency to 10 trains per day and reducing time by 30 minutes, Eurostar is expected to gain a relevant market share of about 28%. The stimulation effect deriving from both increase of HSR frequency and reduction of HSR travel time would lead to the increase in the overall demand by ranging from 5.7% to 9.1% when passing from 5 to 10 daily connection, considering a reduction in travel time of 30 minutes. A net gain of welfare for both passenger type also takes place.

Another interesting combination of policies is the application of an (air) environmental tax together with an increase in Eurostar service frequency. The effects of these two measures on the overall level of demand are indeed opposite. On the one hand, the higher the environmental tax the greater the repression of the overall demand. On the other hand, increasing HSR frequency stimulates increased demand. Considering the joint application of these measures it is therefore possible to identify the combination of increase in HSR frequency and amount of the environmental tax to levied that keeps the overall level of demand unchanged, thus ensuring that all the reduction in air passengers is diverted (compensated) to the HSR (by an increase of HSR passengers). This optimal combination is represented by 9 daily HSR connection and an environmental tax of about £15. Under this condition, about 364,000 passengers would cease to travel by air and diverted to HSR. However, it is worth mentioning how this combination, albeit ensuring a stable level of the demand, would erode leisure passenger welfare by about 5%, while increasing business passenger welfare by 24%, thus leading to significantly different impacts on the different type of passengers. Furthermore, as mentioned, this combination keeps the overall level of demand unchanged, and there is no guarantee this combination of tax and frequency actually maximizes overall welfare. The theoretical derivation of an optimal tax and frequency is beyond the scope of the current paper.

Lastly, the current critical situation in terms of queues, delays and cancellation experienced at several European airports as of spring 2022 opens up the opportunity to investigate the potential impacts on the overall level of demand as well as on air-to-rail diversion that the continuation of these circumstances could unleash. The impact of these circumstances on the convenience of air transport over HSR is twofold. First, the situation of uncertainty undermines the perceived reliability of air travel (compared to other transport modes) due to frequent cancellations of flights. Second, queues caused by staff shortage disadvantage air transport over HSR owing to the need for air passengers to arrive earlier to the airport for check-in and security checks. The size of these disruptions is constantly evolving and varies greatly on a daily basis and at the airport level. In this paper, we test different increases in the amount of time in advance passengers have to arrive at the airport (compared to the base values presented in sub-Section 6.3.2). Results of this scenario are described in Table 6.10. For instance, an increase of the airline departure waiting time by 30 minutes would cause a contraction by about a quarter of the airline traffic (almost 1.2 million passengers). Part of this reduction would be diverted to HSR transport (176,000 passengers), which would gain market share up to about 16.7% (+7%). Even greater impacts are expected in the event of a 60-minute time increase. In this case, the decrease in air traffic is estimated at over 2 million passengers and the gain in HSR's market share at +17.1% (for an overall market share of 27%). Note that the effects of

Increase air departure waiting time (min)	HSR market share	Δ% overall demand	Δ % HSR traffic	Δ % air traffic	Diverted demand	Reduced demand	Δ % welfare leisure passenger	Δ % welfare leisure passenger
15	12.87%	-10.65%	15.75%	-13.56%	80,167	545,559	-23.55%	-44.34%
30	16.67%	-19.79%	34.56%	-25.78%	175,937	1,013,825	-41.15%	-67.60%
45	21.41%	-27.57%	56.10%	-36.80%	285,580	1,412,316	-54.35%	-79.94%
60	27.05%	-34.12%	79.35%	-46.64%	403,890	1,748,106	-64.26%	-86.58%

Table 6.10: Simulation output assuming different increase in the air departure waiting time.

increased travel time by air on HSR market share is larger than the effect of a ticket tax. The queues at the airports, unwanted and undesirable for various reasons, do have a positive effect on HSR ridership, and more so than a ticket tax to increase the relative price of the aviation alternative. Drastic reductions in the welfare of both passenger characteristics emerge. These effects are obtained by assuming that negative contingencies persist throughout the year. Lower estimates are obtained by assuming that these effects only affect the spring and summer traffic peaks.

