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The effect of cooperative infrastructure fees on high-speed rail and airline competition☆

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ABSTRACT

This paper explores the effects of cooperation between rail and air infrastructures in setting per-passenger fees prior to competition among airlines and high-speed rail (HSR) in a transport network. It is shown that, for a sufficiently low degree of substitution, cooperation results in lower fees and greater HSR traffic than under competition. Besides, it leads to more connecting passengers. An empirical application allows for a quantitative assessment of cooperation. Gains to passengers and operators are sizeable when cooperation either involves all infrastructure managers or the rail and the hub airport managers. Welfare gains are in the range of 10.4–11.1%. Our contribution offers an ex-ante analysis about the benefits of intermodal cooperation at the upstream level.

1. Introduction

The changes that have occurred in infrastructure governance have implications on how access fees are set. Many airports that were fixing fees close to non-profit levels are now governed by for-profit objectives (Gillen 2011; Zhang and Czerny, 2012) and the reorganization of the rail industry has also produced variations in the levels of access fees (Sánchez-Borràs 2010 and IRG-Rail, 2020). In a transport network, airports and rail stations are input providers to downstream air and rail operators. How access fees are set in such a vertically linked industry becomes crucial for an effective competition in the passenger market and, in particular, for the performance of high-speed rail (HSR) services. The development of HSR services has intensified the competition between airlines and rail operators, which are not just alternative modes but also complementary for those passengers that interline to reach their final destinations (Socorro and Viecens, 2013; Xia and Zhang, 2016; Jiang et al., 2017; Álvarez-SanJaime et al., 2020b). However, complementarities also occur at the upstream level since railway infrastructure can also be seen as part of the air transport infrastructure (Givoni and Banister, 2006). In this paper we set up a transport network that reaches two different countries to explore the effects of cooperation between domestic transport infrastructures in setting per-passenger fees in order to assess their impact on traffic, rail traffic in particular, industry profitability, passenger surplus as well as social welfare.

Since the mid 80s the air industry has witnessed an important move towards airport privatization. Private majority ownership with for-profit objectives can be found in Europe, Asia-Pacific and North America (Oum et al., 2006). As a result of such process, aeronautical charges become decisive once airports no longer depend on public financing. Apart from air infrastructures, road and rail infrastructures are also owned or managed by private investors. In fact, some of these groups are running different transport infrastructures. This is the case of Spanish Ferrovial and French Vinci that operate rail, air and road infrastructures. In particular, VINCI Railways is involved in high-profile infrastructure projects in France (like the South Europe Atlantic High-Speed Rail Line),[1] apart from managing 45 airports all over the world. Interactions

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[1] See "RFF selects Vinci to build Tours–Bordeaux LGV". Railway Gazette International. 30 March 2010; and "Presidential inauguration for LGV Sud Europe Atlantique". Railway Gazette International. 1 March 2017.

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between private operators of different infrastructures in transport networks are very likely to be observed in the future. Our contribution is a first step in this direction and wishes to provide an ex-ante analysis of the outcome resulting from infrastructure cooperation at a domestic level regarding the choice of access fees in different transport modes.[2]

We propose a network with two links connecting three cities, one in a different country, where HSR and air are substitutes in the link connecting the two cities in the same country and complements for those passengers that make a combined trip including the two links; there is airline competition in the link connecting the two countries. The domestic airport infrastructure comprises a hub and a spoke airport, the former one directly connected to the other two cities in the network, the latter only to the hub airport. The first part of our paper develops a theoretical model where per-passenger fees are endogenously set by domestic infrastructure providers prior to competition between transport operators. Fees can be set either independently or cooperatively with a profit maximizing objective. These are compared with welfare maximizing fees. Under symmetry in marginal infrastructure costs, it is shown that welfare maximizing access fees are always the lowest ones, noting that the spoke airport sets it equal to the marginal cost of providing the service while for the hub airport and the HSR station, the fees are larger than marginal costs. Cooperation leads to a lower access fee at the hub airport (above marginal cost) and so happens with the rail access fee for a low enough degree of substitution, relative to independent choices of fees. Air traffic in the local and the connecting markets is closer to the welfare maximizing level under cooperation but this is so in the international market under competition. Finally, local HSR traffic under cooperation ranks higher than under competition for a low enough degree of substitution yet the opposite typically happens for the connecting market. It is interesting to underline that under full cost symmetry, competition upstream implies a larger market share for HSR services while cooperation and welfare maximization do not; the reason for it is that rail infrastructure enjoys a strategic advantage with respect to the airport system since the two HSR stations are jointly managed. Finally, focusing on the connecting number of passengers, it is shown that when services are rather differentiated cooperation upstream generates the level of traffic closest to the one under upstream welfare maximization, while competition upstream takes this role when services are very similar.

