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Research paper

Diverted and induced demand: Evidence from the London-Paris passenger market

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A B S T R A C T

The paper investigates passengers' preferences and demand induction (or reduction) patterns for the London-Paris passenger market. By leveraging an integrated model calibrated on an extensive dataset about passenger flows between London and Paris during the period 2009–2019, we investigate key dimensions by which travelers evaluate transport modes and how both socio-economic characteristics and supply-attribute variations contribute to stimulating or reducing the overall demand. The research confirms the importance of attributes, such as travel times, fares, and frequencies on passenger modal choice, providing some sketches about passengers' propensity toward air or high-speed rail (HSR) mode. Based on data in this study, we find that *ceteris paribus* 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 a reduction of HSR travel time by 10 min would increase current flows by at least 1.3%. Analyzing the demand implications of a possible policy of ending air routes for environmental purposes, we prove that the cancellation of air connections would result in a reduction of current demand higher than 6%. HSR service providers could offset the reduction in service levels resulting from air routes closure mainly by leveraging service frequency.

1. Introduction

Nowadays, competition between high-speed rail (HSR) and air transport is becoming fiercer. Over the last two decades, HSR networks 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 of railway stations to the city centers (Xia & Zhang, 2016; Zhang et al., 2019b). The introduction of HSR in such a type of routes 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). The implications of the HSR introduction are not limited to those on air transport supply but also cover the demand side. More in detail, besides the more straightforward diversion effect (i.e., attracting passengers who previously traveled by other modes), new HSR connections (or improvement of the existing ones) contribute to stimulating total demand, resulting in induced demand.

A further intensification of competition between HSR and air transportation will occur in the years to come. This is likely to be most evident in the European scene due to the ongoing EU climate policies and initiatives promoted by the European Commission (EC). EC's initiatives insist along two main directions. 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.[1] Considering the former aspect, the EC set the objective of tripling the length of the existing HSR network by 2030, promoting the connection of core airports to the rail network, preferably high-speed, by 2050 (EC, 2011). This network expansion will result in an increasing number of markets being subject to multimodal competition. As regards competition, instead, since 2001 the EU started the process of liberalization of the passenger railway market with the ultimate goal of establishing conditions, similar to what was done in the '90s with air transportation deregulation, for the development of a more efficient and competitive EU-wide railway network (Single European Railway Area).

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[1] European Council Conclusions of 3 June 2021, Putting Rail at the Forefront of Smart and Sustainable Mobility — https://data.consilium.europa.eu/doc/document/ST-9396-2021-INIT/en/pdf.

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On the other hand, to build a sustainable future, the EU has pledged to become climate-neutral by 2050. To this end, the EC in the European Green Deal has undergone a series of policies aimed at achieving the ambitious target of a 90% reduction in transportation emissions by 2050 compared to 1990 levels (EC, 2019). In this direction, the growing pressure to reduce aviation-related negative externalities has already resulted in a wide set of sustainability measures and policies including improvements in aircraft energy efficiency, new aircraft technologies (e.g., electric-powered aircraft), more efficient air traffic management (improvement of the Single European Sky), use of sustainable aviation fuels (SAFs), and modal shift initiatives. This last option (promotion of air-to-rail modal shift) gained momentum over the recent years as a measure with the potential of contributing to reducing the environmental impact of short- and medium-haul air routes. While emissions on these routes account for only a portion of the aviation industry's overall emissions, they are the ones that can be most easily reduced due to competition from alternative transportation modes (Chapman, 2007; Rothengatter, 2011). Recently, different European countries, such as France and Austria, have introduced specific regulations to ban short-haul internal flights on routes where train alternatives exist (Avogadro et al., 2021). Overall, both the prospects for the HSR network development and the need to reduce transportation emissions stand 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 toward either transport mode. Even more crucial is the estimation of the impact on demand resulting from changes in supply attributes. 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, only a few studies strived to explicitly investigate supply-demand interactions in a multimodal context. This paper complements the body of literature on air-to-rail substitution and induced demand by analyzing passenger preferences and demand induction (or reduction) patterns due to changes in the attributes of available travel alternatives for the London-Paris market. The final aim is to explicitly extrapolate the relationships between variations in supply attributes on both the air and HSR sides and fluctuations in the overall travel demand. With this aim, we formulated an aggregate nested logit model able to jointly model trip distribution and generation in an intermodal context taking a cue from the model adopted by Hsiao and Hansen (2011) and Wei and Hansen (2005) to estimate air transportation supply-demand interaction. The proposed methodological setting allows us to describe the competitive dynamics across different transport modes understanding passengers' preferences concerning supply attributes and providing some sketches about different propensities of passengers toward HSR or air transport. Furthermore, the integrated modeling approach making demand generation sensitive to supply variation, enables us to understand how both socio-economic characteristics and supply attributes contribute to capturing a higher or lower portion of potential travel demand (demand generation). Such a model is applied to estimate induced or reduced demand resulting from different scenarios concerning, for instance, changes in the attributes of single transport modes or market composition (i.e., entry or exit of an alternative). Lastly, we provide interesting insights in terms of compensation mechanisms that HSR providers, in cooperation with regulators, may implement to ensure the same level of service for passengers following the implementation of policy initiatives to promote air-to-rail modal shift.

The remainder of this paper is organized as follows. Section 2 frames the previous streams of research on competition between HSR and air transport and induced demand. Section 3 describes the integrated trip generation and distribution model formulation and estimation. Section 4 specifies the data sources and the data aggregation methodology, while Section 5 discusses the empirical results. Section 6 presents the outcomes of the scenario analysis simulating the impacts in terms of induced or dissuaded demand resulting from changes in supply attributes or the implementation of policy initiatives. Finally, Section 7 summarizes the main findings and suggests future research directions.

2. Literature review

Over the last two decades, the significant expansion of the worldwide HSR network from less than 6000 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 analyze the mechanisms of competition between different transport modes as well as the effects (substitution and induction) on the final demand following the introduction of a new HSR connection.

As regards the former aspect, previous studies pointed out strong competition between HSR and air transport in short-medium-haul markets (Givoni & Banister, 2006; González-Savignat, 2004). Specifically, HSR has been recognized as the dominant transport mode for travel distances between 300 and 800 km with attractiveness and market share gradually decreasing as travel distances and travel times increase (Dobruszkes, 2011; Román et al., 2007; Rothengatter, 2011). Various empirical assessments have been developed and implemented to investigate how different modes' attributes impact the choice of one or the other, resulting in heterogeneous market shares in different markets. Service frequency and the number of offered seats, as well as HSR average speed and travel time, are crucial factors affecting the outcome of air-HSR competition (Albalate et al., 2015; Castillo-Manzano et al., 2015; Dobruszkes, 2011; Jiménez & Betancor, 2012). 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) investigated how the introduction of HSR in this market affects passengers' preferences and consequently market shares of travel alternatives. The authors reported fairly constant customer preferences over the analyzed period identifying frequency, total travel time, and fare as the main determinants of passengers' choice. Lastly, the heterogeneous behavior of leisure and business passengers regarding these dimensions has been identified. To summarize, previous literature recognized travel time as the main factor in determining the level of modal diversion toward 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. For instance, both access and egress time, and waiting time at departure play a relevant role in passengers' choice between alternative transport modes.

