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Should short-haul flights be banned? A simple transportation network analysis[☆]

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ABSTRACT

We assess the effects of a short-haul flights ban on a transportation network that includes local, international and connecting markets and modal competition between high-speed rail (HSR), air and private car. When connecting markets are relatively important or there is sufficient modal substitution, bans induce more private car traffic, less local HSR traffic due to higher prices and also more international air and connecting traffic since international prices decrease. Our simulation results unveil that when air and private car are the closest substitutes the ban increases environmental damages. Welfare gross of damages typically falls.

1. Introduction

The exponential growth of air traffic in the last two decades (86% between 2000 and 2019, see European Commission et al. (2021)) has generated concerns about its climate impact, specially because of its high environmental costs. Among the various measures to reduce greenhouse gas emissions, there are proposals by some European countries to implement short-haul flight bans on routes where there is a fast rail alternative. The idea is that the ban policy will shift passenger traffic towards a more environmentally friendly mode such as rail, and high-speed rail (HSR) in particular. However, policy makers should not ignore that in some routes, the private car, which is a more polluting mode, is an actual option for many users, and furthermore, the effect that such a measure may have on connecting passenger traffic in a transportation network cannot be disregarded; the welfare and environmental effects of a prohibition on short-haul flights are a priori unclear.

In the context of the European Green Deal, the EU is taking actions to reduce aviation emissions in Europe. According to the International Energy Agency, in 2018 transport accounted for 24% of CO_2 emissions from energy, 8 billion tonnes. Road travel supposes 75%, while aviation represents 11.6% of transport emissions, and rail travel and freight emits just 1%. Long flights account for the vast majority of aviation CO_2 emissions in Europe.[1] Here more efficient aircraft types can produce reductions in the carbon footprint. For short-haul flights which are responsible for less than 20% of CO_2 emissions, the negative environmental effects can be lessened by replacing and/or banning some of the flights with fast train connections.

The 2011 European Commission's White Paper (Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system) took in proposals to substitute shorter flights by rail. In this regard, KLM Royal Dutch Airlines has developed a plan (as of March 2020) with Thalys and NS Dutch Railways to gradually reduce flight frequency between Brussels and Amsterdam Schiphol, an airport used by passengers to take connecting flights to intercontinental destinations.[2] France has recently officially prohibited short domestic flights when journeys can take less than two and a half hours by train. The routes between Paris-Orly Airport and the cities of Nantes, Bordeaux and Lyon are affected; the bans do not apply to connecting flights.[3] Note that in both these cases we find big cities that are connected by reliable, regular, fast, and efficient train services. The short-haul flights ban initiative is being considered by the Spanish

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[1] See https://stats.oecd.org/Index.aspx?DataSetCode=AIRTRANS_CO2.
[2] See https://news.klm.com/klm-thalys-and-ns-dutch-railways-have-joined-forces-to-replace-flights-between-brussels-and-amsterdam-airport-schiphol/.
[3] See https://www.smithsonianmag.com/smart-news/france-ban-short-haul-flights-180982268/.

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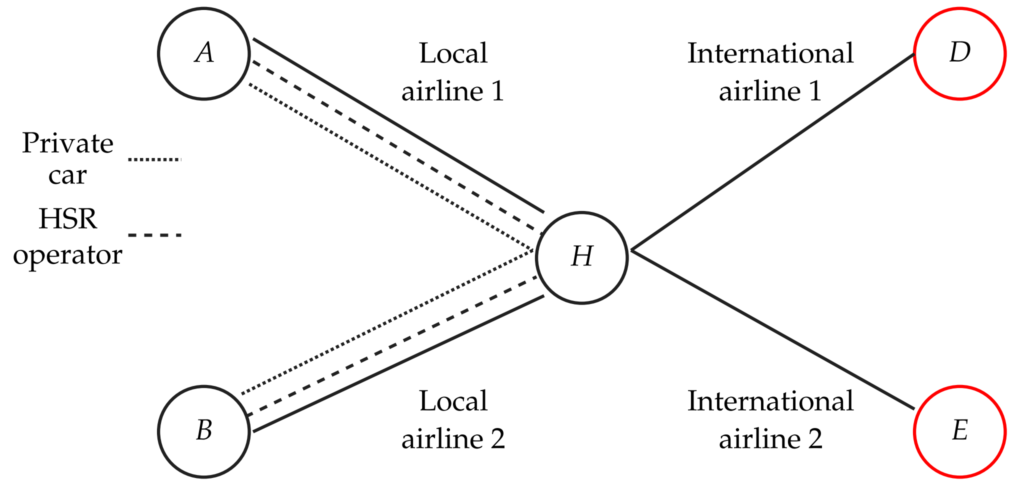

Fig. 1. Transportation network.

Government, and has been discussed in Germany, Italy, the UK and Poland.

The purpose of this paper is to provide a formal analysis to study the effects of short-haul flights bans in a transportation network. Transport markets are viewed as the edges connecting nodes forming transportation networks. The network, see Fig. 1, consists of two domestic cities linked with an airport hub city, from which international flights depart to two cities elsewhere. Local trips can be made by air, HSR and road (users have the option to use their private car). In this manner, modal substitution is taken into account while also contemplating the complementarities that arise due to the presence of connecting passengers travelling from a domestic to an international destination. The consideration of several modes and markets, each having a different environmental impact, is most appropriate for an informed assessment of the proposed market-based measure to aid in meeting climate change targets associated with passenger transport.

In the first part of the paper, we shall develop a formal model with the above features and characterize the price equilibrium in the benchmark scenario where all modes are available to passengers. That is, prices for the two modes in the local markets and prices for the two international markets will be reported. Connecting passengers in the transportation network pay a composite price, that is, the sum of the corresponding prices in each of the legs. Then, two scenarios are considered. In one of them, the *partial-ban scenario*, air transport is eliminated in just one of the two local routes. In another, the *full-ban scenario*, all local flights are eliminated. Equilibrium prices and traffics are compared which allows us to analyse the strategic responses by operators and the distortions induced by the bans, and may provide an intuition of what to expect regarding passenger surplus, profits, welfare and environmental damages. A quantitative evaluation of the latter is given in the second part of the paper. There the model is calibrated for a transportation network where domestic cities are Barcelona and Valencia, the hub city is Madrid, and the international destination cities are Miami and New York City. This empirical application sits well with our theoretical setting and allows us to quantify the changes in users' surplus, welfare and all types of external costs, which follow from a short-haul flights ban.

Our contribution is twofold. On the theoretical ground, when connecting markets are relatively more important[4] for operators or when transport modes are not too differentiated, we find that, (i) bans of either type imply larger car traffic in all local markets, even on those not affected by a partial-ban policy; (ii) the modal shift from air travel to HSR in local markets is not achieved due to the increase in HSR prices; (iii) international air traffic increases by the strategic reaction of international airlines to either ban implying that reductions in local flights pollution are traded off for increases in international flights pollution, and finally; (iv) bans of either type imply more HSR connecting traffic. On the empirical ground, we find that the effects of bans are very sensitive to the corridor analysed.[5] In corridors like Barcelona-Madrid-Miami, where HSR and air are similarly perceived by passengers and all markets are evenly viewed by operators, short-haul flights bans may reduce environmental damages and external costs in general, except for external costs in local markets which increase mainly due to the growth in private car use. Passengers of either market are worse off and airlines of either type suffer high losses. However, in corridors like Valencia-Madrid-New York City, where private car and air transport are the closest substitutes for passengers and connecting markets are more relevant for operators, bans can neither reduce environmental damages nor external costs in any market. HSR local traffic falls since passengers pay more for the service and many shift to the private car. A remarkable strategic effect is observed as international airlines decrease their prices what implies increases in traffic and passenger surplus in international and connecting markets. Interestingly, such a local policy has important effects in international and connecting markets, showing that when markets are shaped in networks an overall assessment is required in order to properly measure the effectiveness of bans.

The paper is organized as follows. Section 2 includes the literature review. Section 3 develops the model, characterizes the equilibria and offers the price and traffic effects of the no-flights policy. The empirical application is given in Section 4. Section 5 is for robustness and contains a sensitivity analysis and Monte Carlo simulations. Finally, we conclude with some remarks and policy recommendations in Section 6.

[4] Airlines acknowledge that connecting traffic is an important part of their business model implying that losing the connecting passenger traffic for some routes can make a difference between operating and dropping service. For instance, in 2019, there were about 8.5 million passengers from the United Kingdom to the United States, and 46% of them made a connection as part of their trip (see https://www.oag.com/blog/power-connecting-passengers-later-guest-arrivals-become-new-normal).

[5] The criteria for the chosen corridors are (i) their relevance in terms of traffic (the three Spanish largest cities with HSR connections and two of the top 5 international destinations outside the EU are considered); (ii) their qualitative difference in terms of passenger type and modal distribution (Barcelona-Madrid has a greater proportion of business passengers where air and HSR are strong substitutes, whereas Valencia-Madrid has a large share of domestic touristic passengers and private car and HSR are the closest substitutes). In this manner, we can have a broad picture of what effects to expect after a short-haul flights ban. We believe that these are good representative corridors and expect that similar qualitative conclusions will show up in many other corridors with these features (in fact, Sevilla-Madrid, Malaga-Madrid and Alicante-Madrid are similar to Valencia-Madrid).

2. Related literature

Global aviation generates environmental problems through all kinds of aircraft operations. Tools that help achieving an environmentally sustainable growth of the aviation sector are required, given the growth of air transportation demand. Rupcic et al. (2023) review life cycle assessments studies in the civil aviation sector, distinguishing aircraft systems, alternative fuels and airports; direct fuel combustion, both in freight and passenger transport, accounts for the vast majority of CO2 and NOx emissions. Interestingly, Mayeres et al. (2023) provide a rigorous and detailed cost analysis of policies that promote sustainable aviation fuels in Europe; setting a minimum penetration share is far more expensive than other options. For Switzerland, Wild et al. (2021) survey the effects of market-based measures, such as flight taxes, carbon offsetting and low-carbon technologies, as well as other governmental policies to reduce CO2 emissions. Flight tax programs do not seem to have a strong influence on travel behaviour and the authors note that a combination of emission reduction measures is needed. However, for a European sample, Bernardo et al. (2024) find that flight ticket taxes notably influence low-cost airlines supply and derived emissions. The recent contribution by Kang et al. (2022) provides an ex-post evaluation of the effects of the EU Emission Trading System on aviation supply; it has triggered a reduction in flight frequency with a significant impact on low-cost and regional carriers, and short-haul routes. Some of the challenges of mitigation measures to reduce the climate impact of aviation are listed in Gössling and Lyle (2021) and Lai et al. (2022).

At any rate, modal interactions should be looked at for a general evaluation of any CO2 reduction measures - see e.g. Zhang et al. (2019) for a survey on recent research on air-HSR competition and Jiang et al. (2021) for a review on the environmental implications of the interplay between HSR, air and road transport. As noted above, one of the benefits of a modal shift from air transport to rail relates to the superior greenness of HSR. Improving connectivity through the development of HSR and the entry of HSR operators adversely influences air traffic, fares and flight frequencies. While the introduction of HSR may generate new travel demand Givoni and Dobruszkes (2013), which brings benefits to users, whether HSR projects deliver positive environmental effects is unclear and should definitely consider all transportation modes involved. The study by Wang et al. (2019) demonstrates that investments in China's HSR have a beneficial impact on lowering emissions from the aviation sector, in particular those related with short distances, because the substitution effects are important. However, net emissions reductions cannot be realized unless HSR attracts substantial traffic from highway and aviation sectors, as shown by Chen et al. (2021) for the Beijing-Shanghai HSR corridor. The papers by D'Alfonso et al. (2015, 2016) inquire into this idea and throw light on the tradeoff between the substitution and the traffic generation effects in an origin–destination link. These analyses, where operators compete in quantities, identify conditions under which the introduction of HSR may be detrimental for the environment. In contrast, Cantos-Sánchez et al. (2023) assume price competition and include private car as an option. They study how the removal of air transport impacts welfare and the environment and find that, provided that the per unit external cost of road transport is sufficiently large, a no-flights policy is detrimental to society as it generates larger external costs.

As suggested above, a proper evaluation of the modal competition must consider not only the substitution effects across modes but also the complementarity that arises for users that combine modes to reach their destination. This demands a transportation network analysis, as done by Socorro and Viecens (2013), Jiang and Zhang (2014), Xia and Zhang (2017), Álvarez-SanJaime et al. (2020a) and Álvarez-SanJaime et al. (2021), among others, which look at the scope for cooperation between air and rail transport. These papers disclose gains for consumers, specially for connecting passengers. More specifically, the contribution by Socorro and Viecens (2013) addresses the environmental effects of airline and HSR integration; if there is a reduction in the number of passengers carried by plane and HSR emits a level of pollution much lower than air, then integration produces positive environmental effects. Zanin et al. (2012) show that constructing a HSR connection at Madrid airport, an example of intermodal integration, can bring environmental gains. However, they note that an increase in the cost of using cars is picked up by air transport rather than by HSR. The analysis by Chiambaretto and Decker (2012) suggests that, although air-rail intermodal agreements may raise competition concerns, they should be allowed once environmental benefits are considered. It is only recently that some contributions exist that explicitly investigate the effects of policies that ban short-haul flights from an applied perspective. Their impact at the European level has been estimated by Szymczak (2020) and Avogadro et al. (2021). The former identifies airports affected concluding that a ban across all countries would imply modest environmental gains. The latter emphasizes that, though positive in terms of CO2 savings, the benefits are not equally distributed across Europe. Dobruszkes et al. (2022) also insist on the limited effects in emissions reductions that a ban would have, given that the share of fuel burnt in such type of flights is barely 5.9% of the total despite they account for 27.9% of departures in 31 European countries. Finally, a couple of country studies are worth citing. Baumeister and Leung (2021) look at the case of Finland, where a HSR network does not exist. Banning all short-haul flights would result in savings of CO2-eq emissions of 4.23%. Reiter et al. (2022) report, for the case of Germany, that substitution of short-haul flights with rail services would produce significant reductions in CO2 emissions – between 2.7% and 22%. Both these papers note that travel time costs should not be disregarded and hence suggest investments in HSR infrastructure. Although the efficacy of several voluntary, market-based and regulatory measures has been carefully examined, a short-haul ban policy has not received formal examination, except by Cantos-Sánchez et al. (2023) which, to the best of our knowledge, is the first thorough study on the welfare and environmental effects of such measure. We complement this line of research by developing a transport network analysis to unveil operators' strategic reactions to short-haul flights ban policies. Besides, an empirical application will allow us to offer a knowledgeable assessment of the impacts of a short-haul flights ban on environmental and external costs, user surplus and social welfare.