In the second part of the paper, the model is calibrated to a specific network that connects Valencia (Spain), Madrid (Spain) and New York, which allows us to exploit asymmetries - in terms of passengers' willingness to pay, own and cross elasticities and costs- and to offer a detailed assessment of the effects of cooperation upstream regarding traffic, passenger surplus, industry profitability and social welfare. The analysis throws some interesting results. Cooperation upstream among all infrastructure managers leads to the same changes in fees identified above. The corresponding changes in prices are such that connecting and international traffic increase. Operators profit goes up (e.g. HSR by 14.5%) and welfare increases by 10.4%. Cooperation between the rail manager and the hub airport leads to similar changes in fees, yet all prices fall, which generates gains to all passengers and welfare increases by 11.1%. Cooperation outcomes involving the rail manager result in higher rail traffic (in the range of 7.0–10.3%), connecting passengers that combine rail and air modes, in particular. When cooperation comprises both airports, the welfare gains are smaller (3.1%) and HSR profit falls by 0.7%. The received literature that we discuss below has examined the effects of cooperation downstream (either rail-air or air-air cooperation) when fees are exogenous. We have also simulated these cases where now fees are endogenous and set independently. The welfare gains are in the range of 0.03–1.9%, well below those achieved with cooperation between infrastructure providers. Upstream agreements produce lower prices in net terms than downstream agreements, and all agents can be made better off. These findings offer relevant policy implications regarding the opportunity for collaboration upstream and levels of access fees with intermodal competition to promote HSR.

1.1. *Related literature*

Recent contributions have looked into the role of access fees in a setting with airport competition.[3] Abstracting from network issues, Haskel et al. (2013) compare a number of vertical structures with two airports and several airlines. They consider airport profit-maximizing per-passenger landing fees and show that fees are higher when airports are jointly owned whereas airline concentration lowers landing fees; discriminatory fees are typically lower than uniform fees. Noruzoliaee et al. (2015) assume away airline market power to focus on capacity and pricing decisions in a multi-airport region for several privatization regimes; they find that service prices tend to increase after privatization. In a setting with two complementary airports, each one based on a different country, Mantin (2012) examines whether governments wish to keep an airport public - choosing the welfare maximizing fee - or privatize it - choosing the profit maximizing fee. He shows that there is an incentive to privatize, although national welfare and traffic are higher when airports are kept public. This prisoners' dilemma result calls for some coordination regarding the charges set by airports. Some recent papers consider strategic interactions between airport regulators in an intercontinental transport network. Benoot et al. (2013) investigate the welfare losses, relative to the first-best solution, arising from the competition of welfare-maximizing airports regulators that choose airport charges and capacities. Their numerical analysis suggests that cooperative capacity decision and fewer regulators setting charges lessens the overall welfare decrease. Lin and Mantin (2015) develop a game of privatization between governments to conclude that there is an incentive to privatize when the international hub-hub market is sufficiently large; however, coordinating the privatization of local airports may make governments better off just as keeping airports under public ownership. Finally, from a country's perspective and an international hub-and-spoke network, Álvarez-SanJaime et al. (2020a) show the relevance of aeronautical fees when airlines compete in prices and frequencies; profit-maximizing charges only at the spoke airport will likely induce a welfare increase when frequencies in the hub are highly valued by connecting passengers; welfare losses are lower when airports are granted to a unique infrastructure manager rather than to independent ones.

Some papers have also studied the role of access charges in the competition in rail markets.[4] Regarding the impacts of rail access charges on the rail market, Nash (2005) identifies the wide variety of both structure and levels of rail charges in Europe. As for new HSR lines, it is understandable that governments wish to charge a non-discriminatory mark-up over marginal infrastructure and external costs to recover part of the large investment costs. Sánchez-Borràs et al. (2010) analyze the impacts that rail infrastructure charges have on

[2] Ex-ante analysis may prove useful to give an informed description of the effects on total traffic, intermodal traffic distribution and welfare when governments contemplate the integration of infrastructure management for a given intermodal transport network.

[3] Certainly, there exist rationales for airport pricing, such as congestion fees, and/or airport regulation, which we disregard (see e.g. Oum et al., 2004; Zhang and Czerny, 2012).

[4] A relevant part of the literature has been devoted to study the efficiency - and productivity - effects of the vertical and horizontal restructuring of the European rail industry (see e.g. Asmild et al., 2009; Friebel et al., 2010; Cantos-Sánchez et al., 2010; 2012; Lérida-Navarro et al., 2019).

traffic levels and mode split for the main European countries, concluding that their levels are significantly reducing passenger rail shares and the social benefits from these lines.[5] At the same time rail infrastructure fees may act as an entry barrier of new rail operators (Crozet and Chasagne, 2013). Nash et al. (2019) carefully looks into the introduction of competition experiences for Sweden, Germany and Britain. Among other considerations, such as the size and length of franchises and the provision of commercial services by entrants, they note that track access charges, based either on marginal costs and/or fixed costs of the system, may not favor the provision of frequent services thus making new entry problematic. Finally, Álvarez-SanJaime et al. (2016) provide an ex-ante analysis of entry for some Spanish HSR routes which considers competition in prices and frequencies and access fees that are endogenous. Interestingly, low access fees (that follow marginal cost pricing) will more likely make entry of HSR operators profitable and lead to welfare gains.