Air-to-rail substitution measures are often promoted in an attempt to reduce aviation emissions.[2] One of the main statements to justify such policy refers to the *greenness* of HSR compared to air transport on a per-seat basis (see e.g. Jiang et al., 2021). Nonetheless, substitution to HSR can have different effects on overall CO_2 emissions (Jia et al., 2021). The most apparent reduction of emissions follows from modal diversion if HSR is a cleaner alternative to aviation. However, the introduction of HSR services does not necessarily lead to environmental advantages. Indeed, diverted demand toward HSR constitutes only a portion of the overall demand for a new HSR service. As a matter of fact, the introduction of a new HSR service (or the improvement of an existing one) also increases the total travel demand due to improved travel conditions (induced demand). The determinants of induced demand follow from

[2] Recent studies reported a positive impact of HSR not only on greenhouse gas emissions but also on air quality and urban carbon emission efficiency (Li & Cheng, 2022; Zhu et al., 2022).

the microeconomic theory, according to which any reduction in the cost of goods (in this case, the transportation service) leads to an increase in demand (Noland, 2001; Pagliara & Preston, 2013; Yao & Morikawa, 2005). The concept of induced demand encompasses a wide range of 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 regional development patterns. Over the years, both *ex ante* and *ex post* assessments have been developed to quantify the relative weight of diverted and induced demand stimulated by the introduction of HSR services. For instance, Givoni and Dobruszkes (2013) in a review of *ex post* studies after the introduction of HSR quantified induced demand in the range of 10–20%, while diverted demand from other transport modes in about 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 the diverse boundaries of the concept of induced demand considered. Demand induction (or reduction) 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. From an environmental perspective, modal shift to HSR may lower emissions, but if additional demand is accommodated using the available aviation capacity, overall CO_2 emissions may not decline, thus leading to a negative environmental effect (D'Alfonso et al., 2015, 2016). This negative effect could occur not only at the route level but also on other routes served by the same airport. First, air-HSR integration might impose a threat to the environment, as HSR tends to feed international flights which emit more than short-haul flights (Jiang & Zhang, 2014; Li & Sheng, 2016; Liu et al., 2019; Socorro & Viecens, 2013; Wan et al., 2016; Xia et al., 2019; Zhang et al., 2019b). Second, the integration between airlines and HSR is less likely to be environmentally beneficial if the airport is capacity-constrained. Substitution between modes in short-haul markets opens up slots that may be used elsewhere (Givoni & Banister, 2006; Socorro & Viecens, 2013). In this case, if slots released are used to accommodate more polluting long-haul flights, the environmental benefits of modal substitution may be reduced or erased.

Albeit the importance of estimating the magnitude of 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 policymakers to not consider these aspects when undertaking regulation initiatives (Zhang et al., 2019a). Some examples are proposed by Ben-Akiva et al. (2010), Cascetta et al. (2013), and Cascetta and Coppola (2014). More in detail, Ben-Akiva et al. (2010) estimated induced demand for the Naples-Rome corridor based on the relationship between existing HSR demand and current HSR travel times and costs, including as covariates socio-economic variables related to population and employment. Further, 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 by applying a trip-frequency model which estimates the probability that a user undertakes a given number of ex-province trips for a given purpose and in a specific period.

The main reason for the lack of explicit modeling of induced demand in a multimodal context can be attributed to the difficulty of disentangling via the traditional 4-step travel demand model the portion of new passengers traveling due to improved supply from the portion resulting from demand growth due to fluctuations in GDP and, more in general, to the macro-economic context (Kitamura et al., 1997). A possible solution to these problems is to jointly model trip generation and distribution in an integrated model able to capture the sensitivity of demand to supply attributes. By including an explanatory variable capturing the level of service into the generation model, trip generation will become sensitive to changes in service level. Therefore, at least short-term effects on demand can be estimated (Yao & Morikawa, 2005). Such a type of approach has recently received increasing attention in the field of air transportation to model supply-demand interactions. More in detail, several studies have adopted it leveraging integrated nested logit models (Birolini et al., 2020; Hsiao & Hansen, 2011; Wei & Hansen, 2005). In a multimodal context, only Yao and Morikawa (2005) proposed to introduce in the trip generation model an accessibility measure able to capture the short-run behavioral effects on demand generation.

Based on these premises, the contribution of this paper is twofold. First, borrowing from aggregated nested logit models previously applied to estimate air transportation supply-demand interactions, we propose an integrated methodological setting able to jointly consider demand generation and distribution in 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 the state-of-the-art procedure used by policymakers to estimate diverted and induced demand so far. Second, from an empirical perspective, we analyze passenger preferences and demand generation and degeneration dynamics in the multimodal passenger market between London and Paris. Accordingly, we 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 (induction or reduction) due to changes in the attributes of available travel alternatives. The findings about supply-demand interactions are then applied to provide evidence about the compensatory mechanisms that HSR providers may have to implement the in case of a complete withdrawal of short-medium haul air routes for environmental purposes to ensure passengers similar travel conditions.

3. Methodological framework

3.1. Model formulation

To jointly model trip generation and passenger modal choice in an intermodal context, we proposed a two-level aggregate nested logit formulation (Fig. 1), similar to that applied by Wei and Hansen (2005), Hsiao and Hansen (2011), and Birolini et al. (2020) to model air travel demand distribution and generation. The upper nest models the binary choice of whether or not to make a trip in sub-market *m* and period *t*.[3] The lower nest models passengers' choice among itineraries (i.e., the joint decision of the mode, route, and carrier). As such, this structure simultaneously describes the competition across different routes and transport modes (demand allocation) and how the socio-economic characteristics of origin and destination zones and supply-side attributes contribute to stimulating travel demand (demand generation).

The integrated trip decision-making process in submarket *m* and period *t* can thus be formulated as follows:

$$P_{i,mt} = P_{Travel,mt}\, P_{i|Travel,mt} \tag{1}$$

where $P_{i,mt}$ is the probability of choosing travel alternative *i* in submarket *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

[3] Within the no-travel option, we consider even passengers traveling using other transport modes (e.g., the combination of car and ferry) than those explicitly analyzed in the current paper (i.e., air and HSR). To practically estimate the model, within the overall market under examination (i.e., London-Paris) we consider different submarkets based on the departure zone in London and the arrival zone in Paris.