3. A simple transportation network

Consider the transportation network shown in Fig. 1. A given country mobility pattern linking three cities (A, B and H) that allows for international connections to cities D and E via the national hub H is shown. A distinction between local and international airline connections is made so that short-haul and medium to long-haul flight connections can be analysed. The network structure allows for two local city-pair markets, the local markets AH and BH, where travellers are allowed to use HSR services, local airline services or use a private car. Two international markets, HD and HE, that provide airline services between the hub and two international destinations. Finally, users leaving from cities A and B are allowed to reach cities D and E abroad via H, thus defining four connecting markets, i.e. AHD, AHE, BHD and BHE. These users can combine the three available transport modes in the first link with the airline connecting the corresponding international destination with the hub. As indicated in Fig. 1, the simplest set-up is that each different airline service is provided by an independent airline. Also, to fit with the Spanish situation in 2018 the HSR services are provided by one and the same company.

3.1. Utility functions and demands for the different markets

In order to model demand for each corresponding market indicated in the superscript, we define Spence-Dixit representative user utility functions (see Dixit, 1979) as follows:

(i) The utility function for each local market iH, where $i = A, B$ and subscript a stands for air transport, t for rail transport, and c for car, is

$$U^{iH}(q_a^{iH}, q_c^{iH}, q_t^{iH}) = y^{iH} + \sum_{m=a,c,t} \alpha_m^{iH} q_m^{iH} - \frac{1}{2} \sum_{m=a,c,t} \beta_m^{iH} (q_m^{iH})^2 - \gamma_{ac}^{iH} q_a^{iH} q_c^{iH} - \gamma_{at}^{iH} q_a^{iH} q_t^{iH} - \gamma_{ct}^{iH} q_c^{iH} q_t^{iH} . \quad (1)$$

(ii) The utility function for each international market Hj, where $j = D, E$, is

$$U^{Hj}(q_a^{Hj}) = y^{Hj} + \alpha_a^{Hj} q_a^{Hj} - \frac{1}{2} \beta_a^{Hj} (q_a^{Hj})^2 . \quad (2)$$

(iii) Finally, the utility function for each connecting market k, where $k = AHD, AHE, BHD, BHE$, and passengers can use three different combinations of modes, denoted by b, where $b = aa, ca, ta$, is

$$U^k(x_{aa}^k, x_{ca}^k, x_{ta}^k) = y^k + \sum_{b=aa,ca,ta} \alpha_b^k x_b^k - \frac{1}{2} \sum_{b=aa,ca,ta} \beta_b^k (x_b^k)^2 - \gamma_{ac}^k x_{aa}^k x_{ca}^k - \gamma_{at}^k x_{aa}^k x_{ta}^k - \gamma_{ct}^k x_{ca}^k x_{ta}^k . \quad (3)$$

Note that the representative user's budget constraint for the iH city-pair domestic market, or local market, is defined by $I^{iH} = p_t^{iH} q_t^{iH} + p_a^{iH} q_a^{iH} + r_c^{iH} q_c^{iH} + y^{iH}$. Hence, q_m^{iH} denotes the number of trips, or passenger traffic, by mode m in local market iH. Similarly, p_t^{iH} and p_a^{iH} are the HSR and airline prices, while r_c^{iH} is the cost of private car use (fuel, depreciation, maintenance and repair, etc.), I^{iH} is the user's income and y^{iH} stands for the numeraire of the economy in market iH. The representative user's budget constraint for the Hj international market is $I^{Hj} = p_a^{Hj} q_a^{Hj} + y^{Hj}$, where p_a^{Hj} and q_a^{Hj} are the airline price and the number of trips between H and j. Finally, the representative user's budget constraint for the connecting market k is $I^k = s_{aa}^k x_{aa}^k + s_{ta}^k x_{ta}^k + s_{ca}^k x_{ca}^k + y^k$; where for instance in market $k = iHj$, x_{ta}^{iHj} denotes passenger traffic that takes the HSR in link iH and an international airline in link Hj, and s_{ta}^{iHj} is the sum of p_t^{iH} and p_a^{Hj} with the obvious notation for the other possible combinations.

For each market, α_m^{iH} is the maximum willingness to pay for travelling by mode m, for $m = a, c, t$ in market iH, for $i = A, B$; α_a^{Hj} is the maximum willingness to pay for travelling by air in Hj markets for $j = D, E$. Similarly for α_b^k, for $b = aa, ta, ca$ in each connecting market k. Maximum willingness to pay per mode encompasses a number of characteristics for each transport mode such as service quality, travel time, frequency of services, reliability, likelihood of congestion and so on that are considered by users to make their decisions.[6] Differences in α's owe to differences in such characteristics. For instance, focusing on travel time it usually includes in-vehicle time, plus access/egress time and finally the mismatch between users' preferred departure time and the actual time of departure. Thus, an air journey has lower in-vehicle time than a car or train journey, but suffers from longer access/egress times in addition to schedule delay costs. It may be possible that a car journey has longer in-vehicle time than an air journey, but lower total travel time since it does not incur in other items. For m and n services, own price effects on service $m's$ demand are denoted by β_m, while the cross price effects of service n in demand of service m is denoted by γ_{mn}, noting that own effects are bigger than aggregate cross effects. Services become less differentiated as γ_{mn} tends to β_m. In fact, the ratio $\frac{\gamma_{mn}^2}{\beta_m \beta_n}$ expresses the degree of product differentiation between modes m and n ranging from zero for independent goods to one for perfect substitutes (see Vives, 1999, page 146). Then, less differentiation implies ratios closer to one.

Inverse demand functions

Each market system of inverse demand functions is easily obtained from the maximization of the corresponding utility function subject to its budget constraint as follows:

[6] For example, Wang et al. (2018) emphasize the relevance of train speed and note that its effect is more important for short-haul routes where airline and HSR services are stronger competitors.

(i) inverse demand functions in local market iH,

$$p_a^{iH} = \alpha_a^{iH} - \beta_a^{iH} q_a^{iH} - \gamma_{at}^{iH} q_t^{iH} - \gamma_{ac}^{iH} q_c^{iH} , \quad (4)$$

$$p_t^{iH} = \alpha_t^{iH} - \beta_t^{iH} q_t^{iH} - \gamma_{at}^{iH} q_a^{iH} - \gamma_{ct}^{iH} q_c^{iH} , \quad (5)$$

$$r_c^{iH} = \alpha_c^{iH} - \beta_c^{iH} q_c^{iH} - \gamma_{ac}^{iH} q_a^{iH} - \gamma_{ct}^{iH} q_t^{iH} . \quad (6)$$

The first two equations above correspond to the inverse demand functions for the HSR and airline transport services, while (6) is the condition that defines the optimal use of private car.

(ii) The inverse demand function in international market Hj,

$$p_a^{iH} = \alpha_a^{Hj} - \beta_a^{Hj} q_a^{Hj} , \quad (7)$$

(iii) inverse demand functions in connecting market k,

$$s_{aa}^k = \alpha_{aa}^k - \beta_{aa}^k x_{aa}^k - \gamma_{at}^k x_{ta}^k - \gamma_{ac}^k x_{ca}^k , \quad (8)$$

$$s_{ta}^k = \alpha_{ta}^k - \beta_{ta}^k x_{ta}^k - \gamma_{at}^k x_{aa}^k - \gamma_{ct}^k x_{ca}^k , \quad (9)$$

$$s_{ca}^k = \alpha_{ca}^k - \beta_{ca}^k x_{ca}^k - \gamma_{ac}^k x_{aa}^k - \gamma_{ct}^k x_{ta}^k . \quad (10)$$

3.2. Operators' profit functions

The different markets in the transportation network are served by an HSR operator that covers the two local markets AH and BH, by two different local airlines serving each one its local market and two different international airlines that provide airline services in each international market HD and HE (see Fig. 1). The rail operator and airline profits read as follows, where subscripts in profits (denoted by π) and constant marginal costs (denoted by c) refer to the corresponding operator:

$$\pi_{HSR} = (p_t^{AH} - c_{HSR}) Q_{HSR}^{AH} + (p_t^{BH} - c_{HSR}) Q_{HSR}^{BH} , \quad (11)$$

$$\pi_{L1} = (p_a^{AH} - c_{L1}) Q_{L1} , \quad (12)$$

$$\pi_{L2} = (p_a^{BH} - c_{L2}) Q_{L2} , \quad (13)$$

$$\pi_{I1} = (p_a^{HD} - c_{I1}) Q_{I1} , \quad (14)$$

$$\pi_{I2} = (p_a^{HE} - c_{I2}) Q_{I2} , \quad (15)$$

where $Q_{HSR}^{AH} = q_t^{AH} + x_{ta}^{AHD} + x_{ta}^{AHE}$ and $Q_{HSR}^{BH} = q_t^{BH} + x_{ta}^{BHD} + x_{ta}^{BHE}$ are the total number of passengers travelling by HSR; $Q_{L1} = q_a^{AH} + x_{aa}^{AHD} + x_{aa}^{AHE}$ and $Q_{L2} = q_a^{BH} + x_{aa}^{BHD} + x_{aa}^{BHE}$ are the total number of passengers travelling with the local airline 1 and 2, respectively. Finally, $Q_{I1} = q_a^{HD} + \sum_{b=aa,ca,ta} (x_b^{AHD} + x_b^{BHD})$ and $Q_{I2} = q_a^{HE} + \sum_{b=aa,ca,ta} (x_b^{AHE} + x_b^{BHE})$ are the total number of passengers travelling with international airline 1 and 2, respectively. Note that all operators choose prices so that the $q's$ and $x's$ appearing in their profit functions are the corresponding demand functions obtained by inverting the corresponding systems of inverse demand functions described above.

3.3. Equilibria

In this section we will provide the equilibria of three different scenarios corresponding to (a) *the benchmark*, (b) *the partial-ban scenario*, and (c) *the full-ban scenario*. The first scenario, the benchmark, is the one presented in the above section where the two city-pairs AH and BH are connected by private car, air and train. The second scenario, presents the case where one city-pair, say AH, is not served by a local airline because that short-haul flight has been banned. Finally, the third scenario supposes that none of the local city-pairs is connected by local airlines so all local short-haul flights are banned.

Note that travellers may use their private cars in the local routes which imply that the conditions that define the optimal use of private car in each route need to be taken into account, that is conditions (6) in local markets and (10) in connecting markets. Also, and since operators are serving passengers of different markets, all the markets are connected and the corresponding equilibrium is the solution of the full set of first-order-conditions of the active operators plus the set of conditions that capture the optimal use of private car. In particular, for the *benchmark scenario*, as operators choose simultaneously and independently their profit maximizing prices, the equilibrium prices are the solution of the following system of twelve equations: six first-order conditions, $\frac{\partial \pi_{HSR}}{\partial p_t^{AH}} = 0$, $\frac{\partial \pi_{HSR}}{\partial p_t^{BH}} = 0$, $\frac{\partial \pi_{L1}}{\partial p_a^{AH}} = 0$, $\frac{\partial \pi_{L2}}{\partial p_a^{BH}} = 0$, $\frac{\partial \pi_{I1}}{\partial p_a^{HD}} = 0$ and $\frac{\partial \pi_{I2}}{\partial p_a^{HE}} = 0$ plus the two conditions (6) for local markets AH and BH plus the four conditions (10) for each connecting market k. For the *partial-ban scenario*, the local airline 1 is not active, then, only five first-order conditions, since p_a^{AH} does not apply, together with the other six conditions need to be satisfied. Similarly, for the *full-ban scenario*, both local airlines are not operative and the equilibrium prices are the result of the solution of the four remaining first-order conditions plus those capturing the optimal use of private car.