Overall, HSR service frequency and travel time emerge as the main levers able to stimulate diversion between air and HSR, resulting in a significant increase in HSR market share in the market between London and Amsterdam. Conversely, policies based on the introduction of (air) environmental taxes or reductions in HSR fares appear to be effective only if adequately complemented with improvements in HSR service characteristics. Lastly, in case the current difficult situation experienced by European airports (above all Amsterdam Schiphol and London airports) and airlines due to severe staff shortages in post-pandemic recovery will continue, aviation traffic would experience a conspicuous downsizing and HSR might benefit a significant boost in terms of traffic.

6.6 Conclusions

This paper analyzed the potential of the HSR alternative in the London-Amsterdam market. Eurostar has been offering services in this market for a few years, and since HSR is mentioned as a "cleaner alternative" to aviation because GHG emissions are lower, important questions therefore concern the best leverages to act on to enhance the HSR market share. This paper studied the impacts of a possible air ticket tax, a price reduction/increase in HSR frequencies, a reduction in HSR travel time, and an increase in air travel time, following the recent events at, for example, Amsterdam Airport Schiphol, where long queues appeared owing to staff shortages.

A ticket tax of £20 (similar to that proposed by the Dutch government) results in a decrease in air traffic of 4.5% (-210,000 passengers), with a significant decrease also on overall market demand (-3.7%). Only about 8% of the reduction in air passengers would be diverted to HSR (whose market share thus increases only marginally), while the remainder would cease to travel. Accordingly, the application of a ticket tax appears, at first instance, to be only moderately effective, or maybe even ineffective in increasing HSR market share. The increase in air fares leads to a decrease in passenger welfare, especially for the more price-sensitive leisure passengers.

A decrease of the HSR fare, to reduce the relative price difference between modes, of £20 results in an increase in HSR traffic of 41,500 passengers (+8.1%). Only 16,750 of these passengers are diverted from air to rail. The remainder are new (stimulated) travelers. This policy measure has a somewhat more pronounced effect compared to the ticket tax, but the overall effect on HSR market share is still relatively small.

An increase in Eurostar frequency to 5 daily trains, already planned before COVID-19 pandemic by HSR operator, would increase HSR traffic by about 161,00 passengers (+32%), reaching a market share of 12.9%. A further increase to 10 daily connections would increase HSR ridership to 387,000 passengers, of which more than 228,000 would be diverted from air alternatives. Impacts in terms of passenger welfare are positive, especially for business passengers, who are more sensitive to frequency.

A change in relative travel times potentially has a, relatively speaking, bigger effect. A decrease of HSR travel time by 30 minutes, which could be achieved if less time is needed for immigration, would increase the HSR market share by 7% compared to the 2019 levels. An increase of the airline departure waiting time by 30 minutes causes a decrease of about 25% in airline traffic (almost 1.2 million passengers). Part of this reduction is diverted to HSR transport (176,000 passengers), which gains market share up to about 16.7% (+7%). A 60-minute time increase decreases air traffic by over 2 million passengers, and the gain in HSR's market share is at +17.1% (for an overall market share of 27%).

From a policy perspective, it therefore seems the relative travel times offer the quickest opportunities to increase HSR-ridership, if such an increase is desired. Finetuning immigration checks and train schedules could lead to an increase in HSR-market share, and likely this increase will be higher than the increase following the ticket tax. The recent queueing at airports, following staff shortages, potentially has an upward effect on HSR market share. Solutions for the queues (and staff shortages) should also be looked for in the HSR alternative in the market under consideration, and in other markets where a train alternative is feasible.

Unfortunately, no information about Eurostar load factors are publicly available. Thus, it still remains to be evaluated whether the potential demand shift from air to HSR can be accommodated while keeping the current HSR frequency stable. The same applies for the evaluation of the possibility to increase Eurostar frequency given the limited capacity of railway infrastructure and the congestion of the core of Europe’s rail network.