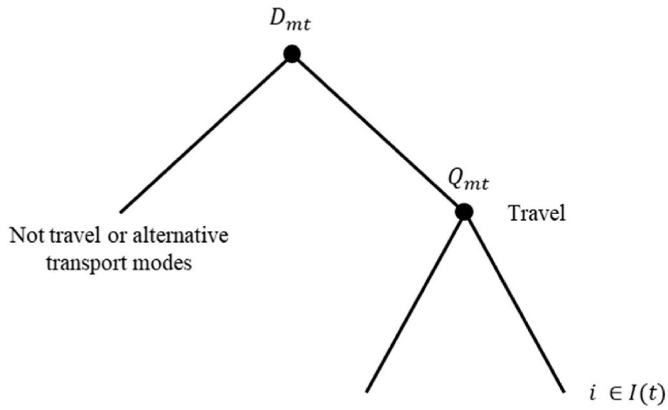

Fig. 1. Two-level nesting structure.

of alternative i in submarket m and period t, which can be defined as:

$$P_{i|Travel,mt} = MS_{i,mt} = \frac{\exp\left(V_{i,mt}\right)}{\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)} \tag{2}$$

where $I(t)$ is the set of available alternatives (choice set) in 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 submarket m and period t.

Considering the upper level, the number of passengers traveling in submarket m and period t (Q_{mt}) can be expressed as a share of saturated demand D_{mt}:

$$Q_{mt} = D_{mt}\, P_{Travel,mt} \tag{3}$$

The saturated demand (D_{mt}) represents the potential maximum number of trips in submarket m and period t, including either trip that are made by air and HSR or by other transport modes as well as those that could potentially be made but, due to lack of supply (i.e., high travel impedance), currently are not. The probability of deciding to travel ($P_{Travel,mt}$) depends on the compound utility of available alternatives in the travel nest and the utility of not traveling, with the latter representing the "outside option". Normalizing the utility of not traveling, $\overline{V}_{0,mt}$, to zero,[4] the passenger traffic flow in each submarket m and period t, Q_{mt},[5] can be expressed as:

$$Q_{mt} = D_{mt}\, P_{Travel,mt} = D_{mt} \frac{\left(\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)\right)^{\theta}}{1 + \left(\sum_{j\in I(t)} \exp\left(V_{j,mt}\right)\right)^{\theta}} \tag{4}$$

where $\sum_{j\in I(t)} \exp(V_{j,mt})$, is the log-sum term, hereinafter denoted as LoS (level of service), which measures the aggregate utility provided by travel alternatives of the lower branch. θ is the nesting coefficient, measuring 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).[6] The larger the nesting coefficient, the greater the sensitivity of total demand to changes in supply attributes.

Assuming that the actual demand (i.e., part of the demand that is met) is far less than the overall saturation demand (Wei & Hansen, 2005),[7] the formulation of Q_{mt} can be approximated to:

$$Q_{mt} \approx D_{mt}\, Los_{mt}{}^{\theta} \tag{5}$$

Saturated demand and, more in general, intercity travel demand is typically modeled 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 saturated demand according to these specifications, the total demand in submarket m and period t can be expressed as:

$$Q_{mt} = \exp(K_{mt})\, Pop_{mt}{}^{\rho}\, GDP_{mt}{}^{\delta}\, Los_{mt}{}^{\theta} \tag{6}$$

where K_{mt} is a set of time (quarter dummies) and market-specific constants. Pop_{mt} and GDP_{mt} are the geometric mean of origin and destination zones' population and pro-capita GDP, respectively. Total demand in a specific submarket and period is therefore modeled as a function of demand-side attributes and a composite measure of the characteristics of the transportation services offered (supply-side attributes such as the availability and quality of the travel options). 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 attributes and those that are liable to population and GDP fluctuations. Ultimately, it ensures to estimate demand generation and degeneration effects following variations in supply attributes.

3.2. Model estimation

Nested logit models can be estimated either simultaneously using maximum likelihood techniques or sequentially by decomposing them from the bottom to the top level into simple multinomial logit models. Albeit the simultaneous approach has been recognized to be more efficient, the sequential approach ensures consistent estimates and represents the base strategy for estimating nested logits when dealing with aggregate data (Allenby & Rossi, 1991; Forinash & Koppelman, 1993; Train, 2003). Coherently with previous studies estimating aggregate nested logit models in an aviation setting (Birolini et al., 2020; Hsiao & Hansen, 2011; Wei & Hansen, 2005), the sequential approach has been adopted in the current study.

To practically estimate the two-level aggregated model, the deterministic utility function of a passenger traveling with alternative i in submarket m and period t needs to be specified. For the purposes of this paper, $V_{i,mt}$ is defined as:

$$V_{i,mt} = \alpha ln(freq_{i,t}) + \beta\, PPM_{i,t} + \gamma\, TT_{i,mt} + \tau fare_{i,t} \tag{7}$$

Adopting this formulation, passenger choice is modeled based on the average weekly frequency ($freq_{i,t}$), the average on-time arrival ($PPM_{i,t}$), the total travel time ($TT_{i,mt}$), and the average fare ($fare_{i,t}$). Due to the expected diminishing returns in incremental service utility from an additional connection, the average weekly frequency has been included in the utility function using the logarithmic form (Hansen, 1990). This formulation has been recognized as the most suitable for characteristic

[4] 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).

[5] The total number of passengers traveling in period t from London travel facilities to Paris can be derived as $Q_t = \sum_{m\in M} Q_{mt}$, where M is the set of submarkets composing the overall market under examination.

[6] θ coefficient can be used to determine whether the nested logit model is consistent with utility-maximizing behavior (Train, 2003). When θ is equal to 1, the substitutability is perfect within the nest and the model reduces to an unnested model (Berry & Jia, 2010). Otherwise, for $0 < \theta < 1$, the total market demand is sensitive to the service level but less than in the unnested model.

[7] This assumption enables to simplify the trip generation model, allowing its estimation via log-linearization of the Cobb-Douglass function.

capturing the size of an aggregated alternative (Ben-Akiva & Lerman, 1985). Thus, this variable allows us not only to model the impact of service frequency on passenger mode choice but also to indirectly internalize the effect of on-board seat capacity. Average on-time arrival represents the so-called Public Performance Measure (PPM), a common indicator used in aviation and rail transport to determine the percentage of on-time arrival (defined as flights or trains arriving less than 15 min late compared to the scheduled time). Although some studies have suggested that passengers may not be fully informed about punctuality, PPM has been included in the deterministic utility function as it is a core feature that cannot be disregarded in the specification of mode choice models (Bates et al., 2001; Hensher & Li, 2012; Li et al., 2010; Schefer et al., 2020). Specifically, over the recent years, different qualitative and attitudinal studies on travel choice behavior have found that punctuality and reliability of a transport mode significantly affect carriers' reputation and passenger modal choice.[8] This is particularly true for business passengers who associate high values to travel time and punctuality since they are interested in reaching their destination in the most efficient way. Total travel time is the sum of four components: on-board travel time, departure waiting time,[9] access and egress time, and expected delay. Fare is the average price paid by a passenger traveling with alternative i in period t. The average fare is needed to fully model the average utility of alternative i because in our model consumers choose an aggregate travel alternative i and not a specific flight/train or seat. The use of the average fare rather than the flight/train or seat-specific fare, as well as its aggregation along a given time period, reduces the dependence on the overall level of demand, thus dampening the potential supply endogeneity issue.[10]