As formulated, the transportation network allows for asymmetries in the size and degree of product differentiation across modes in each particular market that may differ across markets. To exploit the richness of the model we develop an empirical application in Section 4. However, in this section we are interested in analysing the strategic effects and distortions on benchmark equilibrium prices and traffics derived from either the partial or the full-ban policy. There are two important dimensions to understand the effect of the ban. The first one is how the degree of product differentiation explains the new after-ban redistribution of traffic across modes and also, how the relative relevance of connecting traffic affects operators' prices and whether that pricing pattern is affected by flights bans in local markets. For the sake of the presentation, we will assume symmetry as follows to provide simpler expressions to facilitate the analysis. First of all, symmetry in the degree of product differentiation across modes and markets is considered. This implies that $\gamma_{ac} = \gamma_{at} = \gamma_{tc} = \gamma$ in all the local and connecting markets and also $\beta_a = \beta_t = \beta_c = \beta_{aa} = \beta_{ta} = \beta_{ca} = \beta$ in all markets. In that way, the ratio $\frac{\gamma}{\beta} \in (0,1)$ shows the degree of product differentiation across modes in the network. Secondly, symmetry in the willingness to pay in the local and international markets is assumed, that is, $\alpha_a^l = \alpha_t^l = \alpha_c^l - r_c^l = \alpha$, for all l; and also symmetry in those in the connecting markets: $\alpha_{aa}^k = \alpha_{ta}^k = \alpha_{ca}^k = \overline{\alpha}$ for all k. Hence, the ratio $\frac{\overline{\alpha}}{\alpha} > 1$ measures the relative willingness to pay between connecting and the other markets, and a larger ratio means that connecting markets are more appealing than the other for operators.[7] Finally, to ease the presentation in this section, we will not consider connecting passengers using private cars. This implies that the effect of flight bans towards private car traffic is underestimated. Furthermore, for the sake of the presentation and without loss of generality, operators' marginal costs are assumed to be zero. The empirical application, though, considers positive marginal costs.

The benchmark scenario equilibrium

The equilibrium prices in the local markets are equal and denoted by p^n, where the superscript n refers to the benchmark case where no ban has been implemented, i.e., $p_a^{AH} = p_a^{BH} = p_t^{AH} = p_t^{BH} = p^n$. By the same token, the international airline prices are equal in international markets and denoted by $\hat{p}^n$, i.e., $p_a^{HD} = p_a^{HE} = \hat{p}^n$. Finally, connecting passengers that use HSR and air are paying the same in the four markets regardless of the transport mode they use in the first leg, in particular, $s^n = p^n + \hat{p}^n$.[8]

The partial-ban scenario equilibrium

In this case, one flight connecting one domestic city with the hub is banned, say in the city-pair market AH, while the one connecting B and H remains active. This introduces an asymmetry in the transportation network that implies different HSR service prices in the two local markets because the competition is different in each of them. Thus, the equilibrium price in the local market AH is denoted by p^{AHp} where superscript p after AH refers to "partial ban", while the equilibrium price in the local market BH, the one not directly affected by the ban, is p^{BHp}. Airline prices set by international airlines are the same and denoted by $\hat{p}^p$. Finally, the price paid by connecting passengers leaving from city A is different from the one paid by passengers leaving from city B, these prices are denoted by s^{AHp} and s^{BHp}, respectively.

The next result presents the price effects of a partial short-haul flights ban. This is a preliminary step that is helpful to get intuitions of such policy measure. Comparing the equilibrium prices in the two local markets, the following result holds.[9]

Result 1. *For all $\frac{\gamma}{\beta} \in (0,1)$ and for all $1 < \frac{\bar{\alpha}}{\alpha}$, the equilibrium local price in the market affected by the partial ban is greater than that in the market not affected by the ban, i.e. $p^{BHp} < p^{AHp}$. Hence, prices paid by connecting passengers leaving from city A are greater than those from passengers leaving from city B, i.e., $s^{BHp} < s^{AHp}$.*

It is worth commenting that, the effect of a partial ban is to induce a price asymmetry in markets affected by the ban, that is, passengers will pay more for the same service (given symmetry in modes and markets) in the routes affected by the ban because competition has become weaker. Similarly, Result 2 considers the effect on traffic in the local and connecting markets.

Result 2. *For all $\frac{\gamma}{\beta} \in (0,1)$ and all $1 < \frac{\bar{\alpha}}{\alpha}$, the equilibrium local HSR traffic in the market affected by the partial-ban is lower than that in the market not directly affected, while road traffic is larger in the former market, i.e., $q^{AHp} < q^{BHp}$ and $q_c^{BHp} < q_c^{AHp}$. Also, there is more connecting traffic leaving from city A than leaving from city B, i.e., $x^{BHp} < x^{AHp}$.*

The full-ban scenario equilibrium

In this case, all local markets become symmetric again as in the benchmark scenario since no flight connection exists for cities A and B leading to the hub. Hence, the equilibrium price in the local markets is denoted by p^f, where superscript f refers to "full ban". Similarly, $\hat{p}^f$ denotes the international airline price and s^f is the price paid by connecting passengers.

Proposition 1 shows the effect on equilibrium prices of the different short-haul flights bans implemented.

Proposition 1. *In case modes are not very differentiated, that is, for $0.371 < \frac{\gamma}{\beta} < 1$ and for all $\frac{\bar{\alpha}}{\alpha}$; or if the relative relevance of connecting markets is sufficiently large, that is, $\frac{3}{2} < \frac{\bar{\alpha}}{\alpha}$ and for all $\frac{\gamma}{\beta} \in (0,1)$; the effect of a short-haul fights ban is:*

(i) To increase local prices in all local markets and transport modes. Prices rise even for the local markets not affected by the ban in a partial-ban scenario. The increase is the largest for the full-ban scenario. In particular,

$$p^n < p^{BHp} < p^{AHp} < p^f.$$

(ii) To decrease international prices in all markets, where the decrease is the largest for the full-ban scenario, that is,

$$\hat{p}^f < \hat{p}^p < \hat{p}^n.$$

The effect on prices paid by connecting passengers appears in the next Proposition,

Proposition 2. *Depending on the degree of product differentiation and the relative relevance of connecting markets, the ranking on the price paid by connecting passengers is:*

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[7] A visible effect following deregulation was the development of hub and spoke networks thus distinguishing short markets from long markets. It is reasonable to assume that travellers have a higher willingness to pay for a longer trip. Note that a longer trip entails the combination of two flights that are complementary and the valuation of a bundle is normally larger than the valuation of just one of its components. Besides, the benefits to passengers increase when more flights are available; connecting passengers will more likely be willing to pay more since they value the number of flights both at the spoke and at the hub – see e.g. Heimer and Shy (2006), Kawasaki (2008) and Álvarez-SanJaime et al. (2020b). A potential limitation of the aforementioned assumption is the typical business model of low-cost carriers that focus on point-to-point routes.

[8] Equilibrium price and traffic expressions are reported in the Appendix.

[9] Proofs are relegated to the Appendix.

(i) $s^{BHp} < s^n < s^f < s^{AHp}$,
when $0.371 < \frac{\gamma}{\beta} < 1$ *for all* $\frac{\bar{\alpha}}{\alpha}$*; or when* $\rho_1(\frac{\bar{\alpha}}{\alpha}) < \frac{\gamma}{\beta} < 0.371$ *and* $\frac{3}{2} < \frac{\bar{\alpha}}{\alpha}$.
(ii) $s^{BHp} < s^f < s^n < s^{AHp}$,
when $\rho_2(\frac{\bar{\alpha}}{\alpha}) < \frac{\gamma}{\beta} < \rho_1(\frac{\bar{\alpha}}{\alpha})$ *and* $\frac{3}{2} < \frac{\bar{\alpha}}{\alpha}$.
(iii) $s^f < s^{BHp} < s^n < s^{AHp}$,
when $\rho_3(\frac{\bar{\alpha}}{\alpha}) < \frac{\gamma}{\beta} < \rho_2(\frac{\bar{\alpha}}{\alpha})$ *and* $\frac{3}{2} < \frac{\bar{\alpha}}{\alpha}$.
(iv) $s^f < s^{BHp} < s^{AHp} < s^n$,
when $0 < \frac{\gamma}{\beta} < \rho_3(\frac{\bar{\alpha}}{\alpha})$ *and* $\frac{3}{2} < \frac{\bar{\alpha}}{\alpha}$.

Whether a partial or a full-ban on short-haul flights is implemented, competition becomes weaker since there is one means of transport less. One then expects to see price increases; prices under a full ban will be the highest since the competition has been dampened in all local markets. Note, however, that trips in AH and BH markets constitute also a part of the longer trip reaching cities D and E (these price effects are collected in Proposition 1). Such complementarity is the main reason underlying the decrease in international prices in an effort to attract connecting passengers - this is important for operator profits since $\bar{\alpha}$ is bigger than α. Proposition 2 ranks the prices paid by connecting passengers. Thus, a partial ban can lead to the highest price paid by those passengers directly affected by the ban, that is, the increase in the local price is larger in magnitude than the decrease in the international price. Similarly, a full ban can benefit connecting passengers in terms of prices when transport modes are sufficiently differentiated, cases (iii) and (iv).

The following Proposition describes the effect of the different ban policies on traffic.

Proposition 3. *In case modes are not very differentiated, that is, for* $0.371 < \frac{\gamma}{\beta} < 1$ *and for all* $\frac{\bar{\alpha}}{\alpha}$*; or if the relative relevance of connecting markets is sufficiently large, that is,* $\frac{3}{2} < \frac{\bar{\alpha}}{\alpha}$ *and for all* $\frac{\gamma}{\beta} \in (0,1)$*; the effect of a short-haul fights ban is:*
(i) To increase private car traffic in all local markets. It rises even for the local markets not affected by the ban in a partial-ban scenario. The increase is the largest for the full-ban scenario. In particular,
$q_c^n < q_c^{BHp} < q_c^{AHp} < q_c^f$.
(ii) To decrease HSR traffic in all local markets, the decrease is the largest for the full-ban scenario, that is,
$q^f < q^{AHp} < q^{BHp} < q^n$.
(iii) To increase international air traffic in all markets, the increase is the largest for the full-ban scenario, that is,
$\hat{q}^n < \hat{q}^p < \hat{q}^f$.
(iv) To increase connecting traffic using HSR as follows: $x^n < x^{BHp} < x^{AHp} < x^f$.

One of the interesting features of our analysis is the consideration of private car transport. It is well known - and will become apparent in the next section - that private car is the most pollutant mode. Therefore, it is relevant to establish the traffic split that results from a short-haul flights ban, whether partial or full. Part (i) indicates that car traffic will increase, even in markets not directly affected by bans. Since competition becomes weaker, the price of HSR goes up and so HSR local traffic inevitably falls (part ii). The price effects explained above lead to an increase in international air traffic (part iii), and therefore there is pollution transfer from local to international levels. Note that the total demand of an international airline also includes connecting passengers that have reached the hub using HSR, hence the choice of international air price depends on the HSR price. It can be checked that these prices are strategic substitutes and the aforementioned strategic response follows. Finally, connecting HSR passenger traffic is the highest following a full ban, which is a beneficial consequence of such a measure. That is, the ban implies that some former connecting users using local airlines now move to HSR and this increase more than compensates the reduction in those formerly using HSR before the ban since HSR price increases.[10] These mixed effects on traffic make it hard to reach definite conclusions regarding welfare and environmental damages. The objective of the next section is to provide an empirical application that allows for a quantitative assessment, which should be helpful for evaluating these policy measures.

Table 1
Data for the four considered city-pair markets in 2018.
Source: AENA, RENFE, DG. of Transport, Ministry of Works and own elaboration.

	BCN-MAD	VLC-MAD	MAD-MIA	MAD-NYC
HSR				
km by HSR	506	303		
Pass. per day and direction	5879	3021		
% connect. HSR passengers	0.4	0.3		
Air				
km by air	487	293	7100	5762
Pass. per day and direction	3382	495	957	1068
% connect. air passengers	0.5	0.6		
Private transport (car)				
km by car	617	356		
Pass. per day and direction	3041	8386		
% connect. car passengers	0.1	0.1		

4. An empirical application to Spain

The analysis in this section is a follow-up of earlier work in Cantos-Sánchez et al. (2023), and so the data on the domestic routes are the same. The novelty here is the presence of an international flight and of connecting passengers to airports in the USA; in that way we are more accurate in simulating the actual world-spanning network feature in transport markets. There are no official statistics about the proportion of connecting passengers. For this reason, we have used qualitative information coming from managers of airlines and train operators in order to provide a first approximation to the proportion of connecting passengers depending on the mode and the analysed route. A sensitivity exercise will be undertaken in order to provide a greater consistency to our results.

Following the notation in Fig. 1, and considering the markets for the corridor Barcelona-Madrid-Miami (denoted BCN-MAD-MIA) we assume that Barcelona is the local airport A which connects with the hub airport H placed in Madrid and Miami International is airport D. As of 2018, there was no direct connection between Barcelona and Miami, nowadays American Airlines operates one non-stop flight. Table 1 reports data on traffic per mode and between these city pairs. A proportion (40%) of HSR passengers is assumed to be connecting of which 5% have Miami as their final destination.[11] The remainder of connecting passengers go to other international destinations grouped as city E. The percentages of connecting passengers for air and car traffic are 50% and 10%, respectively, of which 5% fly to Miami.

Further note that there are also some connecting passengers reaching Madrid from other local cities, grouped as city B.[12] Finally, there is a number of passengers that board in Madrid, which together with the connecting passengers add up to the actual data between Madrid and Miami reported in Table 1. A similar procedure is followed in the calibration of the corridor Valencia-Madrid-New York City (denoted VLC-MAD-NYC), noting that there are slight differences in the percentages owing to conversations with operators' managers.

[10] The same qualitative results are obtained had we assumed quantity competition instead. Computations are available upon request.

[11] From total passengers moving in Madrid-Barajas outside the EU in 2018 (close to 16 millions), 5.4% travelled to and from Miami International Airport.

[12] There are several routes where there is competition between HSR and air, and where Madrid can be connected in less than three hours and a half by train. Among these, the most important routes link Madrid with Barcelona, Valencia, Sevilla, Alicante and Málaga.