It is nevertheless more realistic to examine a transport network that stresses both modal substitutability and complementarity between HSR and airlines (see Zhang et al. (2019) for a survey on recent research on air-HSR competition); such interactions also occur at the upstream level with infrastructure provision. Although the literature has studied the effects of cooperation downstream between HSR and air operators in a transport network, to our knowledge, the examination of cooperation upstream involving different infrastructure suppliers has not been undertaken. There are a few analytical contributions that study the impact of HSR-air cooperation as, for instance, Socorro and Viecens (2013); Jiang and Zhang (2014); Xia and Zhang (2016); Jiang et al. (2017); Avenali et al. (2018); Álvarez-SanJaime et al. (2020b).[6] These analyses contemplate different competing assumptions and various types of partnership, yet only the latter investigates the effect of different (exogenous) per-passenger airport and rail infrastructure fees. Lower fees increase the private profitability and welfare levels of downstream cooperation. We wish to contribute to this strand of the literature and investigate infrastructure manager decisions on access fees, that may be set cooperatively, with network demand complementarities involving rail and air transport. It is well known that the independent pricing of complementary products results in market inefficiencies (Cournot, 1838) that may be solved by cooperation. The transport network that we examine exhibits a mix of complementarities and substitutabilities between infrastructure providers that may distort operators' competition and so we wish to investigate the desirability of cooperation upstream regarding traffic and welfare when fees are endogenously set.

The paper is organized as follows. Section 2 presents the model. Different subsections describe the downstream equilibrium that involves interactions between operators (subs. 2.1), as well as the upstream equilibrium (subs. 2.2) when there is competition, cooperation and welfare maximization regarding the choice of fees. Subsection 2.3 offers some results. The empirical application is given in Section 3. Finally, we conclude with some remarks and policy recommendations in Section 4.

2. The model and analysis of equilibria

Fig. 1 illustrates a transportation network with three nodes and identifies three markets. Both the hub (H) and the spoke (A) airports are located in the same country, while the other spoke airport (B) is abroad.[7] The local market *AH* is served by a local airline and by a HSR operator. The international market *HB* is supplied by two airlines. Finally, the connecting market *AB*, where there is no direct service and passengers must take a combined trip.[8] Note that connecting passengers can make four different combinations and two of them involve both air and rail transport.

The utility functions of a representative passenger in the local *AH* market, in the international *HB* market and in the connecting *AB* market are, respectively, given by (see Dixit, 1979):

$$U_l = a_l(q_t + q_a) - \frac{b}{2}(q_t^2 + q_a^2) - d_l q_t q_a, \quad (1)$$

$$U_i = a_i(q_{i1} + q_{i2}) - \frac{b}{2}(q_{i1}^2 + q_{i2}^2) - d_i q_{i1} q_{i2}, \quad (2)$$

$$\begin{aligned} U_c &= a_c(x_{t1} + x_{t2} + x_{a1} + x_{a2}) - \frac{b}{2}(x_{t1}^2 + x_{t2}^2 + x_{a1}^2 + x_{a2}^2) \\ &- d_c(x_{t1}x_{t2} + x_{t1}x_{a1} + x_{t1}x_{a2} + x_{t2}x_{a1} + x_{t2}x_{a2} + x_{a1}x_{a2}), \end{aligned} \quad (3)$$

where q_t and q_a denote the number of passengers by HSR and by the domestic airline, respectively. Similarly, q_{i1} and q_{i2} stand for the number of passengers of airlines 1 and 2 in the international market. Finally, x_{t1} denotes passenger traffic that takes the HSR in link *AH* and airline 1 in link *HB*, with obvious notation for the other three possible combinations. Constants a_l, a_i and a_c are positive and represent the maximum willingness to pay for travelling in the local (subscript l), international (i) and connecting (c) markets, respectively. It is also assumed that $b > d_l, d_i, d_c > 0$, and services become less differentiated as $d's$ tend to b.

A system of inverse demand functions is obtained from the maxi-

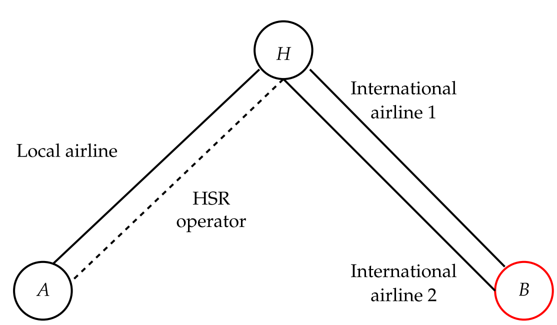

Fig. 1. Transportation network.

[5] It must be noted that the pattern of rail and air infrastructure fees are not strictly equivalent. Rail infrastructure fees are basically composed of three different items: a variable fee for the use of the rail tracks depending on number of train-km, a fee for using the station services depending on the number of passengers, and a fixed fee for the right to access the rail network (see Sánchez-Borràs et al., 2010, for a detailed description). Air infrastructure fees comprise a part for the use of the aeronautical services and air transit services per flight depending on the type of aircraft, a fee for passenger services offered at the terminal depending on the number of passengers, and other fees related to parking and handling services based on aircraft weight (see Zhang and Czerny, 2012).