The research agenda derived from this paper is as follows. The ticket tax now is treated as a general tax. Although it may be for environmental reasons, no effort is made (at least in this paper) to derive a welfare maximizing tax on CO_2, and fuel use, or to internalize congestion. The taxes used in the current paper follow taxes observed in reality in the market under consideration, with a sensitivity analysis showing the effects of a higher or lower tax. In follow-up research, an actual “optimal” tax can be derived. Furthermore, the welfare effect of the different policies considered in the current paper is limited to passengers. To follow-up, the effect on airlines, HSR operator, and the environment should be considered. In the current work, an optimal fare or frequency are not derived, and therefore the effect of a tax on firm behavior and overall welfare is hard to determine. Our study, however, shows the effect of the various policy measures on demand, market share, and consumers' welfare, and proposes that changes in relative travel times and HSR frequency likely have the strongest effect on market share.

Chapter 7 – General conclusions

This thesis dealt with the topic of air-to-rail modal shift as a policy with the potential to contribute reducing GHG emissions from aviation. Together with the recovery of traffic following the COVID-19 pandemic, sustainability is the main challenge the aviation industry faces nowadays. The high growth rates experienced over the recent decades are indeed no longer sustainable in light of the need to completely overhaul the impact humanity has on our planet's climate. In this regard, several initiatives have been recently implemented at different levels to stimulate a reduction of aviation emissions. Focusing on short- and medium-haul routes, which obviously account for only a portion of the aviation industry's overall emissions, the promotion of air-to-rail substitution, plays a pivotal role towards sustainability goals. However, to date, despite claims and different initiatives advocated or implemented, an extensive substitution between HSR and air at the European level is still far from being achieved. The contribution of this thesis to the emerging stream of research concerning multimodal competition is twofold. First, an innovative methodological approach to deal with jointly modeling demand distribution and generation in a multimodal context has been proposed. Second, a comprehensive evaluation of the possibilities of substitution between air and rail at the European level as well as the assessment of the effectiveness and the impacts of different policy initiatives in this direction has been conducted. All in all, the three contributions constituting this manuscript adopt different perspectives to provide compelling evidence for both researchers and policymakers interested in understanding and incentivizing modal shift dynamics.

Chapter 4 provided a first attempt to map at the European level the current degree of substitutability between air and rail transportation. Specifically, following recent policy initiatives implemented by France and Austria and considered by other countries such as Germany and Spain, the contribution assessed the extent of a possible ban on short-haul flights if train alternatives are available. Route substitutability has been primarily evaluated based on the increase in travel time faced by passengers due to the enforced modal shift, ultimately decoupling the analysis from currently offered services (in terms of frequency and capacity) and providing an assessment of potential substitutability considering the current infrastructure provision. The results revealed that, considering the current infrastructure network, only 52 routes (less than 1% of intra-European air routes) can be replaced by a viable alternative that does not cause significant increases in travel times. Air capacity on replaceable routes accounts for about 3% of intra-European offered seats in 2019 and the potential environmental benefit of closing these connections is quantified in about 1.3 million tons of CO_2 (-2%). These statistics increase to 116 routes, 7.2% of offered seats, and 3.1 million CO_2 tons considering routes with alternative connections that guarantee travel time increases up to 20%. All in all, this evidence pinpoints how, net of the investments focused on the extension of the HSR rail network on a continental level already implemented, a further significant effort is required to meet the EC target of converting the majority of short- and medium-haul passengers to rail by 2050. In this regard, the most complete and rapid implementation of the Trans-European Transport Network (TEN-T) in all its steps, namely the core network (to be completed by 2030), the extended core network (by 2040), and the comprehensive network (by 2050), needs to be supported. Indeed, the transition towards a comprehensive network, connecting not only the large European capitals, plays a crucial role in providing a viable alternative to air transport even for connections between medium-sized cities whose market over recent decades outlined a high permeability to the advent of low-cost carriers. Considering the potential replacement of short-haul routes feeding long-haul connections at major European hubs (e.g., AMS, FRA, and CDG), the implementation of direct connections between HSR network and airports is crucial as well as offering passenger integrated services such as coordinated baggage handling and integrated ticketing. Alongside infrastructure development, policymakers need to conduct careful assessments of the alternative transport modes' capacity and promote competition within the railway industry. In this respect, two goals have to be achieved. On the one hand, establishing on-track competition between different rail providers to promote both cost efficiency and service quality. On the other hand, the increase in the number of supranational routes served by efficient HSR connections that potentially may constitute a significant key to the substitution of a large share of short- and medium-haul air flights. Finally, it is worth mentioning how the construction of new HSR lines requires considerable monetary resources as well as generates significant emissions. Adopting a life-cycle perspective, the implementation of such investments appears justified only on particularly dense routes where diversion from more polluting transport modes is significant. The substitutability of thin routes, including regional ones, rather than through rail infrastructure development can instead leverage new technologies such as electric aircraft that are expected to provide zero-emission solutions in the short/medium term.