Table 2
Own and cross demand elasticities.
Source: See Ortega-Hortelano et al. (2016), Martín and Nombela (2008) and Román et al. (2010).

	HSR	Air	Car
HSR	−0.65	0.39	0.21
Air	0.39	−1.22	0.25
Car	0.21	0.25	−0.53

Table 3
Operating costs per passenger in €.
Source: Own elaboration from Campos and De Rus (2009) and Swan and Adler (2006).

	BCN-MAD	VLC-MAD	MAD-MIA	MAD-NYC
HSR	65	45	–	–
Air	80	65	450	400

The Barcelona-Madrid and Valencia-Madrid are two routes to which a short-haul flights ban would potentially be applied and where a HSR service connects both cities in less than three and a half hours. We consider these two routes because they represent two good examples of an interurban market where HSR and air compete strongly, but with significant differences. In terms of the total traffic (HSR, air and car)[13] the number of passengers is close to 12,000 passengers per day and direction, but the modal distribution is totally different between both routes. In Barcelona-Madrid, private car represents 26% of total traffic, but is 70.4% in Valencia-Madrid. And air traffic in Barcelona-Madrid represents 28.9% but only 4.2% in Valencia-Madrid. Finally, HSR supposes 45.1% of total traffic in Barcelona-Madrid, and 25.4% in Valencia-Madrid. These figures denote that the modal distribution is more balanced in Barcelona-Madrid than in Valencia-Madrid, and the relevance of the private car is much greater in Valencia-Madrid. Finally, Madrid-Barajas airport is the largest Spanish international hub totalling 46.7 million passengers, of which more than 73% flew abroad and with more than 175 airlines using its facilities. About 17 million passengers reached extra-EU destinations. Madrid-New York City and Madrid-Miami are among the top 5 non-EU destinations.

In order to calibrate the parameters of the utility functions, values on prices, traffic levels and price elasticities were used. In particular, values on own and cross price elasticities are displayed in Table 2. Regarding transport operating costs, we employ data for the cost per passenger by HSR and air for each city-pair, as displayed in Table 3.

Compared with (Cantos-Sánchez et al., 2023), there are three additional connecting passengers using HSR, air or private car in the first leg of their trip, plus other passengers moving from the hub either to Miami or to New York City. Table 4 reports values for the calibrated parameters. Note that the calibrated relative willingness to pay between the connecting and the other markets for the VLC-MAD-NYC corridor is larger than for the BCN-MAD-MIA. Besides, the air mode is the closest substitute to private car in the former corridor, while it is HSR in the latter. The differences in these two dimensions will prove important in explaining the diverse effects of bans in the simulations below.

Finally, in order to introduce the external costs in our model we use the classification of external costs borrowed from the Handbook elaborated by the EU ("Handbook on the external costs of transport", version 2019 – 1.1). As we did in Cantos-Sánchez et al. (2023), we will follow two approximations. In the first one, only external costs of environmental type are considered. In this case we take into account effects on air pollution, climate change, congestion and well-to-tank. We assume that congestion implies additional pollution and environmental effects. In the second approximation we include all the external costs provoked by transport. Then, the external costs in terms of accidents, habitat damage and noise are added to the former costs. We differentiate between the external costs per transport mode and also by those provoked by short and by long-haul flights. Table 5 displays the values of such external costs per passenger-km.

Results for the simulation process are shown in Tables 6 to 11. Two columns appear for each simulation, one where air transport competes with HSR and car, and another where local air transport is removed. In the latter, a full short-haul flights ban is assumed. This is a simplification since the Spanish proposal would apply to all local flights where HSR can offer a service in less than three hours and a half. In any case, simulations of a partial ban have been run with no qualitative changes. The percentage variation due to the ban is shown in a row below the corresponding item.

Table 6 shows the results in terms of the different prices. The ban would induce a 10.8% increase in train prices in BCN-MAD, but by much less, 1.9%, for VLC-MAD. These increases are smaller than those obtained in Cantos-Sánchez et al. (2023), where all users were

[13] The passengers by interurban bus hardly represent 4.4% in Madrid-Barcelona and 2.2% in Madrid-Valencia.

Table 4
Calibrated utility function parameters.

Local market:	BCN-MAD	VLC-MAD
β_t^{iH}	0.046	0.036
β_a^{iH}	0.066	0.375
β_c^{iH}	0.059	0.016
γ_{ac}^{iH}	0.030	0.046
γ_{ta}^{iH}	0.029	0.029
γ_{tc}^{iH}	0.025	0.009
α_t^{iH}	402.14	235.13
α_a^{iH}	406.46	535.98
α_c^{iH}	360.16	172.89
International market:	**MAD-MIA**	**MAD-NYC**
β_a^{Hj}	0.744	0.797
α_a^{Hj}	727.49	762.70
Connecting market:	**BCN-MAD-MIA**	**VLC-MAD-NYC**
β_{ta}^k	0.378	0.734
β_{aa}^k	0.287	1.967
β_{ca}^k	2.908	0.782
γ_{ac}^k	0.101	0.578
γ_{ta}^k	0.140	0.439
γ_{tc}^k	0.124	0.248
α_{ta}^k	697.05	681.89
α_{aa}^k	662.23	706.97
α_{ca}^k	641.24	635.38

Table 5
Average external costs per passenger-km and transport mode (€ cents per pass-km)
Source: "Handbook on the external costs of transport". 2019. European Commission et al. (2021)

	HSR	Air (short-haul)	Air (long-haul)	Private car
Air pollution	0.0	0.30	0.06	0.7
Climate	0.0	2.39	2.24	1.2
Congestion	0.0	0.00	0.00	4.2
Well-to-Tank	0.3	1.06	0.91	0.4
Total environm. costs	0.3	3.75	3.21	6.5
Accidents	0.1	0.04	0.00	4.5
Habitat damage	0.6	0.03	0.00	0.5
Noise	0.3	0.46	0.01	0.6
Total external costs	1.3	4.28	3.22	12.1

Table 6
Simulated prices of the no-flights policy.

Prices	BCN-MAD-MIA		VLC-MAD-NYC	
	HSR+Air	Flights ban	HSR+Air	Flights ban
HSR	125.11	138.58	95.39	97.23
		10.8%		1.9%
Local air	111.14		92.78	
International air	513.83	516.42	507.33	504.82
		0.5%		−0.5%

Table 7
Simulated traffics from BCN and VLC to MAD.

Passenger traffic	BCN-MAD		VLC-MAD	
	HSR+Air	Flights ban	HSR+Air	Flights ban
Total HSR	5880	6020 2.4%	3321	3385 1.9%
• local	3528	3909 10.8%	1992	1957 −1.8%
• connecting to other destinations	2234	2005 −10.3%	1261	1357 7.5%
• connecting BCN-MAD-MIA	118	106 −9.9%		
• connecting VLC-MAD-NYC			66	71 7.5%
Total air	3382		495	
• local	1691		198	
• connecting to other destinations	1606		282	
• connecting BCN-MAD-MIA	85			
• connecting VLC-MAD-NYC			15	
Total private car	3041	3802 25.0%	8387	9209 9.8%
• local	2737	3447 25.9%	6708	7285 8.5%
• connecting to other destinations	289	337 16.7%	1593	1828 14.8%
• connecting BCN-MAD-MIA	15	18 18.4%		
• connecting VLC-MAD-NYC			83	96 14.8%

considered local. Although, the intensity of competition is lessened, the presence of connecting passengers in the current paper and the complementary feature of international prices moderate the increases in train prices in order not to lose too many passengers in the international leg. A key point in our results is how the air international price responds in a different way depending on the corridor considered. In BCN-MAD-MIA, the ban would lead to an increase in the international price by 0.5%, while in VLC-MAD-NYC it would decrease by 0.5%. This qualitative difference can be explained in terms of Proposition 1 above. Note that, with the required simplifications, we observe that if the relative relevance of connecting markets is sufficiently large (as defined earlier and clearly larger in the VLC-MAD-NYC corridor), then a short-haul flights ban would lead to a reduction in the international air price.

Table 7 shows the traffic generated in the first leg of the two corridors and its distribution depending on the transport mode and whether passengers travelling from VLC or BCN to MAD belong to the local or connecting markets as defined in Section 3. Note that changes in the HSR traffic levels for the local markets are similar in BCN-MAD and VLC-MAD. In particular, the air ban would lead to increases by 2.4% and by 1.9% respectively. However, their distribution is different, for instance, HSR local passengers in BCN-MAD increase (by 10.8%) while connecting passengers either to Miami or to other destinations decrease by 10.3% and 9.9%, respectively. For the VLC-MAD route the increase in HSR passengers is explained by a notable increase in connecting passengers partially outweighed by a decrease in the number of local market passengers. Regarding private car, passengers increase notably by 25.0% in BCN-MAD and by 9.8% in VLC-MAD. But again there are differences across markets since the increase is larger in connecting markets for VLC-MAD, while passengers of the local market increase the most in BCN-MAD.

Table 8 shows the results for traffic in the leg from MAD to NYC and MIA distinguishing between passengers in the international market and those connecting passengers with origin VLC or BCN and other origins. The ban would have different effects depending on the corridor. Hence, the total number of passengers would increase by 1.4% in the MAD-NYC route following the decrease in the international air price, while it would decrease by more than a 30% in the MAD-MIA as the corresponding international air price increases. The local air ban would affect connecting passengers the most since it produces a significant decrease by more that 40% in both the passengers with origin BCN and with other origins connecting to MIA. Opposite effects arise in MAD-NYC.

Table 8
Simulated traffic from MAD to MIA and NYC.

Passenger traffic	MAD-MIA		MAD-NYC	
	HSR+Air	Flights ban	HSR+Air	Flights ban
Total	957	663 −30.7%	1068	1083 1.4%
• international	287	284 −1.1%	320	324 1.3%
• connecting from other origins	453	254 −43.9%	641	650 1.4%
• connecting BCN-MAD-MIA	217	126 −41.9%		
• connecting VAL-MAD-NYC			107	109 2.8%

Table 9 shows operating profits and passenger surplus in the different markets. Regarding profits, the HSR operator increases its profitability in both routes specially BCN-MAD (by 25.3%). However, international airlines will see a profits reduction, especially in MAD-MIA, where they fall by 27.8%. Considering passenger surplus, all types of passengers are worse off in the BCN-MAD-MIA corridor. Passengers in the local market are worse off by 10.2%, and connecting passengers are the most affected, their surplus is reduced by 51.1%. In the other corridor, the small increase in HSR price leads to a decrease in passenger surplus for local passengers, while the decrease in the international air price and in the composite price will make connecting and international passengers slightly better off. Adding the effect on operators' profits and passenger surplus per market, we find that social welfare in the BCN-MAD-MIA corridor is reduced for all markets. However, for the other corridor there is a welfare increase in the international market.

Table 10 displays the environmental effects of the short-haul flights ban. Firstly, we provide the total effect per corridor and distinguish by traffic located in Spain including all modes, and by traffic served by

Table 9
Simulated Profits and passenger surplus.

	BCN-MAD-MIA		VLC-MAD-NYC	
	HSR+Air	Flights ban	HSR+Air	Flights ban
Operating profits				
HSR	353,433	442,914 25.3%	167,320	176,799 5.7%
Local airline	105,308		13,751	
Intern. airline	61,065	44,066 −27.8%	114,626	113,470 −1.0%
Passenger surplus				
Local market	1,149,150	1,032,385 −10.2%	645,629	637,165 −1.3%
International market	30,661	29,921 −2.4%	40,911	41,719 2.0%
Connecting market	5,716	2,795 −51.1%	7,324	7,449 1.7%

Table 10
Environmental costs per type and market.

	BCN-MAD-MIA		VLC-MAD-NYC	
	HSR+Air	Flights ban	HSR+Air	Flights ban
Environmental costs				
Total	410,765	312,733 −23.9%	400,050	416,406 4.1%
• Spain	192,655	161,629 −16.1%	202,513	216,181 6.7%
• Abroad	218,110	151,104 −30.7%	197,537	200,225 1.4%
Environmental costs per market				
Local	146,005	144,164 −1.3%	159,231	179,347 7.0%
International	65,413	64,619 −1.2%	59,261	59,844 1.0%
Connecting	51,869	28,974 −44.1%	32,705	33,299 1.8%

Table 11
External costs per type and market.

	BCN-MAD-MIA		VLC-MAD-NYC	
	HSR+Air	Flights ban	HSR+Air	Flights ban
External costs				
Total	551,959	472,093 −14.5%	577,677	609,859 5.6%
• Spain	333,236	320,419 −3.9%	379,524	409,010 7.8%
• Abroad	218,723	151,674 −30.7%	198,153	200,894 1.4%
External costs per market				
Local	261,004	281,057 7.7%	298,721	320,911 7.4%
International	65,617	64,820 −1.2%	59,446	60,030 1.0%
Connecting	53,302	30,156 −43.4%	34,677	35,508 2.4%

the international airlines, and hence abroad.[14] Secondly, we separate the effects produced by traffic in the different markets. Again, the results are very sensitive to the considered corridor. In the case of BCN-MAD-MIA, the ban would produce a reduction of total environmental costs by 23.9%, and such reduction occurs regardless of the place and the market considered. Note that the reduction in damage in Spain is 16%, which is slightly higher than the one obtained in Cantos-Sánchez et al. (2023). The largest reduction, however, is produced abroad reaching 30.7%. Hence, a local policy measure produces a bigger effect abroad than that in the target area. In terms of markets, the largest reduction happens through traffic in the connecting market, while the environmental costs reduction reached by the other markets is limited.