Considering Equation (2) and the aggregate nature of the model, the difference between logarithms of market shares of two alternatives i and j can be expressed as follows:

$$\ln\left(MS_{i,mt}\right) - \ln\left(MS_{j,mt}\right) = \boldsymbol{\vartheta}\left(\boldsymbol{X}_{i,mt} - \boldsymbol{X}_{j,mt}\right) + \varepsilon_{ij} \quad i,j \in I(t) \tag{8}$$

where $\boldsymbol{X}$ is the vector of alternative-specific components of the deterministic part of utility, $\boldsymbol{\vartheta}$ is the vector of coefficients in Equation (7) to be estimated, and ε_{ij} is the difference between the unobserved utility components of alternative i and j. The parameters of interest can be estimated by regressing this log-linear format of the market share model on the difference in attribute variables of two alternatives of the same submarket and period (Berry, 1994). Alternative-pairs need to be identified before running the regression. Following an approach similar to Hsiao and Hansen (2011), we randomly pick for each analyzed submarket and period one alternative within the choice set as base alternative for the others. 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. Therefore, our model was estimated separately for the two passenger groups.

Based on the estimated trip distribution model, the LoS measure for each submarket and period can be computed and entered into the trip generation model. Trip generation model parameters are then estimated by linearizing the Cobb-Douglass demand function by applying the logarithmic operation to both sides of Equation (6). The resulting log-linear travel demand model is estimated via ordinary least squares regression (OLS) considering the total amount of passengers traveling during each period t in submarket m.

4. Empirical setting

Our research focuses on the London-Paris passenger market. More in detail, our attention is paid to origin-destination passengers traveling between the Greater London Area[11] and Paris over the period 2009–2019. As already mentioned, the London-Paris represents a unique case study as it was one of the first markets at the European level to highlight intermodal competition between HSR and aviation. 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 (Eurostar) operated via the Channel Tunnel since 1994.

To practically estimate the proposed integrated model, defining a territorial aggregation level is required to compute the market share of the single alternatives accordingly, as well as the overall passenger flows in each period. For the current paper, within the overall passenger market between London and Paris, we identified different submarkets based on the departure/arrival zone in the UK. Specifically, by breaking down the Greater London Area into 21 zones according to International Territorial Levels (ITL) classification[12] level 3, we analyzed the passenger flows from and to each ITL London area. Due to the lack of specific information about the passengers' departure zone or final destination in Paris, we assumed that the origin/destination of passengers using Paris HSR station and airports is located within the Paris Urban Area.[13] Therefore, in this study, a submarket represents the passenger flow between a single London zone and Paris Urban Area. The following subsections describe the data used to estimate the proposed two-level aggregate nested logit formulation. Specifically, a comprehensive dataset on passenger flows and supply characteristics was assembled from multiple data sources.

4.1. Data collection

4.1.1. Passenger flows

Data on passenger flows between London and Paris were collected from the International Passenger Survey (IPS), a continuous survey carried out by the UK Office for National Statistics (ONS) providing information on the numbers and types of passengers traveling to and from the UK by air, sea, or the Channel tunnel. The data collected include travelers' socio-demographic characteristics, details of the travel arrangements used, such as departure and arrival travel facilities (i.e., airport or railway station) and carrier, the trip purpose, and the fare paid. Based on field interviews, the UK ONS applies a weighting procedure to yield reliable estimates of route-level traffic for each sampling

[8] For instance, Chen and Chao (2015) found that punctuality is one of the most important factors for passengers when choosing an airline. Considering a multimodal context, punctuality has been investigated also in the previous study focused on the London-Paris passenger market by Behrens and Pels (2012).

[9] 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 control activities.

[10] The Durbin-Wu-Hausman specification test has been conducted to evaluate potential endogeneity in the sample using oil price as an instrument for the average fare. The null hypothesis that average price is not endogenous for both leisure and business passenger models is accepted by the test. The p-values of the Hausman test of 0.444 for leisure and 0.987 for business passengers, much higher than the usual critical significance level of 0.1, confirm that there is no evidence of endogeneity in our sample.

[11] The Greater London Area is an administrative area around the city of London covering 1572 km^2 with nearly 9 million inhabitants in 2019 — https://www.ons.gov.uk.

[12] 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.

[13] 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.

Table 1
Number of observations per year, alternative, and type of passengers. Market shares computed considering the IPS weights in brackets.

	QQS-XPG-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
Leisure									
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)
Business									
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)

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.

period. 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. Furthermore, we excluded observations concerning air passengers claiming to travel through London and/or Paris airports for a connecting flight. The sample assembled according to these specifications consists of 9655 leisure and 3570 business observations. Considering the weight associated with each observation, the sample covers around 13 leisure and 4.6 business million passengers. Passengers traveling to/from the London Greater Area account for around 39.1% of leisure and 44.1% of business passengers traveling through London airports and HSR stations. Table 1 reports the number of observations per year, alternative, and type of passengers. Both leisure and business markets are largely dominated by Eurostar with a market share of almost 89%. The market share of full-service carriers (FSCs) is about 10% for business passengers while it is lower (6.6%) for leisure ones. Finally, low-cost companies (LCCs) hold a marginal market share for business (1.6%) and a more significant one for leisure passengers (4.2%).

4.1.2. *Supply characteristics*

Supply characteristics of available aviation and HSR connections between London and Paris were collected from several secondary sources. The average weekly frequencies and on-board travel times were gathered from the OAG Schedule Analyzer database for the air alternatives, while HSR's ones from official timetables published by Eurostar. The departure waiting times (i.e., time in advance with which passengers are advised to arrive at the airport/station with respect to the scheduled time) were collected from the carriers' website. Air France and British Airways indicate 60 min, easyJet and Vueling 40 min, and Eurostar 30 min. On-time punctuality data were provided by the Civil Aviation Authority[14] and the Eurostar press release, respectively. In addition to on-time punctuality data, average delays were also collected for air routes. Average fares paid per passenger type and alternative were computed considering the fare indicated in the IPS questionnaire responses. Lastly, access and egress times from HSR stations and airports were collected using the multimodal search engine Rome2Rio.[15] On the London side, we consider 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). Considering Paris, we compute the population-weighted average access/egress time by car from the single HSR station and airport to Paris Urban Area. All supply characteristics were collected on a quarterly basis, apart from Eurostar on-time punctuality data that are provided on a yearly basis.