[6] The literature has studied complementary airline alliances (Park (1997); Brueckner (2001); Bilotkach (2005); Park et al. (2001), and Flores- Fillol and Moner-Colonques (2007), among others. It is nevertheless true that rail-air cooperation has some distinguishing features relative to air-air cooperation. Thus, rail-air cooperation improves people's mobility, reduces the negative environmental impact of transportation, stimulates economic growth and improves spatial redistribution of traffic and economic development across regions (Zhang et al., 2019).

[7] We consider a star network of three nodes. In this type of networks, the hub node is defined as the node directly connected with the other nodes (the spokes). Spoke nodes are only directly connected with the hub node. A typical hub-and-spoke network in the airline competition literature assumes congestion in the hub airport and economies of traffic density. We do not consider congestion in our model to be consistent with our empirical application since neither the Madrid airport nor the Valencia-Madrid HSR corridor are congested.

[8] There are examples of international markets served by HSR operators although this would imply that the hub airport is located abroad. For the sake of the exposition and to be consistent with the calibration example presented below, we use the terminology local and international.

mization of the utility functions subject to the budget constraints. The demand functions that correspond to the three markets are the following:

i) Local market demand system, *AH* market:

$$q_t(p_t,p_a) = \alpha_l - \beta_l p_t + \gamma_l p_a, \tag{4}$$

$$q_a(p_t,p_a) = \alpha_l - \beta_l p_a + \gamma_l p_t, \tag{5}$$

so that p_t and p_a are the price of an *AH* trip by train and by air, respectively.

ii) International market demand system, *HB* market:

$$q_{i1}(p_{i1},p_{i2}) = \alpha_i - \beta_i p_{i1} + \gamma_i p_{i2}, \tag{6}$$

$$q_{i2}(p_{i1},p_{i2}) = \alpha_i - \beta_i p_{i2} + \gamma_i p_{i1}, \tag{7}$$

where p_{i1} and p_{i2} are the price of an *HB* trip by airline 1 and airline 2, respectively.

iii) Connecting market demand system, *AB* market:

$$x_{t1}(s_{t1},s_{t2},s_{a1},s_{a2}) = \alpha_c - \beta_c s_{t1} + \gamma_c \sum_{\forall l \neq t1} s_l, \tag{8}$$

$$x_{t2}(s_{t1},s_{t2},s_{a1},s_{a2}) = \alpha_c - \beta_c s_{t2} + \gamma_c \sum_{\forall l \neq t2} s_l, \tag{9}$$

$$x_{a1}(s_{t1},s_{t2},s_{a1},s_{a2}) = \alpha_c - \beta_c s_{a1} + \gamma_c \sum_{\forall l \neq a1} s_l, \tag{10}$$

$$x_{a2}(s_{t1},s_{t2},s_{a1},s_{a2}) = \alpha_c - \beta_c s_{a2} + \gamma_c \sum_{\forall l \neq a2} s_l, \tag{11}$$

where x_{t1} passengers pay p_t in link *AH* and p_{i1} in link *HB*. Total price $s_{t1} = p_t + p_{i1}$ is inversely related to x_{t1} and positively related with the total price of the other three combinations $s_{t2} = p_t + p_{i2}$, $s_{a1} = p_a + p_{i1}$, and $s_{a2} = p_a + p_{i2}$, because combinations are substitutes to one another in the eyes of connecting passengers. A similar logic applies to demands x_{t2}, x_{a1} and x_{a2}. Further note that, $\alpha_k = \frac{(b-d_k)a_k}{b^2-d_k^2}$; $\beta_k = \frac{b}{b^2-d_k^2}$ and $\gamma_k = \frac{d_k}{b^2-d_k^2}$ for $k = l, i$. While $\alpha_c = \frac{(b-d_c)a_c}{(b-d_c)(b+3d_c)}$; $\beta_c = \frac{b+2d_c}{(b-d_c)(b+3d_c)}$ and $\gamma_c = \frac{d_c}{(b-d_c)(b+3d_c)}$.

Marginal (operating) cost per passenger by train and air are denoted by c_t and c_a, respectively. Finally, operators incur marginal costs in the form of per-passenger fees as per use of infrastructure both at the origin and at the destination points[9]; f_T is the per-passenger rail fee and f_A, f_B and f_H denote the per-passenger airport fee at airports *A*, *B* and *H*, respectively.[10]