The second and the third contribution (Chapter 5 and Chapter 6) dealt with modeling passenger choice and demand generation in a multimodal context by leveraging the innovative methodological approach. While Chapter 5 is more focused on modeling and analyzing demand stimulation effect (induced demand), Chapter 6 is more related to potential modal diversion dynamics.

More in detail, Chapter 5 investigated how variations in supply characteristics affect demand distribution and contributes to stimulating or reducing overall demand in the multimodal passenger market between London and Paris. The results confirmed the importance of travel times, fares, and frequencies on passenger modal choice. As regards the overall level of demand, the study identified how overall demand depends on both socio-economic characteristics of connected zones and the qualitative level of supply. Considering the latter, we extrapolated how supply variation of both air and HSR alternatives may contribute to inducing or reducing the overall demand. More in detail, focusing on the HSR alternative, we found that *ceteris paribus* a one-trip increase in the daily frequency of Eurostar connection would stimulate demand for more than 94,500 passengers per year (2.3% of current ridership), while infrastructural investments aimed at reducing HSR travel time by 10 minutes would increase current passenger flows by about 1.3%. Eventually, the study analyzed the demand implications of a possible policy of ending air routes for environmental purposes as well as possible compensation mechanisms that HSR providers could implement to prevent the detrimental effects on passengers resulting from such a policy. The empirical analysis outlined that the cancellation of all air connections in the market under analysis would result in a reduction in 2019 demand of about 6% (about 240,000 passengers). However, HSR service providers could mitigate the reduction in service levels resulting from such a policy by increasing service frequency. Overall, the contribution confirmed the importance for policymakers, when dealing with policies aimed at encouraging modal shift, of taking into account trip generation patterns that could potentially offset the effects of the pure modal substitution. Besides, the analysis revealed the impact that policies to incentivize air-to-rail modal shift would have on passengers' welfare, thus suggesting to policymakers the importance of implementing compensatory mechanisms to ensure the level of service for passengers. For the market under consideration, a substitution rate between new HSR daily connections and air flights canceled of 0.12 was estimated. Yet, this value would increase whether the antitrust and regulatory authorities fail to mitigate the possible fare increase resulting from the market concentration. This, once again, highlights the leading role played by regulators in stimulating competition within the railway industry.