Table 2 reports the average weekly frequency and the average scheduled main mode travel time (i.e., sum of on-board travel time and departure waiting time) per alternative and year. Over the period 2009–2019, the London-Paris market was highly dynamic. For each analyzed 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 British Airways and Air France and that operated by easyJet from LTN) have been continuously operated throughout the analyzed period. These connections also exhibited the highest and most stable weekly frequencies. Two new connections offered by the LCCs easyJet and Vueling have been in operation since 2014 and 2015, respectively. Conversely, the alternative to ORY from LCY operated by Air France ceased in 2017. Shortly after, this connection has been reactivated by British Airways. Looking at HSR services, Eurostar over the entire period offered significantly higher frequency (slightly declining since 2017) compared to the single air alternatives. The main mode travel times, including on-board travel time and departure waiting time, were quite stable over the years. Eurostar connection has a significantly longer on-board travel time than air alternatives, nevertheless, this is partially offset by the shorter departure waiting time (no security control required). Air connections exhibit similar on-board travel times and differ mainly due to the heterogeneous departure waiting times passengers are advised to arrive at the airport. Considering access and egress times, the HSR connection benefits from the location of railway stations closer to city centers than airports.

Fig. 2 shows the average fare paid by respondents per year, carrier

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

[15] Rome2Rio — www.rome2rio.com.

Table 2
Average weekly frequency and scheduled main mode travel time (sum of on-board travel time and departure waiting time) per alternative and year.

	QQS-XPG-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
Average weekly frequency									
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									
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

type, and passenger type. The Eurostar fare was generally lower than FSCs' one for both categories of travelers, but higher than the low-cost one. As regards FSC, prices for leisure travelers were more volatile than the business fare, which appeared quite stable except for the period 2012–2013. Additionally, 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 offered by easyJet from LTN.

4.2. 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 described in Section 3. As already mentioned, the overall market between London and Paris was divided into different submarkets, 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. Passenger flows were aggregated considering a quarterly granularity over the period 2009–2019. As such, for each submarket, passenger type, and period (i.e., quarter), the number of passengers traveling using each alternative was estimated by aggregating the selected IPS observations. The market share of the single alternative was then derived considering the total flow of passengers of a given type in each submarket and period.

The estimation of the trip distribution model is possible considering the functional form of the deterministic utility adopted (Equation (7)). While weekly frequency, average on-time arrival (PPM), and average fare directly derive from supply characteristics data described in the previous subsection, travel time is estimated as the sum of four main components: scheduled on-board travel time, departure waiting time, access and egress time, and finally expected delay. This last term was computed as the product of the average delay in minutes and the percentage of delayed trains/flights (i.e., 1-PPM).[16] The trip distribution model is estimated 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 submarkets where only one alternative was sampled by the IPS survey in a quarter (and accordingly 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 in the choice set.[17]

The utility functions estimated for leisure and business passengers allowed the LoS measure to be calculated for each submarket and period. This measure integrates the utilities provided by the individual alternatives within the passenger's choice set and represents a composite measure of the travel impedance in a specific market and period. The LoS measure together with the total number of travelers of each type traveling in each submarket and period enables the estimation of the trip generation model. The parameters of the Cobb-Douglass travel demand function were estimated for each passenger type by regressing the total passengers flow in each quarter and submarket 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 (i.e., LoS). While the latter was directly obtained from the trip distribution model, the former was explicitly collected. Population and GDP per capita for each ITL zone of the Greater London Area were gathered by the UK Office for National Statistics (ONS).[18] Values of the 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[19] statistics. In addition to the constants described in sub-Section 3.2 to model the seasonal effect throughout the year (quarter dummies), 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

[16] Since Eurostar does not make public 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 min.

[17] 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.

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

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

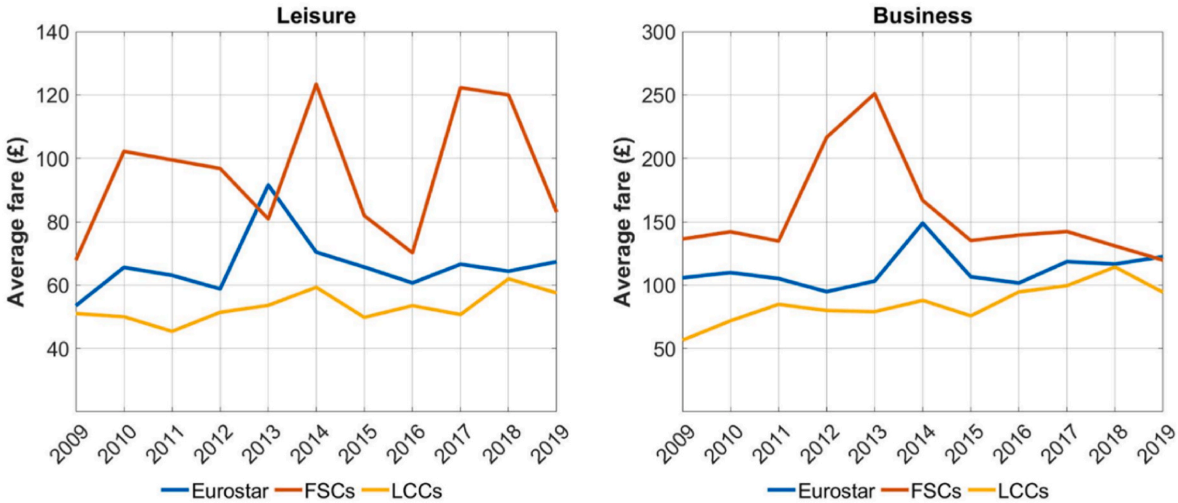

Fig. 2. Average fare paid by respondents per year, carrier type, and passenger type.

Kingdom's exit from the European Union (EU).[20] The literature suggests that specific events can significantly influence travel choices (Arentze & 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 & 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.

5. Empirical results

5.1. Trip distribution model

Table 3 reports the estimated coefficients and robust standard errors for the trip distribution model. The model was estimated separately for business and leisure passengers. To highlight potential heterogeneity in passenger modal preferences, in addition to the base model, a model estimated only on differences in air alternatives' market shares was structured. This second approach, differently from the base model described in Fig. 1, explicitly models in the "Travel" nest only air alternatives, considering HSR mode within the "Not travel or alternative transport modes" branch. This second model allows us to provide a more accurate proxy for passengers' sensitivity to the attributes of the air alternatives. The comparison of base model estimates and those of the model focused only on air alternatives ultimately enables us to pinpoint different propensities of passengers toward air or HSR mode in a multimodal context.