The purpose of the paper is to understand how cooperation by domestic infrastructure managers (IM) of HSR stations and airports in a transportation network affect the endogenous choice of per-passenger fees and how this influences the relative use of HSR versus airlines, passenger surplus, profits and welfare. To do so, we set up a two-stage game where in the first stage, IMs decide on their corresponding fees. Then, in the second stage, airlines and the HSR compete in prices. The first stage considers the interplay among the managers of the upstream layer in the provision of passenger transportation services. We will solve it for two different scenarios: in the first one, all IMs decide on fees simultaneously and independently, so as to maximize each manager's profits; we denote this as the *competition upstream case*. Alternatively, the scenario where all IMs cooperate in the setting of the fees is also obtained and is referred to as the *cooperation upstream case*. For comparative purposes, we will also present the fees that follow from welfare maximization. Notably, the model features are in line with the actual domestic transportation network we calibrate in the empirical application section. In particular, neither of the Spanish airports considered nor the HSR connection in the corridor Valencia-Madrid are congested so that it is reasonable to assume price competition. Besides a hub-and-spoke (or star) transport network is set because there is no direct flight between Valencia and New York; otherwise, a point-to-point (fully connected or complete) transport network should have been considered. In the next subsection, *the downstream equilibrium,* we present the equilibrium prices set by the rail operator and airlines, which is valid for all possible profiles of fees set up in the first stage.

2.1. The downstream equilibrium

The rail operator and airline profits read as follows:

$$\pi_t = (p_t - c_t - 2f_T)Q_t, \tag{12}$$

$$\pi_a = (p_a - c_a - f_A - f_H)Q_a, \tag{13}$$

$$\pi_{i1} = (p_{i1} - c_a - f_B - f_H)Q_{i1}, \tag{14}$$

$$\pi_{i2} = (p_{i2} - c_a - f_B - f_H)Q_{i2}, \tag{15}$$

where, $Q_t = q_t + x_{t1} + x_{t2}$, $Q_a = q_a + x_{a1} + x_{a2}$, $Q_{i1} = q_{i1} + x_{a1} + x_{t1}$ and $Q_{i2} = q_{i2} + x_{a2} + x_{t2}$ are the total number of passengers travelling with HSR, the local airline and each international airline, respectively. Operators choose simultaneously and independently the profit maximizing prices. Equations $\frac{\partial \pi_t}{\partial p_t} = 0$, $\frac{\partial \pi_a}{\partial p_a} = 0$, $\frac{\partial \pi_{i1}}{\partial p_{i1}} = 0$ and $\frac{\partial \pi_{i2}}{\partial p_{i2}} = 0$ define a system of four equations and four unknowns that yield four equilibrium prices. The equilibrium expressions are fairly complex; in fact, prices are actually a function of all per-passenger infrastructure fees because of the network market structure. To illustrate the role of endogenous fees on the corresponding price differences and provide some results under competition and cooperation upstream, consider the following symmetric model with $a_l = a_i = a$, $a_c = 2a$, $b = 1$, $d_l = d_i = d_c = d$and zero operating costs, so that operators' marginal costs only differ by the fees paid in providing their service. These simplifying assumptions serve two purposes: one practical to get neat conclusions on comparative statics signs and results; another methodological since by reducing asymmetries downstream (operators and services) at the maximum, we can focus on the effects of cooperation stemming from interactions at the infrastructure level. As shall be seen below, some unexpected results are found. Their quantitative assessment in the presence of asymmetries will be explored in Section 3. The equilibrium prices are shown below[11]

$$p_t^* = \frac{(5+7d)(1-d)}{8+9d-5d^2}a + \frac{\Omega(d)\left(\Psi_t^A(d)f_A + \Psi_t^B(d)f_B + \Psi_t^H(d)f_H + \Psi_t^T(d)f_T\right)}{6+19d+11d^2}, \tag{16}$$

[9] Note that fees are typically expressed in terms of train-km or airplane-km which are supply measures. These can be converted to passenger-km by assuming that rail and air operators run with an estimated average load factor in their services, given train and aircraft capacity, travel times and some contingency factor (see Campos et al., 2012, for more details). Note that knowing the route length, the number of passenger-km can be directly expressed in terms of number of passengers.

[10] Strictly speaking HRS operators also incur fees per track usage as indicated in footnote 5 above. Therefore, f_T should be understood as the mean of total per passenger fees between stations. That is, $f_T = \frac{\text{fee paid for use of Valencia station+fee paid for use of Madrid station+fee paid for track use}}{2}$.

[11] It is relevant to discuss the effect of the simplifying assumption, $a_c = 2a$. Note that in case we had considered a more general assumption with $a_c = \sigma a$, for $\sigma \geq 1$, the corresponding equilibrium prices in (16) to (18) would have had a different first term. In particular, the numerator of that term would be $(1 - d)(1 + 3d + 2(1 + d)\sigma)a$, which increases in σ. Therefore, we conclude that σ behaves as a shifter of price levels but does not affect price differences across operators.

$$p_a^* = \frac{(5+7d)(1-d)}{8+9d-5d^2}a + \frac{2\Omega(d)\left(\Psi_a^A(d)f_A + \Psi_a^B(d)f_B + \Psi_a^H(d)f_H + \Psi_a^T(d)f_T\right)}{6+19d+11d^2}, \quad (17)$$

$$p_i^* = p_{i1}^* = p_{i2}^* = \frac{(5+7d)(1-d)}{8+9d-5d^2}a + \Omega(d)\left(\Psi_i^A(d)f_A + \Psi_i^B(d)f_B + \Psi_i^H(d)f_H + \Psi_i^T(d)f_T\right) \quad (18)$$