However, the air ban would produce completely opposite results in the VLC-MAD-NYC corridor. The increase is largest for the traffic located in Spain, by 4.7%, and per market the largest increase is generated by local traffic, 6.1%. The following descriptive evidence emphasizes the policy relevance of ban for local markets. For example, Bombardier CRJ-1000 is the model employed by Air-Nostrum for flights between VLC and MAD, which consumes approximately 1804 kg of aviation fuel. This translated to 5.7 tons of CO2. To draw an equivalence for car trips, the most common car brands in Spain in 2018 were SEAT Ibiza, RENAULT Megane and VOLKSWAGEN Golf, which on average emit 139.0 gr of CO2 per km, that is 49.48 kg of CO2 per trip between VLC and MAD. Therefore, in terms of CO2 emissions a flight between VLC and MAD is equivalent to 115 cars. Similar calculations would yield that a flight on an Airbus A320-200 between BCN and MAD is equivalent to 168 cars.[15]

Note that international markets are operated only by airlines on long-haul routes with minimal differences between environmental and external costs. Therefore, these are the markets where pure strategic effects generated by local bans show up. Their effects on such markets are only explained by the strategic reaction of the international airlines by increasing or decreasing the international price set.

Finally, Table 11 shows the effects considering all external cost; it can be seen that they are qualitatively similar to those reported in Table 10. There is one exception, a 7.8% increase in the local market for the BCN-MAD-MIA corridor, mainly explained by the growth in private car traffic.

5. Robustness

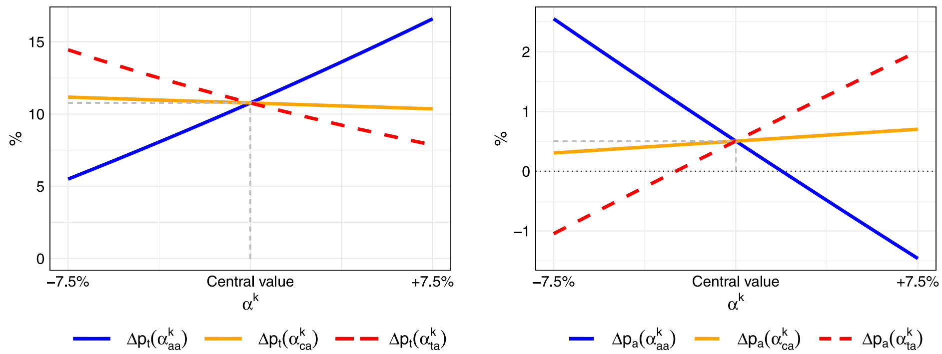
5.1. Sensitivity

In this subsection, we perform a sensitivity analysis to check the dependence of our empirical results on the users' willingness to pay in the connecting market, given its relevance as shown in Section 3. The interval considered is ±7.5% with respect to the calibrated values of α^k_{aa}, α^k_{ca}, and α^k_{ta}. Figs. 2 and 3 display the HSR price and international air price percentage variations (where, e.g. $\Delta p_t(\alpha^k_{aa})$ denotes the one for the HSR price when α^k_{aa} varies) due to the short-haul flights ban for BCN-MAD-MIA and VLC-MAD-NYC corridors, respectively.

Focusing first on BCN-MAD-MIA, Fig. 2(a) shows that the effect on HSR price decreases with α^k_{ta} and α^k_{ca}, while the effect becomes larger as α^k_{aa} increases. Interestingly, opposite effects arise on international air price variations shown in Fig. 2(b). Note, however, that the sign of the effect on the international air price changes for variations in α^k_{aa} and α^k_{ta}. When α^k_{ta} is about 2.5% lower than our calibrated value (see Table 4), a ban would reduce the international air price instead of increasing it. The international air price will also fall if α^k_{aa} is high enough (+2%). In the VLC-MAD-NYC corridor, Fig. 3(a) illustrates similar effects for the HSR price, i.e. the increase in HSR price is lower when α^k_{ca} and α^k_{ta}

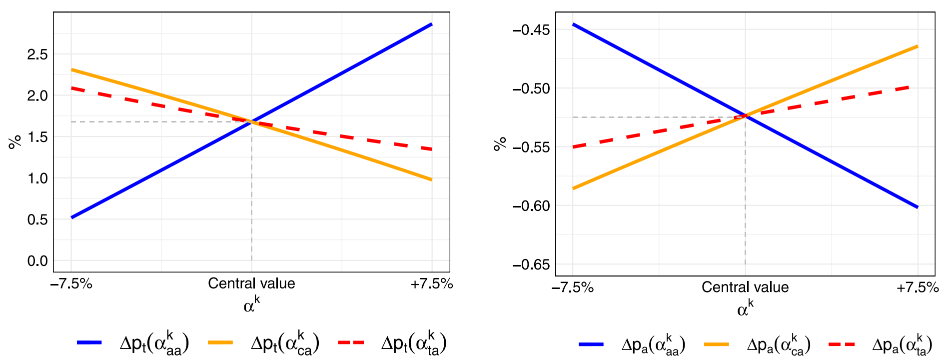
[14] For instance, the environmental damage generated in Spain by the BCN-MAD-MIA corridor is the result of adding the damage per transport mode. In the case of HSR, it is the result of multiplying the damage per passenger-km (0.3) by the passengers using HSR (5880) by the km by HSR between BCN and MAD (506), similarly for the other two modes. While the environmental damage generated abroad is the result of multiplying the number of passengers flying to Miami (957) by its damage per passenger-km as travelling by a long-haul route (3.21) by the 7100 km. between Madrid and Miami.

[15] To evaluate these equivalences, data have been drawn from www.seatguru.com, for aircraft models on 23rd April 2024; coches.idae.es/base-datos/marca-y-modelo for the CO2 emissions per car model; ICAO (2023) for aircraft fuel consumption per distance and IATA for the carbon emission factor.



(a) HSR price (b) International air price

Fig. 2. Sensitivity for α^k parameters for the BCN-MAD-MIA corridor.



(a) HSR price (b) International air price

Fig. 3. Sensitivity for α^k parameters for the VLC-MAD-NYC corridor.

rise and that increment is lower when α^k_{aa} rises. Opposite effects for the international air price. Overall, we can say that the ban effects on prices, Table 6, are robust to relevant variations in α^k's, except for international air price in the BCN-MAD-MIA corridor, where the tolerance is around 2.5%, which is not a negligible change in terms of willingness to pay. This underlines that the relative relevance of connecting markets is a decisive factor to be considered when assessing the consequences of such ban policy and already highlighted in Proposition 1.

We also run a sensitivity analysis for user surplus (US), environmental costs (EC) and external costs (ExtC) for the BCN-MAD-MIA and VLC-MAD-NYC corridors (Figs. 4 and 5, respectively). The first row displays how percentage changes in α^k_{aa} affect percentage variations in US, EC and ExtC by evaluating separately the three markets: local, connecting (con) and international (int). In the BCN-MAD-MIA corridor, the short-haul flights ban reduction in user surplus is robust for the local and connecting markets. The size of the negative effect in the connecting market becomes smaller for larger α^k_{ca} and α^k_{ta} values, while it becomes bigger for larger α^k_{aa} values. In the international market, user surplus improves with the ban when α^k_{aa} is high enough and α^k_{ta} is low enough, both of which are direct consequences of international air price changes. Environmental costs reductions are robust for connecting markets. Regarding local and international markets the effects vary depending on which willingness to pay varies. For instance, when α^k_{aa} is high enough, the ban increases environmental costs in these markets. Finally, both the external costs increase in the local market and the decrease in connecting markets is robust, thus confirming our simulation results.

In the VLC-MAD-NYC corridor, increases in environmental costs and external costs are robust to willingness to pay variations. Regarding the effect on user surplus, it is quite stable except for the connecting market, where the sign of the effect depends on the values of α^k's. For high values of α^k_{aa}, the short-haul flights ban reduces user surplus, while this negative effect takes place when α^k_{ca} and α^k_{ta} are low. These differences mirror the behaviour of HSR price changes.

5.2. Monte Carlo simulations

We have run 1000 replications of the model to further evaluate the consistency of the results to the calibrated own-elasticities, on the one hand, and operating costs and the cost of use of private car on the other hand, ceteris paribus.

For both corridors, we assume that the own-elasticities are uniformly distributed within a reasonable range of values, as considered in the literature (see Ortega-Hortelano et al., 2016; Martín and Nombela, 2008; Román et al., 2010). Similarly, we assume that operating costs and the cost of car use are uniformly distributed within an interval of $\pm 20\%$, except for international air operating costs that is $\pm 10\%$. Table 12 reports the descriptive statistics of the parameters used to perform Monte Carlo simulations for the BCN-MAD-MIA corridor with 1000 realizations.

For the sake of presentation, we only report the simulation results of changes in own-price elasticities, while the results of changes in costs are available upon request. Fig. 6 displays the effect of the ban on HSR and air international price percentage variations (panel a), on local and connecting traffics (panel b), on user surplus per passenger type (panel c) and environmental damages for both Spain and abroad (panel d). The boxes cover all values between the 25th and the 75th percentile, while the whiskers extend to the most extreme values that are not considered outliers. The horizontal lines inside the boxes and diamonds represent the median and mean of the distribution, respectively.

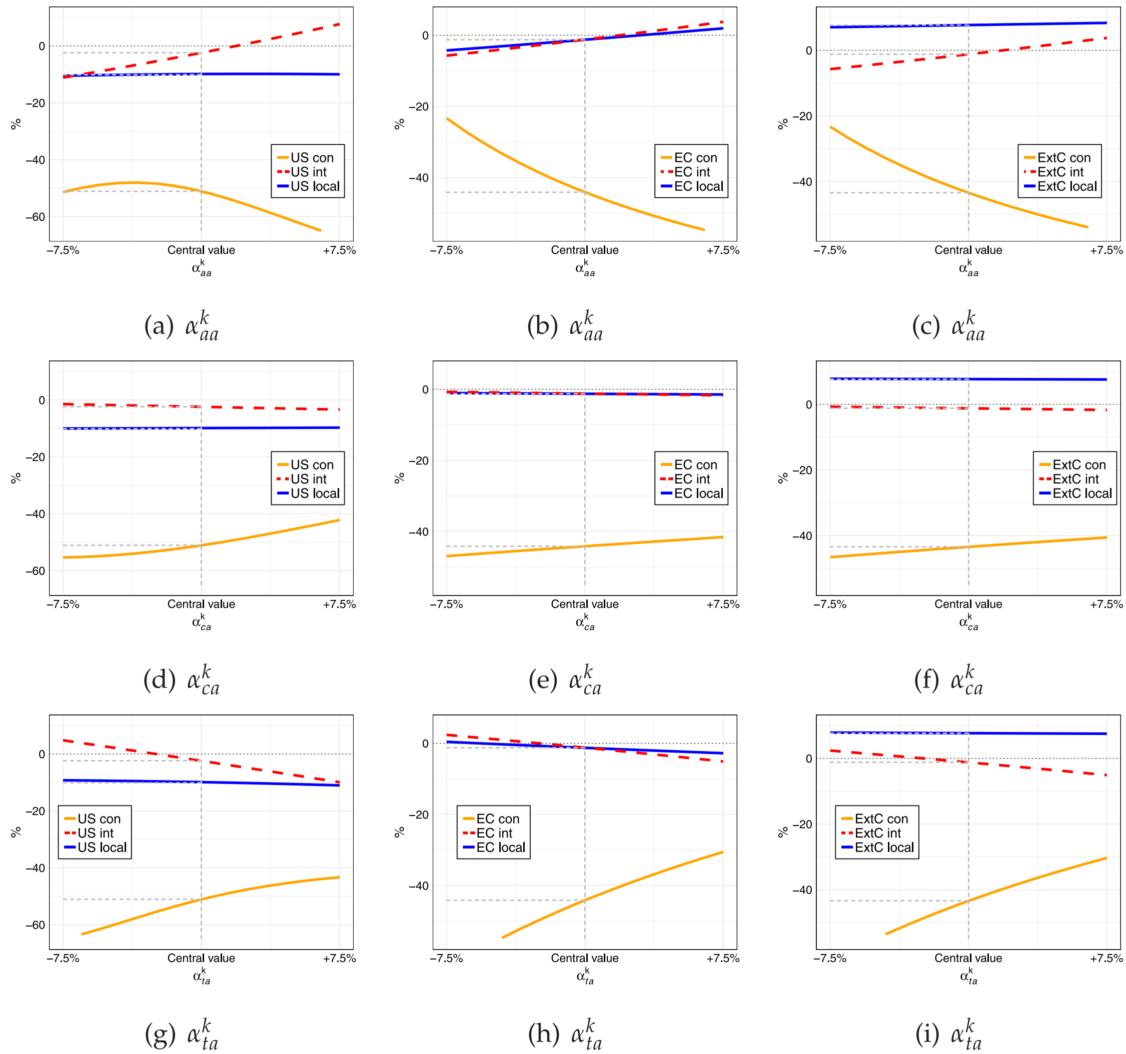


Fig. 4. User surplus, environmental and external costs BCN-MAD-MIA per market.

Table 12
BCN-MAD-MIA descriptive statistics of Monte Carlo simulations.