Lastly, Chapter 6 explored possible tools to increase the HSR market share. More in detail, the contribution assessed the effectiveness of different initiatives aimed at encouraging the use of HSR on the London-Amsterdam route, both examining their potential to stimulate air-to-rail diversion and their impacts on passengers' welfare. The results found policies leveraging on the relative air-rail price difference, such as the reduction of HSR fares and the application of an air ticket tax, ineffective in increasing HSR market share, if not adequately supported by improving HSR service. Conversely, leveraging on HSR frequency and travel times has been identified as the best opportunity to increase HSR ridership. The increase of HSR frequency to five daily trains has been estimated to deliver an increase in HSR traffic by about 161,00 passengers (+32%), of which more than 94,000 (about 58%) diverted from air alternatives. The resulting HSR market share has been quantified at 13%, raising to 17% in case of an increase to 10 daily connections. Besides, the analysis estimated an increase of HSR market share by 7% compared to the 2019 levels in case of a decrease of HSR travel time by 30 minutes which could be achieved if less time is needed for immigration controls. Lastly, relevant impacts have been estimated in terms of reduction of air traffic and diversion toward HSR in case of continuation of the current situation of queues and staff shortages experienced by many European airports since April 2022. For instance, a relevant increase of HSR market share (+7%) has been estimated in case an increase in departure waiting time of 30 minutes becomes structural. All in all, from a policy perspective, the analysis revealed leveraging the HSR level of service as the quickest opportunity to increase HSR ridership. It follows, the importance of both HSR comfort and, most of all, HSR travel times and frequency. Minimizing waiting times and increasing connection frequency may in fact partially offset the higher average speed of air travel compared to HSR, thus boosting its attractiveness. At the same time, the introduction of an air environmental tax and, more in general, acting on relative prices, need to be considered rather than stand-alone solutions, as a complement to the previous measures. Finally, HSR mode, both in the short and long term, should also be considered as a possible solution for the queues and airport congestion. This solution requires direct interconnections between HSR network and the airports (to allow passengers an ease transfer) as well as the offering of integrated tickets and integrated baggage transfer from origin HSR station to the final destination. Furthermore, it is useful to note that the use of HSR as feeder may lead to increased emissions at the airport-level due to the introduction of new long-haul routes. This phenomenon needs to be appropriately monitored to avoid negative environmental effects.

Collectively, the three works contributed to the current literature from both a methodological and a practical point of view. From a methodological perspective, the integrated approach developed in the present thesis represents an advancement in methodologies for modeling supply-demand interactions in a multimodal context. Specifically, it allows the accurate estimation of demand induction or reduction effects based on both the characteristics of the available transport modes as well as the socio-economic characteristics of the connected zones. This approach overcomes the limitations of current models designed to estimate induced demand, which mainly relies on *ex post* counterfactual analysis comparing actual traffic after the entry of HSR (or modification in service characteristics) and the projected traffic as if HSR (or modification in service characteristics) had not been introduced. Furthermore, the innovative approach constitutes an important tool for policymakers to better understand demand diversion and induction dynamics. From a practical perspective, the present thesis outlined the potentialities of substitution between HSR and air transport at the European level and evaluates the effectiveness (and possible criticalities) of policy initiatives intended to stimulate air-to-rail diversion. Several insights for policymakers were also formulated. Specifically, the analyses pinpointed potential criticalities of each measure considering both the impact in terms of demand induction and diversion as well as the resulting impact on passenger welfare. The three main barriers to an extensive and successful air-to-rail modal substitution at the European level can be summarized as follows. First, availability of capacity on the HSR infrastructure to accommodate diverted passengers and related congestion issues. Second, integration of the HSR network with airports and provision of seamless intermodal services proposing integrated ticketing and integrate luggage handling to stimulate substitution of feeding flows at major European hubs. Third, careful identification of (dense) routes where to convey HSR investments and proposal for increasingly competitive services, also thanks to an increase of competition within railway industry.

Of course, the present work is not exempt from limitations that pave the way for future research directions. Besides specific aspects detailed in each Chapter, two are the major directions for future research efforts. First, except for the first contribution, other analyses focused on a single market and therefore suffer from a lack of generalizability. Further research may therefore extend the evaluation of policy initiatives' effectiveness on other routes at the European level, especially those that are already covered or will be served in the future by TEN-T corridors. Second, the effectiveness of initiatives aimed at stimulating modal shift was evaluated by considering passenger choice and traffic generation dynamics, essentially neglecting carriers' competitive reactions (in terms of price and frequency of service) following the implementation of such kinds of policies. Further research may focus on modeling firms' behavior identifying the optimal frequency and fare as well as the identification of the optimal taxation level that ensures the maximization of the overall (or local) welfare, including passenger welfare, companies' welfare, and external cost of pollution. A first theoretical attempt in this direction was presented in Chapter 3. However, considerable room for improvement in this direction remains with a multiplicity of potentially relevant aspects that still to be tackled.

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