In this manner, the equilibrium prices appear in terms of the degree of substitution (d), the maximum willingness to pay (a), as well as each airport and rail fee multiplied by a polynomial in d, denoted by Ψ_j^k, for $k = A, B, H, T$ and $j = t, a, i$.[12] Substitution of (16), (17) and (18) in expressions (4) to (11) as appropriate, leads to the equilibrium traffic levels in the different markets denoted by q_t^*, q_a^* for the local, $q_i^* = q_{i1}^* = q_{i2}^*$ for the international and $x_a^* = x_{a1}^* = x_{a2}^*$ and $x_t^* = x_{t1}^* = x_{t2}^*$ for the connecting market.[13] It is worth noting that fees set by different infrastructure managers introduce asymmetries in prices per mode and link. In particular, for the local market AH, $\frac{\partial p_t^*}{\partial f_T} > \frac{\partial p_a^*}{\partial f_T} > 0$, while $\frac{\partial p_a^*}{\partial f_A} > \frac{\partial p_t^*}{\partial f_A} > 0$, so that rail fees have a positive and greater impact on rail price than on local air price in the AH market, while the spoke airport A fees have a greater effect on local air price. Because fees behave as marginal costs of substitute services in the local market, they have a positive effect on prices and the previous ordering follows from own effects being stronger than cross effects. The effect of the hub airport fee is also asymmetric, its impact is greater on the local air price and the sign of the effect on rail price depends on the degree of substitution. In particular, when HSR and airline services are very differentiated, i.e. for $0 < d < 0.3517$, $\frac{\partial p_a^*}{\partial f_H} > 0 > \frac{\partial p_t^*}{\partial f_H}$, so that an increase in f_H reduces rail prices and increases local air prices; while for $0.3517 < d < 1$ both marginal effects are positive. Airport H is providing a complementary infrastructure for connecting passengers using HSR, while a competing infrastructure for HSR in the local market. Since f_H is a marginal cost for the airline service in the local market, its marginal effect on p_a^* is always positive. However, its effect on p_t^* is negative when the degree of substitution is small so enhancing the complementarity effect of the connecting markets over the substitution effect on the local market. Similarly, in the international market HB, both the hub and the spoke B airport fees have a positive effect on international air prices, while the spoke airport A and the rail fees impact negatively, that is, $\frac{\partial p_i^*}{\partial f_H} > 0$ and $\frac{\partial p_i^*}{\partial f_B} > 0$; while $\frac{\partial p_i^*}{\partial f_T} < 0$ and $\frac{\partial p_i^*}{\partial f_A} < 0$. Finally, the effect of the hub airport fee is greater on international air prices than on local air prices, i.e. $\frac{\partial p_i^*}{\partial f_H} > \frac{\partial p_a^*}{\partial f_H} > 0$, and the effect of the spoke B airport is also asymmetric since $\frac{\partial p_i^*}{\partial f_B} > 0 > \frac{\partial p_a^*}{\partial f_B} = \frac{\partial p_t^*}{\partial f_B}$.

We are also interested in the effect of infrastructure fees on the price and traffic differences in the local and connecting markets. Regarding the local market, the air price is larger than the rail price when the sum of infrastructure airport fees, f_A and f_H, exceeds that of rail fees, $2f_T$. In fact, $p_a^* - p_t^* = \frac{(3+d)(1+2d)}{6+19d+11d^2}(f_A + f_H - 2f_T)$. Note that the pass-through of differences in fees across modes to downstream price differences is always smaller than one for all d. Since $q_t^* - q_a^* = \frac{1}{1-d}(p_a^* - p_t^*)$, a cost advantage in providing the rail services entails a larger HSR market share than that of the local airline in the local market. The same conclusion is obtained on the connecting market.[14]

2.2. The upstream equilibrium

In this subsection we present the three different scenarios corresponding to how the domestic IMs decide on the per-passenger fees: fees are chosen either to maximize individual profits, or to maximize joint profits, or to maximize welfare.[15] The profit functions of the HSR infrastructure manager and the airport managers read as follows

$$B_T = 2(f_T - t_T)Q_t, \quad (19)$$

$$B_A = (f_A - t_A)Q_a, \quad (20)$$

$$B_H = (f_H - t_H)(Q_a + Q_{i1} + Q_{i2}). \quad (21)$$

Parameters t_k for $k = A, H, T$ are the corresponding marginal infrastructure costs of providing the infrastructure service. Note that for the sake of simplicity not all categories of incremental costs are considered. There are costs attached to the wear and fatigue related to frequencies and technical characteristics of the vehicles (weight, length and speed). However, and since increases in frequencies can be related to traffic increases as argued in footnote 9, we assume that infrastructure costs are proportional to traffic in non-congested passenger corridors. Fixed costs have been ignored.[16]

2.2.1. The competition upstream case

Each IM chooses its corresponding fee simultaneously and independently so as to maximize its profits. The upstream equilibrium fees are the solution of the system formed by $\frac{\partial B_T}{\partial f_T} = 0$, $\frac{\partial B_A}{\partial f_A} = 0$ and $\frac{\partial B_H}{\partial f_H} = 0$, which are denoted by $f_A^n(a, f_B, t_A, t_H, t_T)$, $f_H^n(a, f_B, t_A, t_H, t_T)$ and $f_T^n(a, f_B, t_A, t_H, t_T)$, where superscript n denotes non-cooperative. The precise expressions are presented in the Appendix and second order conditions are satisfied. Table 1 shows the comparative statics analysis on equilibrium fees and traffics.