Considering the base model, the coefficients of the average fare, PPM, and average weekly frequency are significant for both trip purposes. Contrariwise, the estimated coefficient for travel time is significant for business passengers, while turns out to be not significant for leisure trips. Notably, the same results emerged from the previous study by Behrens and Pels (2012) focused on the multimodal market between London and Paris considering both a multinomial and a mixed logit model specification. Thus, we confirm that leisure passengers in the specific market are not sensitive to the overall travel time. The estimated coefficients are consistent with those reported in previous transport mode choice studies.[21] 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 PPM, our model returns statistically significant and positive coefficients for both types of passengers, thus confirming the high relevance of punctuality in passenger mode choice (Bates et al., 2001; Hensher & Li, 2012; Li et al., 2010). In magnitude, consistently with the higher value of time and the importance of travel time reliability, the sensitivity toward punctuality of business passengers is greater than for leisure ones (Chen & Chao, 2015). 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. This finding highlights substantial stability in passengers' preferences regarding these attributes over time. A separate discussion should be made for the comparison of the coefficients for the average weekly frequency and on-time arrival performance. Regarding the former, the coefficients in our model are higher in magnitude. This can be traced back to an increase in passengers' sensitivity to service frequency. However, it should be noted that this difference could also derive from the alternative specific constants that in Behrens and Pels' model partially internalized the effect of frequency. On the other hand, considering on-time arrival punctuality, the model calibrated for the period 2003–2009 provided positive and, contrary to our estimates, higher coefficients for leisure passengers than those for business ones. Yet, 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 passenger choice between air alternatives. This second model provides an estimate of the attitudes of each passenger category (business or leisure) about the attributes of air alternatives. Any differences between these estimates and the previous one (i.e., base model) can be

[20] The 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.

[21] The value of time estimated for the model where travel time and fare are both statistically significant (i.e., business passengers model) is consistent with the upper bound of values reported in studies in the existing literature (see e.g. Wardman et al., 2016). More interestingly, the estimated value of time is of the same order of magnitude as that reported in the previous work focused on the London-Paris passenger market by Behrens and Pels (2012).

Table 3
Estimation results for the trip distribution model.

	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 (£)	−0.0170***	0.0015	−0.0072***	0.0009	−0.0140***	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.

interpreted as the presence of heterogeneity in passengers' preferences regarding the attributes of the different transport modes (air and HSR). Overall, both types of passenger 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 is probably due to the higher level of comfort on-board the HSR (more space to work or unwind, with free Wi-Fi service) and the absence of strict safety protocols required instead for air travel. 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. Noteworthy is the coefficient of the average fare that turns out to be not significant for business passengers. This can be directly attributed to the well-documented lower price elasticity of business passengers compared to leisure ones because of their higher value of time and willingness to pay associated with the reimbursement of travel expenses by their own company (Alderighi et al., 2016; Granados, Gupta, & Kauffman, 2012; Granados, Kauffman, et al., 2012; Morlotti et al., 2017). Lastly, the coefficient for 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 the punctuality index over recent years. Recent studies documented how, in some cases, airlines have progressively extended their scheduled times above route technical travel times (allocating block buffer times) intended to improve on-time performance and avoid delays (Forbes et al., 2019). Over the last 15 years, in the London-Paris market, airlines have lengthened their scheduled travel times on average by 6 min, while actual flight times (i.e., technical travel time to cover the route) could reasonably be assumed unchanged. The longer schedule times translated into a 6% improvement in on-time performance metrics. Hence, the punctuality index became less reliable than before in discriminating air alternatives based on their actual punctuality and accordingly lost its importance in air passengers' choice.

5.2. Trip generation model

Estimated coefficients and robust standard errors for the trip generation model are reported in Table 4. Both leisure and business passenger models exhibit good fitting capacity with a mean absolute percentage error (MAPE) on the estimates of quarterly passenger flows between London and Paris of 14.3% and 15.8%, respectively. In both models, population, per-capita GDP, and LoS parameters are statistically significant. As commonly recognized, travel demand for both categories of travelers is positively related to socio-economic characteristics of the origin and destination zones. More in detail, 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. London areas with

Table 4
Estimation results for the trip generation model.

	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.

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 intriguing are the estimates for the LoS parameter, which are positive and significant in both models. This indicates that travel demand is sensitive to changes in supply. 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 quarter dummies, a statistically significant seasonal trend emerges throughout the year for leisure flows. These are higher during the spring and summer seasons and gradually decrease during the fall and winter months. Business passenger flows do not exhibit any statistically significant seasonal pattern. Further, by analyzing the Brexit dummy, no significant impacts on business flows were outlined after the official announcement of the UK exit from the EU and during the negotiations. Contrariwise, Brexit has a negative and statistically significant effect on leisure passenger flows. The UK's withdrawal decision from the EU caused stagnation and a decline in tourist flows, thus confirming the findings of previous studies by Arentze and Timmermans (2009) and Pappas (2019).

6. Scenario analysis

In this Section, based on the sensitivity of demand to supply characteristics extrapolated using the integrated model, we investigate the impacts in terms of induced or dissuaded demand resulting from changes in supply attributes or implementation of policy initiatives to reduce aviation emissions. To this aim, taking 2019 supply characteristics and passenger flows as baseline,[22] we consider different scenarios of supply attribute variations. The scenarios proposed include: (i) the introduction of an additional daily connection by Eurostar, (ii) the reduction of Eurostar travel time by 10 min, (iii) the cancellation of the air route between LHR and CDG operated by British Airways, and (iv) the ban of all the air connections between London and Paris. In the current study, airlines' and HSR operator's strategic reactions in terms of frequency and fare following changes in supply characteristics have not been explicitly modeled. However, in the following, the impacts on the overall demand (induction or reduction) have been discussed even considering potential strategic reactions reported in previous studies.[23]

Estimated impacts on leisure, business, and overall passenger demand in the different scenarios are reported in Table 5. Table 6 details the delta in market share and passenger numbers of both air connections and HSR in each scenario.

Considering the first scenario, namely assuming a one-trip increase in the daily frequency of the HSR connection operated by Eurostar (from an average daily frequency of 15–16), our model estimates a demand stimulation effect of about 94,500 passengers per year. Induced demand is higher for business passengers who proved to be more sensitive to the LoS, other things being equal. Besides the "direct" stimulus effect, the increase in Eurostar frequencies would inevitably increase the competitive level in the market under consideration, with a likely downward effect on competitors' fares. Such a reduction, resulting in an improvement of LoS for passengers, would further increase the demand induction effect. As such, the increase in flows to/from the Greater London Area estimated by our model at 2.3% will be higher the stronger the effect of the increase in competition on fares. Considering trip distribution, the proposed increase in the daily frequency of Eurostar would lead to an increase in HSR market share by about 2.3% in the leisure and 2.1% in the business market segment. Obviously, the increase in HSR frequency needs to cope with the available capacity of the HSR infrastructure. Policymakers together with railways infrastructure managers need to identify to what extent the increase of HSR frequency can be accommodated on the current HSR infrastructure, also considering the congestion in the core of Europe's rail network.