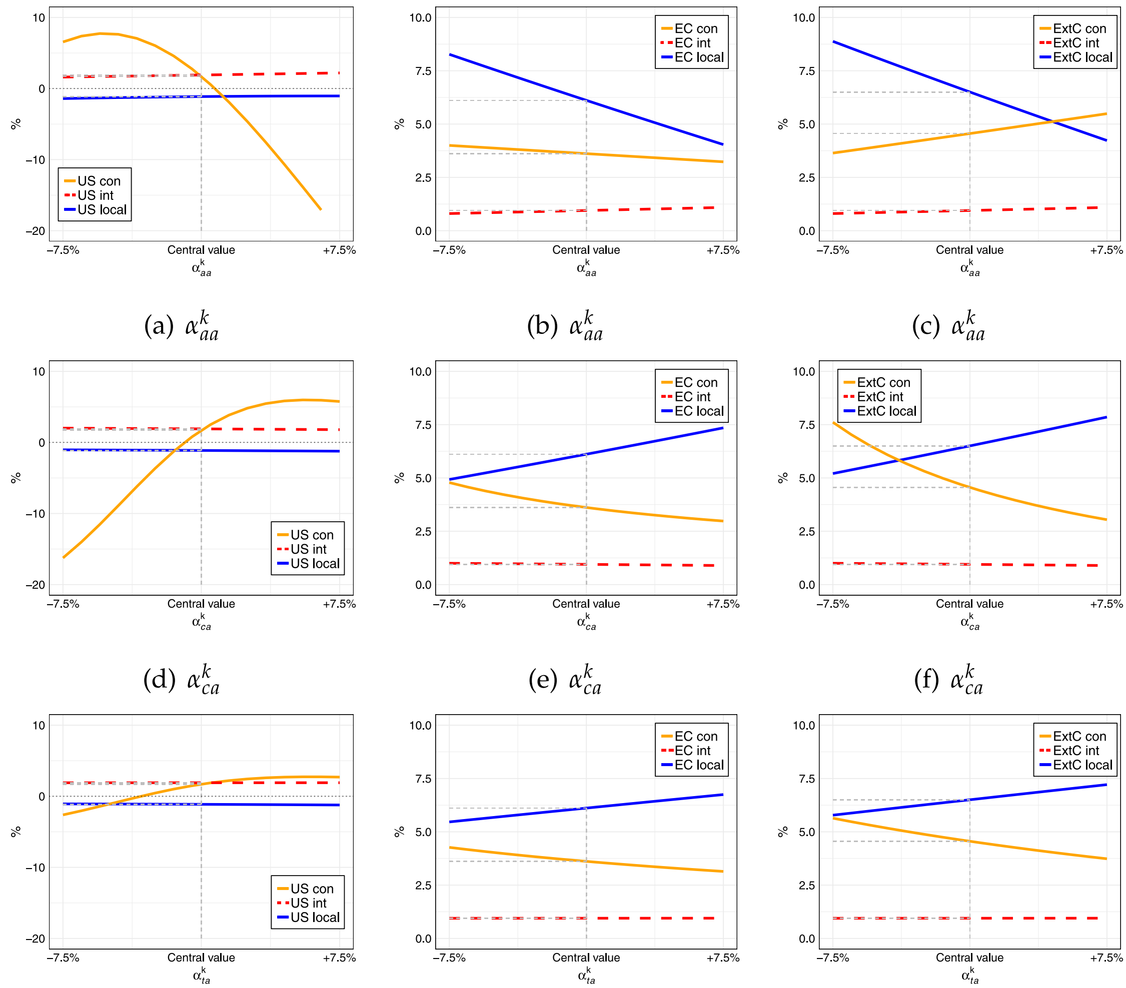
Own-price elasticities						
	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
HSR	−0.72	−0.68	−0.65	−0.65	−0.61	−0.58
Air	−1.53	−1.42	−1.29	−1.29	−1.16	−1.05
Car	−0.60	−0.55	−0.50	−0.50	−0.45	−0.40
Operating costs per passenger						
	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
HSR	52.01	59.13	65.81	65.50	71.94	77.99
Air	64.03	72.38	80.40	80.07	87.97	95.97
Car	48.01	53.92	59.54	59.76	65.59	71.98
Int. Air	405.10	425.60	448.70	449.40	472.40	494.90

Table 13
VLC-MAD-NYC descriptive statistics of Monte Carlo simulations.

Own-price elasticities						
	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
HSR	−0.72	−0.69	−0.65	−0.65	−0.62	−0.58
Air	−1.53	−1.43	−1.31	−1.30	−1.19	−1.07
Car	−0.60	−0.55	−0.50	−0.50	−0.45	−0.40
Operating costs per passenger						
	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
HSR	36.03	40.90	45.31	45.24	49.84	53.99
Air	52.00	58.06	64.69	64.88	71.13	78.00
Car	28.00	31.79	34.91	35.01	38.47	42.00
Int. Air	360.10	379.80	400.80	400.00	419.10	439.80

The pattern of simulation results are in line with our findings. The boxplots seldom cross the dashed-red lines that identify differences in the sign of the changes of the corresponding variable. For instance, in panel (a) the ban may result in a decrease in international air price for values close to the minimum of the distribution of that price change, although that variable is significantly greater than zero (p-value < 0.001, one-tailed one-sample Wilcoxon test). Note, however, that some variables, such as car traffic, show greater dispersion in the face of variations in the own elasticities. The results are also found to be robust to changes in parameter costs. The one-sample Wilcoxon test consistently rejects the hypothesis that policy effects are zero, providing evidence to support the direction of the effects observed in the empirical application section.

Table 13 reports the descriptive statistics of the parameters used to perform Monte Carlo simulations for the VLC-MAD-NYC corridor with 1000 realizations. Fig. 7 displays the simulation results for the VLC-MAD-NYC corridor. It can be seen that, except for some outliers, the effects of the ban policy are robust to variations in own-elasticities. One-sample Wilcoxon tests reject the null hypothesis that policy effects are zero, confirming the results in Section 4.



(a) α^k_{aa} (b) α^k_{aa} (c) α^k_{aa}

(d) α^k_{ca} (e) α^k_{ca} (f) α^k_{ca}

(g) α^k_{ta} (h) α^k_{ta} (i) α^k_{ta}

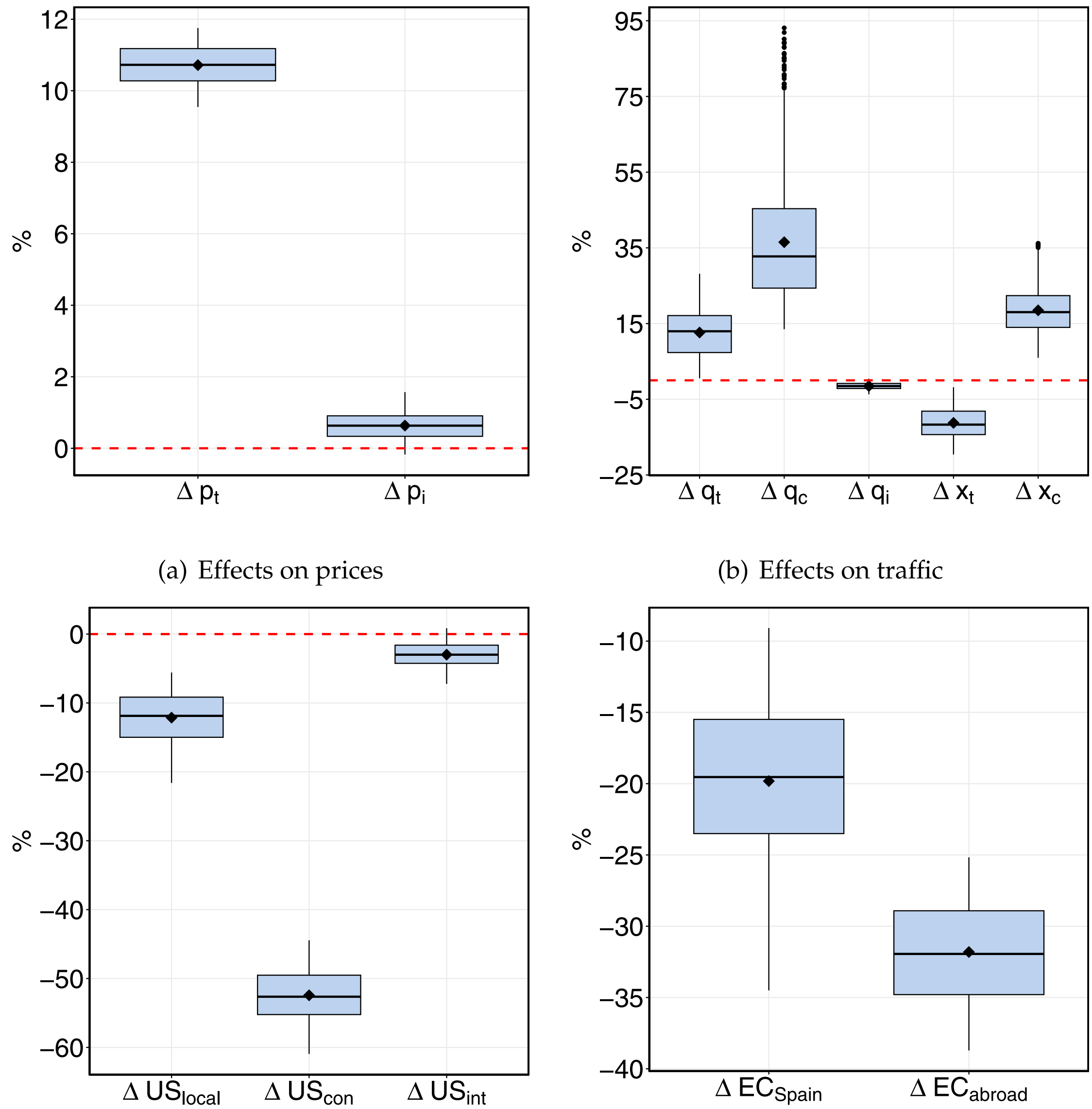
Fig. 5. User surplus, environmental and external costs VLC-MAD-NYC per market.

6. Conclusions and policy recommendations

The air transport sector is on the spot due to its impact on climate change impact in terms of greenhouse emissions. Several European countries are considering banning short-haul flights where more environmentally friendly alternative transportation, such as high-speed rail, is available. However, before adopting such a policy, it is advisable that regulators take a comprehensive picture of all its effects.

This paper has formally examined the consequences of a short-haul flights ban regarding prices, traffic, agents' surpluses, and environmental costs. The distinguishing features of our analysis are: (i) a transportation network, so that demand substitution and complementarity across modes are both accounted for, (ii) users that have the option to use their private car, and (iii) the consideration of a number of external costs associated to each mode. Bans imply the elimination of a transport mode and hence a reduction in competition intensity. As a result, HSR prices will increase, and to make connecting trips more appealing, the strategic response of international air prices is a decrease. Besides, car traffic will increase, which anticipates that, given these effects on prices and traffic, it is unclear whether short-haul flights bans are beneficial in terms of welfare and environmental damages. The simulation for two routes in which the local (Spanish) markets show differences in modal split allow for a quantitative assessment of the expected effects following a short-haul flights ban. Thus, in markets where air and HSR are not too differentiated in the eyes of passengers, bans may reduce environmental damages and total external costs; however, welfare gross of damages falls. In contrast, if instead we examine a market in which air and the private car are the closest substitutes, then bans lead to larger environmental damages and total external costs. Welfare gross of damages always falls in local and connecting markets.

Our study suggests several policy implications. Firstly, a case-by-case approach is recommended since bans may well lead to increased environmental damages. Secondly, although the welfare conclusions may be ambiguous, short-haul flights bans do have distributional implications. From the point of view of firms, bans favour HSR profits whereas those of air operators drop. Looking at passenger type, passengers in the local market experience a decrease in their surplus; passengers in the international and the connecting markets would be better off when air transport and the private car are rather close substitutes, otherwise these passengers would be worse off. Thirdly, and in the light of the local–global pollution dichotomy, note that the (strategic) responses in international air prices may produce an increase in international and connecting traffic, which eventually leads to higher environmental and total external costs in the international segment. Therefore, a local policy measure to reduce pollution may have negative consequences elsewhere. Fourthly, and to mitigate the potential harmful effects of short-haul flights bans, complementary measures would be advisable in further reducing the aerospace industry carbon footprint. Among them, experimenting with new technologies,



(a) Effects on prices (b) Effects on traffic

(c) Effects on user surplus (d) Effects on environmental costs

Fig. 6. Monte Carlo simulation results for percentage variations in the BCN-MAD-MIA corridor own-price elasticities (1000 realizations). Diamonds represent the mean of the distribution.