It is noteworthy to mention that increases in marginal infrastructure costs of competing infrastructures, the HSR station and the spoke airport at A, increase their fees, while increases in the marginal infrastructure costs of complementary infrastructures, the hub and the local spoke airport, reduce the corresponding fees. The relationship among the HSR stations and the hub airport is more complex since they are competing infrastructures in the local market while complementary infrastructures in the connecting market, the sign of the overall effect depends on the degree of substitution; the former feature is stronger when services are more similar. Regarding traffic differences across modes, these are driven by differences in fees, which are replicating differences in marginal infrastructure costs. That is, increases in domestic airport marginal

[12] The precise expressions and sign of polynomials Ψ_j^k together with the expressions for the equilibrium traffic levels appear in the Appendix.

[13] Had we made the assumption that $a_c = \sigma a$, equilibrium traffic levels would have also been affected. In particular, for traffics in the local and international markets, $\frac{\partial q_j^*}{\partial \sigma} = -\frac{(1-d)a}{8+9d-5d^2} < 0$ for $j = t, a, i$, while in the connecting market, $\frac{\partial x_l^*}{\partial \sigma} = \frac{(4+9d-d^2)a}{(1+3d)(8+9d-5d^2)} > 0$ for $l = t1, t2, a1, a2$. That is, the connecting market becomes relatively more relevant with a larger σ, but intermodal traffic differences within the local and the connecting markets do not depend on σ.

[14] The difference in prices, $p_i^* - p_a^* = \frac{(3+d)(1+2d)}{(4+9d-d^2)}\left((f_B - f_A) + \frac{(1+2d)(1+3d)}{(6+19d+11d^2)}(f_A + f_H - 2f_T)\right)$, increases in f_H and f_B and decreases in f_A and f_T. A sufficient condition for a positive difference is that the HSR operator enjoys a cost advantage in the local market and that the local spoke airport provides the service at a lower price than the international spoke airport.

[15] The effect of the abroad airport fee, f_B, is treated in a parametric way. That is, its effect on the equilibrium choices of the domestic infrastructure managers is considered under the different proposed scenarios, but the f_B level does not change in response to changes in the scenario considered. The consideration of airport B behaving in a strategic manner is discussed below.

[16] The rationale of this assumption lies on the behavioral nature of our analysis. The different scenarios considered only differ on the way decisions are made with no other structural changes. It is reasonable to assume that IM 's fixed costs be unaltered across scenarios and thus differences in IM's profits will only capture variable profit differences. On top of that, we abstract from infrastructure investment costs since they are sunk and our behavioral analysis is assumed to be ex post with respect to the infrastructure investments.

Table 1
Competition upstream: Sign of the marginal effects on equilibrium fees and traffics.

	Parameters				
	a	f_B	t_A	t_H	t_T
f_A^n	+	+	+	–	+
f_H^n	+	–	–	+	+ for $d > 0.6536$
f_T^n	+	–	+	+ for $d > 0.6536$	+
$f_A^n + f_H^n$	+	–	+	+	+
$f_A^n + f_H^n - 2f_T^n$	+	–	+	+	–
q_a^n	+	+	–	+ for $d < 0.0839$	+ for $d > 0.4334$
q_t^n	+	+ for $d < 0.8677$	+ for $d > 0.5862$	+	–
q_i^n	+	–	+	+	+ for $d < 0.7954$
x_a^n	+	–	–	–	+
x_t^n	+	–	+	+ for $d > 0.7839$	–
$q_t^n - q_a^n$	+	–	+	+	–
$x_t^n - x_a^n$	+	–	+	+	–

Table 2
Cooperation upstream: Sign of the marginal effects on maximizing fees and traffics.

	Parameters				
	a	f_B	t_A	t_H	t_T
f_A^c	0	+	+	0	0
f_H^c	+	–	0	+	0
f_T^c	+	0	0	0	+
$f_A^c + f_H^c$	+	0	+	+	0
$f_A^c + f_H^c - 2f_T^c$	0	0	+	+	–
q_a^c	+	+	–	–	+ for $d > 0.1446$
q_t^c	+	+	+ for $d > 0.1446$	+	–
q_i^c	+	–	+	+	+
x_a^c	+	–	–	–	+
x_t^c	+	–	+	+ for $d > 0.4857$	–
$q_t^c - q_a^c = x_t^c - x_a^c$	0	0	+	+	–

costs lead to increases in HSR market shares both in the local and in the connecting markets, while increases in HSR stations infrastructure marginal cost reduce those market shares.