In the case of a 10-min reduction of Eurostar travel time (from 140 to around 130 min), induced demand would account at least for about 1.3% of the existing demand, representing in absolute terms more than 55,500 passengers per year. This reduction in travel time can be achieved by improving organizational aspects of the service and optimizing the use of the infrastructure as well as a result of possible infrastructural investments on the HSR line. Induced demand would be higher for business passengers than for leisure ones. Even in this case, besides the "direct" demand stimulus effect following the reduction of HSR travel time, the improvement in supply attributes of the HSR service would trigger the reaction of the competitors (in this case airlines). More in detail, the reduction of HSR travel time would increase the competitiveness of the rail alternative, currently severely penalized in terms of travel time compared to the air alternatives. Airlines would likely react by reducing their fares or increasing their frequencies. This would in turn stimulate an improvement in the overall LoS for passengers rising the traffic stimulus effect above the values estimated by our model (i.e., approximately 18,700 and 37,000 leisure and business passengers), with the higher additional demand induction effect the higher the reaction of competitors to the intensification of competition. Further, a reduction of HSR travel time by 10 min would increase HSR market share by 1.2% compared to the 2019 levels (in absolute terms equal to more than 91,000 passengers).

In addition to scenarios based on the increase in HSR frequencies and decrease in travel times, we investigate the impacts on the total demand resulting from the complete cancellation of a single air route or of all air routes operated 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 estimate the impact in terms of dissuaded demand of a possible policy to ban of short-medium-haul flights for environmental purposes. As already mentioned, due to the growing pressure to reduce aviation emissions, several initiatives in this direction have been recently undertaken in some European countries, such as France and Austria for routes where alternative connections operated by alternative transport modes exist. Similar policies have been considered by Germany and Spain and are encouraged by the EC.

As regards the single air route cancellation, we simulated the closure of the route between LHR and CDG 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 or number of passengers. The closure of this route would lead to a reduction of the overall demand of around 105,000 passengers per year (approximately 2.5% of current ridership), with an estimated increase in HSR market share by about 9.2%. Although higher in absolute terms for leisure passengers, in relative terms the demand degeneration effect would be higher for business passengers whose flows would be reduced by 3.4%. Considering the possible strategic reactions of competitors following the closure of the air route, the demand reduction effect would be even more pronounced. Indeed, the reduction in competition following the closure of the air route will inevitably result in market concentration, and therefore higher fares and lower LoS. This will further increase the overall demand reduction effect. The abolition of all air routes between London and Paris as a result of a policy to reduce aviation emissions, leading HSR to be the only travel option available, would have a much greater impact on travel demand. Our model estimates that at least 6% of passengers (in absolute terms almost 240,000 passengers per year) traveling between the two cities would cease to travel following the end of air services. This reduction will be significantly higher as a result of the market concentration and the consequent increase in fares following the closure of air routes. In this respect, the regulatory and antitrust authorities will be called upon to implement appropriate initiatives to reduce the possibility of misuses 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).

Considering the scenario simulating the closure of all the air connections, it is interesting to deepen how HSR service providers could compensate for the end air services to ensure passengers the same LoS. In the case of enforcement of a policy to ban short-medium-haul flights, regulators might indeed require the remaining service providers to implement appropriate organizational measures (e.g., revision of scheduling and timetables) and investments (e.g., hiring or increasing vehicle fleet) to ensure an appropriate service quality (Avogadro et al., 2021).

Table 7 reports possible compensation mechanisms that the HSR provider can implement to preserve the LoS for passengers following a complete cancellation of the air alternatives.

Overall, the results reveal that, regardless of the attribute on which the HSR service provider focuses to increase its LoS, more effort is needed to compensate for the reduction in the LoS for leisure passengers

[22] The identification of a reference context is necessary because induced demand cannot be directly estimated, but rather only inferred from a reference scenario (Gorham, 2009).

[23] The estimates provided in the current study should therefore be interpreted as a conservative estimate of the effect in terms of stimulated or reduced demand as a result of changes in supply. These impacts will be further amplified the stronger the reactions adopted by the competitors. Future studies may focus on the explicitly modeling of the competitive dynamics as well as the strategic responses of the single operator.

Table 5
Estimates of induced and reduced demand following different supply characteristic changes. Note that these impacts would be further amplified by competitive reactions.

Scenario	Leisure		Business		Overall	
	Δ pax	Δ %	Δ pax	Δ %	Δ pax	Δ %
Additional daily Eurostar connection	48,903	1.7%	45,792	3.8%	94,696	2.3%
Reduction of Eurostar travel time by 10 min	18,685	0.6%	36,987	3.1%	55,673	1.3%
Cancellation of the air route LHR-CDG-BA	−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 6
Estimates of delta market share (MS) and passenger number of both air and HSR in each scenario.

Scenario	Leisure			Business			Overall		
	Δ HSR MS	Δ HSR pax	Δ AIR pax	Δ HSR MS	Δ HSR pax	Δ AIR pax	Δ HSR MS	Δ HSR pax	Δ AIR pax
Additional daily Eurostar connection	2.3%	104,127	−55,224	2.1%	63,081	−17,289	2.3%	167,208	−72,512
Reduction of Eurostar travel time by 10 min	0.9%	40,356	−21,671	1.7%	51,092	−14,104	1.2%	91,448	−35,775
Cancellation of the air route LHR-CDG-BA	9.5%	226,755	−290,884	8.7%	68,102	−108,628	9.2%	294,857	−399,512
Cancellation of all the air connections*	26.2%	615,336	−773,599	20.0%	153,733	−239,757	24.4%	769,070	−1,013,356

* Note that in this scenario the HSR connection would remain the only travel option available.

Table 7
Changes in HSR supply characteristics required to maintain the LoS 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%