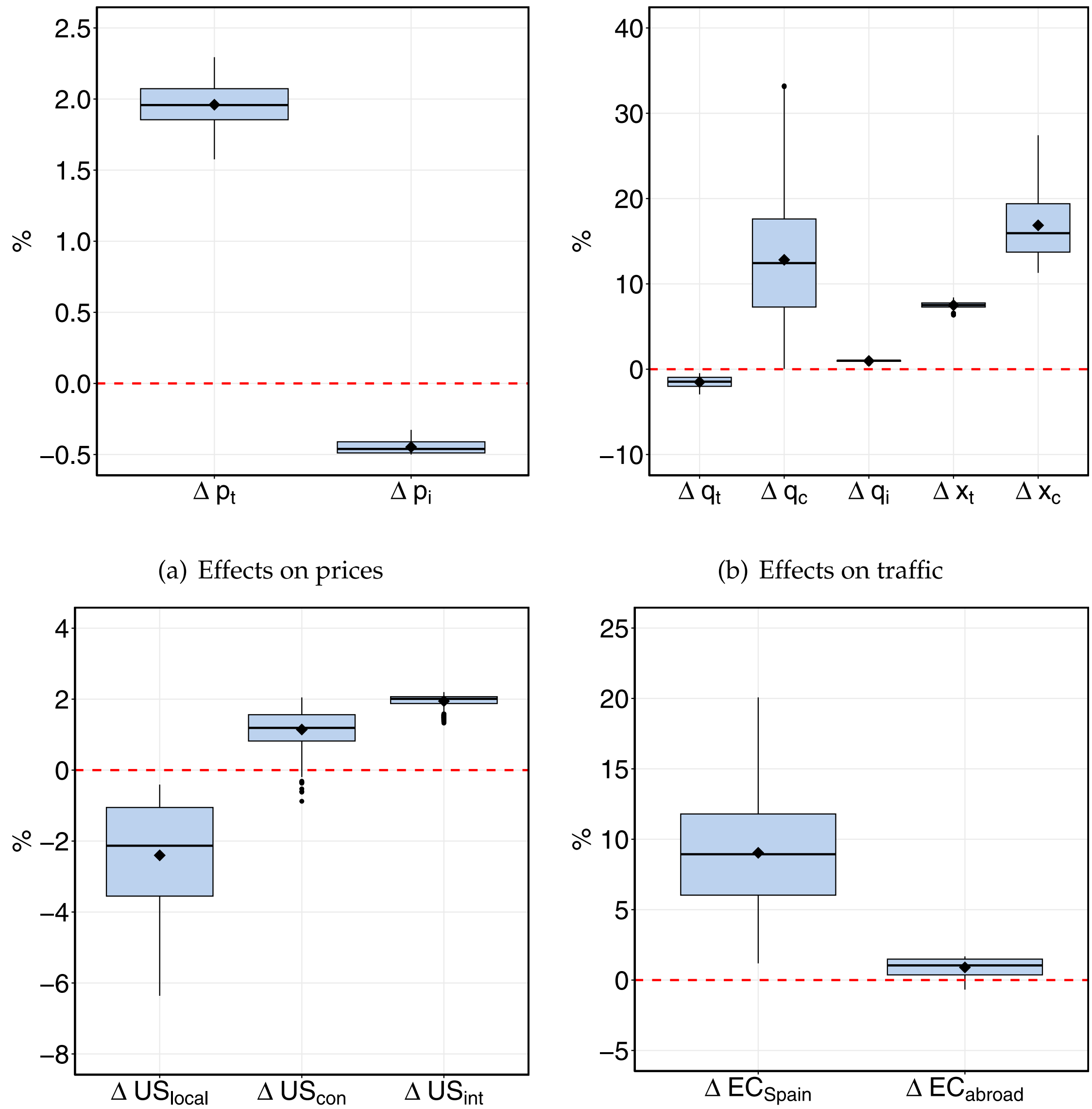
and investing in the design of policies that encourage the use of environmentally friendly travel alternatives (namely, more fuel-efficient cars and the adoption of sustainable aviation fuel). Another measure would be the adoption of carbon taxes on car use. For example an increase in the cost of car use by 19% would offset the negative environmental effects of bans in the VLC-MAD-NYC route. Also, the introduction of on-track competition in HSR services would drive HSR prices down and enhance the use of such a cleaner alternative.

The consideration of the above mentioned elements suffices to simulate, for specific corridors, the various effects that arise from a short-haul flights ban policy. Extending the model to other transportation networks would make the analysis a more complex one, although the same qualitative results are expected. Further research might look into how our findings would be shaped by the presence of infrastructure access fees, the availability of electric vehicle charging networks, frequency choices by operators, changes in passenger preferences towards greener modes, or by considering corridors where the private car is no longer a travelling alternative. We believe that ours is a comprehensive initial setting on the expected effects of short-haul flights bans that may be helpful in the design of informed transport policy measures to attenuate the climate impact of air transportation.

CRediT authorship contribution statement

Pedro Cantos-Sanchez: Writing – original draft, Supervision, Methodology, Conceptualization, Validation, Writing – review & editing. **Rafael Moner-Colonques:** Writing – original draft, Methodology, Formal analysis, Conceptualization, Writing – review & editing. **Alba Ruiz-Buforn:** Writing – original draft, Validation, Software, Methodology, Conceptualization, Writing – review & editing. **Jose J. Sempere-Monerris:** Writing – original draft, Methodology, Formal analysis, Conceptualization, Writing – review & editing.

Appendix A. Equilibrium prices and traffics



(a) Effects on prices

(b) Effects on traffic

(c) Effects on user surplus

(d) Effects on environmental costs

Fig. 7. Monte Carlo simulation results for percentage variations in the VLC-MAD-NYC corridor own-price elasticities (1000 realizations). Diamonds represent the mean of the distribution.

We provide the equilibrium prices and traffics for each scenario.

Benchmark scenario

Equilibrium prices read

$$p^n = \frac{(\beta-\gamma)(\alpha(4\beta-\gamma)(\beta+\gamma)+2\bar{\alpha}(3\beta+\gamma)(\beta+2\gamma))}{26\beta^3+47\beta^2\gamma+2\beta\gamma^2-3\gamma^3}, \tag{1.1}$$

$$\hat{p}^n = \frac{\alpha(\beta+\gamma)\left(2\beta^2+13\beta\gamma-3\gamma^2\right)+4\bar{\alpha}\beta\left(4\beta^2+7\beta\gamma+\gamma^2\right)}{2(26\beta^3+47\beta^2\gamma+2\beta\gamma^2-3\gamma^3)}, \tag{1.2}$$

$$s^n = \frac{\alpha(5\beta-\gamma)(\beta+\gamma)(2\beta+\gamma)+4\bar{\alpha}\left(7\beta^3+11\beta^2\gamma-4\beta\gamma^2-2\gamma^3\right)}{2(26\beta^3+47\beta^2\gamma+2\beta\gamma^2-3\gamma^3)}. \tag{1.3}$$

Provided the symmetry assumed, it happens at equilibrium that $q_a^{iH} = q_t^{iH} = q^n$ and $q_c^{iH} = q_c^n$ for all $i = A, B$. Also, $q_a^{Hj} = \hat{q}_a^n$ for all $j = D, E$. Finally, $x_{aa}^k = x_{ta}^k = x^n$ for all $k = AHD, AHE, BHD, BHE$. Local traffics:

$$q^n = \frac{\alpha\left(22\beta^3+44\beta^2\gamma+3\beta\gamma^2-3\gamma^3\right)-2\bar{\alpha}\beta(3\beta+\gamma)(\beta+2\gamma)}{(\beta+2\gamma)\left(26\beta^3+47\beta^2\gamma+2\beta\gamma^2-3\gamma^3\right)} \tag{1.4}$$

$$q_c^n = \frac{\alpha\left(26\beta^3+55\beta^2\gamma+8\beta\gamma^2-5\gamma^3\right)+4\bar{\alpha}\gamma(3\beta+\gamma)(\beta+2\gamma)}{(\beta+2\gamma)\left(26\beta^3+47\beta^2\gamma+2\beta\gamma^2-3\gamma^3\right)} \tag{1.5}$$

International traffics:

$$\hat{q}^n = \frac{\alpha\left(50\beta^3+79\beta^2\gamma-6\beta\gamma^2-3\gamma^3\right)-4\bar{\alpha}\beta\left(4\beta^2+7\beta\gamma+\gamma^2\right)}{2\beta\left(26\beta^3+47\beta^2\gamma+2\beta\gamma^2-3\gamma^3\right)} \tag{1.6}$$

Connecting traffics:

$$x^n = \frac{-\alpha(5\beta-\gamma)(\beta+\gamma)(2\beta+\gamma)+2\bar{\alpha}(3\beta+\gamma)\left(4\beta^2+7\beta\gamma+\gamma^2\right)}{2(\beta+\gamma)\left(26\beta^3+47\beta^2\gamma+2\beta\gamma^2-3\gamma^3\right)} \tag{1.7}$$

Partial-ban scenario

In this scenario, the ban policy implemented implies asymmetries between the markets affected by the ban (say, the airline connection between A and H is banned) and those not directly affected. This implies the following equilibrium prices:

$$p^{AHp} = \frac{\alpha(\beta-\gamma)^2\left(18\beta^3+41\beta^2\gamma+13\beta\gamma^2-6\gamma^3\right)}{126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5}$$

$$+\frac{3\bar{\alpha}(\beta-\gamma)(\beta+2\gamma)(5\beta+3\gamma)\left(2\beta^2+3\beta\gamma-\gamma^2\right)}{126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5} \quad (1.8)$$

$$p^{BHp}=\frac{\alpha(\beta^2-\gamma^2)\left(18\beta^3+17\beta^2\gamma-25\beta\gamma^2+2\gamma^3\right)}{126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5}+\frac{2\bar{\alpha}(\beta-\gamma)(\beta+2\gamma)(5\beta+3\gamma)\left(3\beta^2+3\beta\gamma-4\gamma^2\right)}{126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5} \quad (1.9)$$

$$\hat{p}^{p}=\frac{\alpha\left(18\beta^5+105\beta^4\gamma+115\beta^3\gamma^2-81\beta^2\gamma^3-85\beta\gamma^4+24\gamma^5\right)}{2(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5)}+\frac{\bar{\alpha}\left(72\beta^5+216\beta^4\gamma+92\beta^3\gamma^2-148\beta^2\gamma^3-52\beta\gamma^4+12\gamma^5\right)}{2(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5)} \quad (1.10)$$

$$s^{AHp}=\frac{\alpha\left(54\beta^5+115\beta^4\gamma+13\beta^3\gamma^2-63\beta^2\gamma^3-35\beta\gamma^4+12\gamma^5\right)}{2(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5)}+\frac{\bar{\alpha}\left(132\beta^5+402\beta^4\gamma+122\beta^3\gamma^2-394\beta^2\gamma^3-118\beta\gamma^4+48\gamma^5\right)}{2(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5)} \quad (1.11)$$

$$s^{BHp}=\frac{\alpha(\beta+\gamma)\left(54\beta^4+85\beta^3\gamma-56\beta^2\gamma^2-55\beta\gamma^3+20\gamma^4\right)}{2(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5)}+\frac{12\bar{\alpha}\left(11\beta^5+31\beta^4\gamma+2\beta^3\gamma^2-36\beta^2\gamma^3-\beta\gamma^4+9\gamma^5\right)}{2(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5)} \quad (1.12)$$

Regarding traffic, it happens at equilibrium that $q_a^{AH}=q_t^{AH}=q^{AHp}$ and $q_c^{AH}=q_c^{AHp}$ while $q_a^{BH}=q_t^{BH}=q^{BHp}$ and $q_c^{BH}=q_c^{BHp}$. Also, $q_a^{Hj}=\hat{q}^p$ for all $j=D,E$. Finally, $x_{aa}^k=x_{ta}^k=x^{AHp}$ for all $k=AHD, AHE$, while $x_{aa}^k=x_{ta}^k=x^{BHp}$ for all $k=BHD, BHE$.

Local traffics:

$$q^{AHp}=\frac{2\alpha\left(54\beta^5+173\beta^4\gamma+78\beta^3\gamma^2-135\beta^2\gamma^3-44\beta\gamma^4+18\gamma^5\right)}{(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)}-\frac{3\bar{\alpha}(\beta+\gamma)(\beta+2\gamma)(5\beta+3\gamma)\left(2\beta^2+3\beta\gamma-\gamma^2\right)}{(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)} \quad (1.13)$$

$$q_c^{AHp}=\frac{3(\beta+\gamma)\alpha\left(3\beta^2+3\beta\gamma-4\gamma^2\right)\left(14\beta^3+31\beta^2\gamma+7\beta\gamma^2-4\gamma^3\right)}{\beta(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)}+\frac{3\bar{\alpha}\gamma(\beta+\gamma)(\beta+2\gamma)(5\beta+3\gamma)\left(2\beta^2+3\beta\gamma-\gamma^2\right)}{\beta(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)} \quad (1.14)$$

$$q^{BHp}=\frac{\alpha\left(108\beta^5+352\beta^4\gamma+159\beta^3\gamma^2-294\beta^2\gamma^3-103\beta\gamma^4+42\gamma^5\right)}{(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)}-\frac{2\bar{\alpha}\beta(\beta+2\gamma)(5\beta+3\gamma)\left(3\beta^2+3\beta\gamma-4\gamma^2\right)}{(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)} \quad (1.15)$$

$$q_c^{BHp}=\frac{\alpha\left(126\beta^5+423\beta^4\gamma+221\beta^3\gamma^2-333\beta^2\gamma^3-147\beta\gamma^4+46\gamma^5\right)}{(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)}+\frac{4\bar{\alpha}\gamma(\beta+2\gamma)(5\beta+3\gamma)\left(3\beta^2+3\beta\gamma-4\gamma^2\right)}{(\beta+2\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)} \quad (1.16)$$

International traffics:

$$\hat{q}^{p}=\frac{\alpha\left(234\beta^5+669\beta^4\gamma+187\beta^3\gamma^2-553\beta^2\gamma^3-117\beta\gamma^4+60\gamma^5\right)}{2\beta\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)}-\frac{4\bar{\alpha}\left(18\beta^5+54\beta^4\gamma+23\beta^3\gamma^2-37\beta^2\gamma^3-13\beta\gamma^4+3\gamma^5\right)}{2\beta\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)} \quad (1.17)$$

Connecting traffics:

$$x^{AHp}=-\frac{\alpha\left(54\beta^5+115\beta^4\gamma+13\beta^3\gamma^2-63\beta^2\gamma^3-35\beta\gamma^4+12\gamma^5\right)}{2\beta\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)}+\frac{12\bar{\alpha}(5\beta+3\gamma)\left(\beta^2+\beta\gamma-\gamma^2\right)\left(2\beta^2+3\beta\gamma-\gamma^2\right)}{2\beta\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)} \quad (1.18)$$

$$x^{BHp}=-\frac{\alpha(\beta+\gamma)\left(54\beta^4+85\beta^3\gamma-56\beta^2\gamma^2-55\beta\gamma^3+20\gamma^4\right)}{2(\beta+\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)}+\frac{2\bar{\alpha}(5\beta+3\gamma)\left(3\beta^2+3\beta\gamma-4\gamma^2\right)\left(4\beta^2+7\beta\gamma+\gamma^2\right)}{2(\beta+\gamma)\left(126\beta^5+387\beta^4\gamma+151\beta^3\gamma^2-317\beta^2\gamma^3-101\beta\gamma^4+42\gamma^5\right)} \quad (1.19)$$

Full-ban scenario

Equilibrium prices are

$$p^f=\frac{(\beta-\gamma)(\alpha(\beta-\gamma)+2\bar{\alpha}(\beta+2\gamma))}{8\beta^2+8\beta\gamma-10\gamma^2} \quad (1.20)$$

$$\hat{p}^f=\frac{\alpha\left(\beta^2+2\beta\gamma-2\gamma^2\right)+\bar{\alpha}\left(2\beta^2+2\beta\gamma-2\gamma^2\right)}{8\beta^2+8\beta\gamma-10\gamma^2} \quad (1.21)$$

$$s^f=\frac{\alpha\left(2\beta^2-\gamma^2\right)+\bar{\alpha}\left(4\beta^2+4\beta\gamma-6\gamma^2\right)}{8\beta^2+8\beta\gamma-10\gamma^2} \quad (1.22)$$

In this scenario, it happens at equilibrium that $q_a^{iH}=q_t^{iH}=q^f$ and $q_c^{iH}=q_c^f$ for $i=A,B$. Also, $q_a^{Hj}=\hat{q}^p$ for all $j=D,E$. Finally, $x_{aa}^k=x_{ta}^k=x^f$ for all $k=AHD, AHE, BHD, BHE$.

Local traffics:

$$q^f=\frac{\alpha\left(7\beta^2+8\beta\gamma-9\gamma^2\right)-2\bar{\alpha}(\beta+\gamma)(\beta+2\gamma)}{2(\beta+2\gamma)\left(4\beta^2+4\beta\gamma-5\gamma^2\right)} \quad (1.23)$$

$$q_c^f=\frac{(\beta+\gamma)\left(\alpha\left(8\beta^2+9\beta\gamma-11\gamma^2\right)+2\bar{\alpha}\gamma(\beta+2\gamma)\right)}{2\beta(\beta+2\gamma)\left(4\beta^2+4\beta\gamma-5\gamma^2\right)} \quad (1.24)$$

International traffics:

$$\hat{q}^f=\frac{\alpha\left(7\beta^2+6\beta\gamma-8\gamma^2\right)-2\bar{\alpha}\left(\beta^2+\beta\gamma-\gamma^2\right)}{2\beta\left(4\beta^2+4\beta\gamma-5\gamma^2\right)} \quad (1.25)$$

Connecting traffics:

$$x^f=\frac{4\bar{\alpha}\left(\beta^2+\beta\gamma-\gamma^2\right)-\alpha\left(2\beta^2-\gamma^2\right)}{2\beta\left(4\beta^2+4\beta\gamma-5\gamma^2\right)} \quad (1.26)$$

2. Expressions and proofs

Proof of Result 1. -By setting $p^{AHp}=p^{BHp}$ and solving for $\frac{\bar{\alpha}}{\alpha}$ we have that if $\frac{\bar{\alpha}}{\alpha}>\Sigma_1(\frac{\gamma}{\beta})$ then $p^{BHp}<p^{AHp}$.

Note that $\Sigma_1(\frac{\gamma}{\beta})=\frac{4(3\beta^3+5\beta^2\gamma-\beta\gamma^2-\gamma^3)}{15\beta^3+64\beta^2\gamma+83\beta\gamma^2+30\gamma^3}$ which is decreasing in $\frac{\gamma}{\beta}$ and smaller than one for $\frac{\gamma}{\beta}>0$. Therefore, $p^{BHp}<p^{AHp}$ for all $\frac{\gamma}{\beta}\in(0,1)$ and $1<\frac{\bar{\alpha}}{\alpha}$.

-Also, $s^{BHp}<s^{AHp}$ by definition, since they are defined adding $\hat{p}^p$ to both p^{BHp} and p^{BHp}.

Proof of Result 2. -By setting $q^{AHp}=q^{BHp}$ and solving for $\frac{\bar{\alpha}}{\alpha}$ we have that if $\frac{\bar{\alpha}}{\alpha}>\Sigma_2(\frac{\gamma}{\beta})$ then $q^{AHp}<q^{BHp}$.

Where $\Sigma_2=\frac{3(-\beta+2\gamma)(\beta+\gamma)(2\beta^2+3\beta\gamma-\gamma^2)}{(\beta+2\gamma)(5\beta+3\gamma)(9\beta^2+14\beta\gamma-3\gamma^2)}$ then $q^{AHp}<q^{BHp}$. Since, $\Sigma_2<1$ for all $\frac{\gamma}{\beta}\in(0,1)$, we conclude that $q^{AHp}<q^{BHp}$ for all $\frac{\gamma}{\beta}\in(0,1)$ and $1<\frac{\bar{\alpha}}{\alpha}$. Regarding private car traffic, note that $q_c^{AHp}-q_c^{BHp}=\frac{\gamma}{\beta}(2q^{BHp}-q^{AHp})$ which is positive since $q^{BHp}>q^{AHp}$.

-Finally, $x^{BHp}<x^{AHp}$ if and only if $\frac{\bar{\alpha}}{\alpha}>\Sigma_3(\frac{\gamma}{\beta})$,

where $\Sigma_3=\frac{(\beta+\gamma)(30\beta^4+69\beta^3\gamma-8\beta^2\gamma^2-55\beta\gamma^3+12\gamma^4)}{2(5\beta+3\gamma)(9\beta^4+22\beta^3\gamma+\beta^2\gamma^2-14\beta\gamma^3+6\gamma^4)}$. However, $0<\Sigma_3<1$ which implies that $x^{BHp}<x^{AHp}$ for all $\frac{\gamma}{\beta}\in(0,1)$ and $1<\frac{\bar{\alpha}}{\alpha}$.

Proof of Proposition 1. -To prove part (i), firstly note that by Result 1, $p^{BHp}<p^{AHp}$ for all $\frac{\gamma}{\beta}\in(0,1)$ and $1<\frac{\bar{\alpha}}{\alpha}$. Next, $p^{AHp}<p^f$ if $\frac{\bar{\alpha}}{\alpha}>\Sigma_4(\frac{\gamma}{\beta})$, where $\Sigma_4=\frac{18\beta^4+49\beta^3\gamma+3\beta^2\gamma^2-43\beta\gamma^3+9\gamma^4}{2(2\beta+3\gamma)(3\beta^3+6\beta^2\gamma+2\beta\gamma^2+\gamma^3)}$ is decreasing in $\frac{\gamma}{\beta}$, smaller than $\frac{3}{2}$ in $0<\frac{\gamma}{\beta}<1$, and smaller than one for $0.370952<\frac{\gamma}{\beta}$. Similarly, $p^n<p^{BHp}$ if $\frac{\bar{\alpha}}{\alpha}>\Sigma_4(\frac{\gamma}{\beta})$. Therefore, we conclude that either for all $\frac{\bar{\alpha}}{\alpha}>\frac{3}{2}$, regardless of $\frac{\gamma}{\beta}$ or if $0.370952<\frac{\gamma}{\beta}<1$, for all $\frac{\bar{\alpha}}{\alpha}>1$; the ranking $p^n<(p^{BH})^p<(p^{AH})^p<p^f$ holds.

-To prove part (ii), note that both inequalities, $\hat{p}^f<\hat{p}^p$ and $<\hat{p}^p<\hat{p}^n$ hold if $\frac{\bar{\alpha}}{\alpha}>\Sigma_4(\frac{\gamma}{\beta})$, therefore we conclude that $\hat{p}^f<\hat{p}^p<\hat{p}^n$ under the same conditions as those in the part (i).

Proof of Proposition 2. -By setting $s^n=s^f$ and solving for $\frac{\bar{\alpha}}{\alpha}$ we obtain that $s^n<s^p$ if $\frac{\bar{\alpha}}{\alpha}<P_1$.

Where $P_1(\frac{\gamma}{\beta}) = \frac{(\beta-\gamma)(6\beta^3+13\beta^2\gamma+4\beta\gamma^2-\gamma^3)}{(2\beta^2-3\beta\gamma-11\gamma^2)(2\beta^2+4\beta\gamma+\gamma^2)}$, which is increasing in $\frac{\gamma}{\beta}$, positive for $0 < \frac{\gamma}{\beta} < 0.311312$ and equal to $\frac{3}{2}$ when $\frac{\gamma}{\beta} = 0$. Also, we define by ρ_1, the $\frac{\gamma}{\beta}$ that is equal to a given $\frac{\bar{\alpha}}{\alpha}$, that is, $\rho_1 = P_1^{-1}(\frac{\bar{\alpha}}{\alpha})$.

-Similarly, $s^{BHp} < s^f$ if $\frac{\bar{\alpha}}{\alpha} < P_2$.

Where $P_2(\frac{\gamma}{\beta}) = \frac{18\beta^6+19\beta^5\gamma-94\beta^4\gamma^2-93\beta^3\gamma^3+95\beta^2\gamma^4+48\beta\gamma^5-29\gamma^6}{12\beta^6-6\beta^5\gamma-242\beta^4\gamma^2-495\beta^3\gamma^3-154\beta^2\gamma^4+285\beta\gamma^5+144\gamma^6}$, which is increasing in $\frac{\gamma}{\beta}$; positive for $0 < \frac{\gamma}{\beta} < 0.180623$ and for $0.492658 < \frac{\gamma}{\beta} < 1$; and equal to $\frac{3}{2}$ when $\frac{\gamma}{\beta} = 0$. Also, $\rho_2 = P_2^{-1}(\frac{\bar{\alpha}}{\alpha})$.

-Also, $s^{AHp} < s^n$ if $\frac{\bar{\alpha}}{\alpha} < P_3$.

Where $P_3(\frac{\gamma}{\beta}) = \frac{72\beta^7+82\beta^6\gamma-389\beta^5\gamma^2-589\beta^4\gamma^3-76\beta^3\gamma^4+14\beta^2\gamma^5+25\beta\gamma^6-3\gamma^7}{48\beta^7-90\beta^6\gamma-1635\beta^5\gamma^2-4300\beta^4\gamma^3-4170\beta^3\gamma^4-1146\beta^2\gamma^5+253\beta\gamma^6+96\gamma^7}$ which is increasing in $\frac{\gamma}{\beta}$ and positive for $0 < \frac{\gamma}{\beta} < 0.127359$ and $0.405906 < \frac{\gamma}{\beta} < 1$, equal to $\frac{3}{2}$ when $\frac{\gamma}{\beta} = 0$. Also, $\rho_3 = P_3^{-1}(\frac{\bar{\alpha}}{\alpha})$.

-Note that $P_1(\frac{\gamma}{\beta}) < P_2(\frac{\gamma}{\beta}) < P_3(\frac{\gamma}{\beta})$ in the interval $0 < \frac{\gamma}{\beta} < 0.370952$ which implies $\rho_3 < \rho_2 < \rho_1$.

Proof of Proposition 3. -By using Result 2 and noting that both inequalities, $q^f < q^{AHP}$ and $q^{BHP} < q^n$, hold for if $\frac{\bar{\alpha}}{\alpha} > \Sigma_4(\frac{\gamma}{\beta})$, we, therefore, conclude that $q^f < q^{AHP} < q^{BHP} < q^n$ holds for all $\frac{\bar{\alpha}}{\alpha} > \frac{3}{2}$, regardless of $\frac{\gamma}{\beta}$ or for $0.370952 < \frac{\gamma}{\beta} < 1$, for all $\frac{\bar{\alpha}}{\alpha} > 1$.

-For part (i), note that $q_c^f - q_c^{AHp} = \frac{\gamma}{\beta}(q^{AHp} - q^f)$ and $q_c^{BHp} - q_c^n = \frac{\gamma}{\beta}(2q^n - 2q^{BHp})$. We conclude that $q_c^n < q_c^{BHp}$ and $q_c^{AHp} < q_c^f <$ since $q^f < q^{AHP} < q^{BHP} < q^n$. These together with Result 2 imply that $q_c^n < q_c^{BHp} < q_c^{AHp} < q_c^f$ holds under the conditions indicated in the Proposition.

- To prove part (iii), note that both $\hat{q}^n < \hat{q}^p$ and $\hat{q}^n < \hat{q}^f$, hold if $\frac{\bar{\alpha}}{\alpha} > \Sigma_4(\frac{\gamma}{\beta})$. Then, $\hat{q}^n < \hat{q}^p < \hat{q}^n < \hat{q}^f$, under the conditions indicated in the Proposition.

-Finally, to prove part (iv), by making use of Result 2 and noting that $x^n < x^{AHp}$ and $< x^{BHp} < x^f$ hold if $\frac{\bar{\alpha}}{\alpha} > \Sigma_4(\frac{\gamma}{\beta})$; we prove that $x^n < x^{AHp} < x^{BHp} < x^f$ for the conditions in the Proposition. Thus, the Proposition is proven.

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