than for business ones. This directly stems from passenger preferences toward the supply attributes: leisure passengers indeed associate less value with increased frequencies and decreased travel times than business ones. Focusing on frequency, stemming the removal of air routes would require increasing the weekly frequency of Eurostar by 19 rides for leisure passengers and only 12 for business ones. Such an increase appears quite small compared to the current frequency of the HSR alternative. Nevertheless, the actual feasibility of this increase requires policymakers a thoughtful evaluation of the available capacity on the HSR network. The introduction of 19 additional trains would increase the number of weekly offered seats by Eurostar in each direction between 14,402 and 17,138.[24] This additional capacity would be more than adequate to accommodate passengers currently traveling by air that would be diverted to HSR (around 3900 passengers per week and direction). However, in such analysis, even the proportion of travelers that use London airports and originated from or are directed to zones of the UK other than the Greater London Area needs to be considered. Assuming that the extra-frequencies would be adequate to guarantee comparable LoS even for these travelers, the overall diverted demand due to flight cancellations can be quantified in 11,200 passengers. Therefore, even considering these travelers the additional capacity would be sufficient to accommodate all diverted passengers from air transportation. Reducing HSR travel time to compensate for the lower LoS due to the withdrawal of air routes does not seem a sustainable option if implemented alone and would be feasible only combined with an increase in HSR frequencies. Indeed, to leverage only travel time for preserving leisure passengers from a reduction of the LoS it would be necessary to almost halve HSR on-board travel time. Notice that this result is due to the low sensitivity of leisure passengers to travel time outlined in the trip distribution model. On the contrary, for business passengers, a reduction of HSR on-board travel time by about 20 min ensures preserving the previously offered LoS. Lastly, a downward revision of HSR fares does not seem a viable option. At the opposite, as described above, the reduction in competition (at least in its multimodal component) following the closure of air routes will result in market concentration, and therefore likely higher fares. The regulatory and antitrust authorities will be called upon to implement appropriate initiatives to reduce the possibility of misuse of market power, notwithstanding, a further increase in HSR frequencies (or reduction in travel times), compared to the scenarios previously described, may be necessary whether the fare increase resulting from the market concentration cannot be sufficiently mitigated. As one might expect, the higher the increase in HSR fares, the stronger compensation mechanisms required to avoid passengers 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% (24.4% and 15.3% in absolute terms) to guarantee comparable LoS for 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 of 20%. In summary, HSR providers can primarily leverage on increasing frequencies to compensate for the reduction in LoS following a possible policy of cancellation of the air alternatives. By comparing the additional HSR frequencies required to the number of canceled flights, we estimated for the London-Paris market a substitution rate of 0.12. This means that the introduction of an additional HSR ride every 9 flights dropped is required to compensate the LoS for passengers. Such a 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.

7. Conclusions

Over the recent years, the global expansion of HSR and the substantial investments planned to extend HSR networks brought intermodal competition to the forefront of discussions among scholars and practitioners. Concurrently, the issue of sustainable growth of the air transport industry led policymakers to promote modal shift to alternative modes, especially HSR, as a key measure with the potential to contribute to coping with emissions from medium- and short-haul air routes (which account only for a portion of the overall industry emissions).

[24] This estimate considers 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 seating capacity of 758 and 902 seats, respectively.

This paper analyzes passenger preferences and demand (de)generation dynamics due to changes in the attributes of available travel alternatives for the London-Paris market. By leveraging an integrated model calibrated on a cross-sectional dataset of revealed preferences collected over the period between 2009 and 2019, we identify the key dimensions by which travelers evaluate transport modes and how both socio-economic characteristics and supply attributes variations concur to influence the total travel demand, stimulating or decreasing the current ridership. The paper complements the body of literature on air-to-rail substitution and induced demand by analyzing passenger modal preference and explicitly extrapolating the relationships between variations in supply attributes on both the air and HSR sides and fluctuations in the overall travel demand, ultimately quantifying induced or reduced demand.

Our analysis confirms the importance of supply attributes, such as travel time, fare, punctuality, and service frequency on passenger choice. Specifically, consistent with previous studies, our research returns a higher sensitivity to fares for leisure passengers. Contrariwise, business travelers associate a higher utility to service frequency, low travel time, and higher on-time punctuality performance. By developing a sub-model intended to understand the attitudes of air passengers toward the different attributes, we further pinpointed heterogeneity in the evaluations of passenger preferences toward air and HSR. Specifically, thanks to the higher comfort on-board HSR, the absence of specific security checks, and no restrictions on items allowed on-board, the travel time on-board the HSR results much less burdensome for travelers than that for the air mode. Considering factors affecting the overall demand, we found both leisure and business travel flows positively related to the mutual socio-economic characteristics of the origin and destination zones. More interestingly, we observed a positive and significant contribution of the LoS on the travel demand of both leisure and business passengers, thus identifying supply-demand interactions. Considering different scenarios of variations in supply attributes, we evaluated demand induction and reduction patterns, namely how supply variation of both air and HSR alternatives contribute to capturing a higher or lower portion of potential travel demand. Focusing on the HSR, the demand stimulus effect (i.e., induced demand) due to an increase in Eurostar frequency by one daily connection is estimated at about 95,000 passengers per year. At the same time, infrastructure investments or organizational measures aimed at reducing the travel time of the HSR line by 10 min result in just over 55,500 extra trips per year (1.3% of the current ridership). On the other hand, considering variations in aviation services, a demand reduction effect of over 2.5% of the current ridership is reported if British Airways would cease to operate the LHR-CDG route. The suspension of all air services between London and Paris, for instance following a policy to reduce aviation emissions or promote an air-to-rail modal shift, would cause a much more relevant impact, repressing current demand by about 6%. Note that these impacts would be further amplified the stronger the reactions in terms of frequency and fare adopted by the competitors. Specifically, in case of an increase in HSR frequencies or reduction of travel times, the increased level of competition, likely resulting in lower fares, would further increase the demand stimulation effect. Conversely, the end of one or more air alternatives would results in higher fares following market concentration, in turn causing a further reduction of the overall demand compared to values estimated by our model. Accordingly, the estimates provided in the current study represent a conservative bound of the effect in terms of stimulated or reduced demand as a result of changes in supply.

In the case of a ban on air routes as a consequence of a policy initiative, compensation mechanisms to ensure the maintenance of the LoS and thus mitigate the detrimental effects on passengers resulting from the closure of air routes might be required. Increasing frequency is found to be the best leverage for HSR service providers to guarantee the LoS after the possible closure of air routes, if such an increase can be accommodated on the current HSR infrastructure. For the analyzed market, a substitution rate of 0.12 has been estimated, namely to compensate for the loss in passengers' LoS it would be necessary to introduce an additional HSR ride about each 9 air flights dropped. This increase in frequency would be more than adequate to accommodate passengers diverted from air transport. Compensation mechanisms based on increased frequencies 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 LoS for passengers, it is worth emphasizing the leading role that the regulatory and antitrust authorities will play during the transition process following a possible cancellation of air routes.

Obviously, this paper is not exempt from limitations that pave the way for future work. First, considering passenger preferences, we provided a first attempt to assess the heterogeneity of traveler preferences toward single transport modes. Future empirical assessments could deepen and further examine the heterogeneity in passengers' attitudes toward air or HSR mode. Second, evidence about induced or reduced demand following variation in supply are evaluated not considering airlines' and HSR operators' strategic reactions. Follow-up research may investigate and model the effect of supply variation on competitors' behavior considering changes in the relative frequency and fare level. Third, the current analysis considers point-to-point passengers. Future research could use the proposed integrated demand model to investigate the factors determining the extent to which HSR can provide a feeder service for long-haul flights, as compared to air feeders. Lastly, the parameters of both trip generation and distribution models are estimated based on a specific market. Accordingly, the representativeness of our results needs to be validated 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.

Author statement

Nicolò Avogadro: Conceptualization, Methodology, Data Curation, Formal Analysis, Writing - Original Draft, Writing - Review & Editing. Renato Redondi: Conceptualization, Writing - Review & Editing, Supervision.

Declaration of competing interest

The authors declare no conflict of interest.

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