2.2.2. The cooperation upstream case

We now consider the case where per-passenger fees follow from IMs' joint profit maximization.

$$B = B_T + B_A + B_H = 2(f_T - t_T)Q_t + (f_A + f_H - t_A - t_H)Q_a + (f_H - t_H)(Q_{i1} + Q_{i2}) \quad (22)$$

Solving the system formed by $\frac{\partial B}{\partial f_T} = 0$, $\frac{\partial B}{\partial f_A} = 0$ and $\frac{\partial B}{\partial f_H} = 0$, leads to the following equilibrium fees[17]

$$f_A^c = \frac{f_B + t_A}{2}, \quad (23)$$

$$f_H^c = \frac{a - f_B + t_H}{2}, \quad (24)$$

$$f_T^c = \frac{a + 2t_T}{4}, \quad (25)$$

where superscript c denotes cooperation upstream, noting that $f_A^c + f_H^c = \frac{1}{2}(a + t_A + t_H)$ and $f_A^c + f_H^c - 2f_T^c = \frac{1}{2}(t_A + t_H - 2t_T)$. Table 2 shows the comparative statics analysis on fees and traffics. Each fee is increasing in its own marginal cost as joint profit maximization internalizes all the interactive effects arising in the competition case. Interestingly, the infrastructure marginal costs difference pass-through on fee differences across modes is one half. After substitution of the maximizing fees in the downstream equilibrium prices (16) to (18), and then substituting such prices in the corresponding demand functions we find that the differences in traffic across modes are $q_t^c - q_a^c = x_t^c - x_a^c = \frac{(3+d)(1+2d)(t_A + t_H - 2t_T)}{2(1-d)(6+19d+11d^2)}$.

2.2.3. The welfare maximizing upstream case

The social welfare function is defined in the next expression[18]

$$SW = U_l + U_i + U_c - (f_B + t_H)(Q_{i1} + Q_{i2}) - (t_A + t_H)Q_a - 2t_T Q_t \quad (26)$$

The solution to the following system of equations, $\frac{\partial SW}{\partial f_T} = 0$, $\frac{\partial SW}{\partial f_A} = 0$ and $\frac{\partial SW}{\partial f_H} = 0$, leads to the welfare maximizing fees shown below[19]

[17] Second order conditions for a maximum are satisfied.

[18] The social welfare expression in (26) is obtained from $SW = CS_l + CS_i + CS_c + \pi_t + \pi_l + \pi_{i1} + \pi_{i2} + B_A + B_H + B_T$, where $CS_l = U_l - p_a q_a - p_t q_t$, $CS_i = U_i - p_{i1}q_{i1} - p_{i2}q_{i2}$ and $CS_c = U_c - (p_a + p_{i1})x_{a1} - (p_a + p_{i1})x_{a1} - (p_a + p_{i2})x_{a2} - (p_t + p_{i1})x_{t1} - (p_t + p_{i2})x_{t2}$.

$$f_A^w = \frac{(5+14d+5d^2)t_A + (1+5d+6d^2)(t_H - 2t_T) - (1-d)(1+3d)f_B}{(3+d)(1+2d)}, \tag{27}$$

$$f_H^w = \frac{-a(1-d)(5+7d) + (1-d^2)(t_A+2t_T)}{(3+d)(1+2d)} + \frac{(7+9d-4d^2)t_H + (3+2d-5d^2)f_B}{(3+d)(1+2d)}, \tag{28}$$

$$f_T^w = \frac{-a(1-d)(5+7d) - d(5+7d)t_A + (2-5d-9d^2)t_H}{2(3+d)(1+2d)} + \frac{4(3+7d+2d^2)t_T + 2(1-d^2)f_B}{2(3+d)(1+2d)}, \tag{29}$$

where superscript w denotes welfare maximization upstream. Table 3 shows the comparative statics analysis on fees and traffics. Note that $f_A^w + f_H^w = \frac{-a(1-d)(5+7d)+2(1-d^2)f_B}{(3+d)(1+2d)} + \frac{2(4+7d+d^2)t_H - 2d(5+7d)t_T + 2(3+7d+2d^2)t_A}{(3+d)(1+2d)}$, and $f_A^w + f_H^w - 2f_T^w = \frac{(6+19d+11d^2)(t_A+t_H-2t_T)}{(3+d)(1+2d)}$. As happens in the cooperation and competition cases, the difference in fees across modes depends on differences in infrastructure marginal costs. Besides, that difference in fees determines the differences in traffics across modes. Welfare maximization in setting the fees also has the effect of segmenting the three markets in the sense that traffics in each market only depend on the infrastructure marginal costs involved in that particular market, i.e. q_i^w does neither depend on t_T nor t_A. Finally, the infrastructure marginal costs difference pass-through is now larger than one. This is explained by the fact that welfare maximization upstream reverses the distortion derived from imperfect competition downstream so that the pass-through to final prices equates just the differences in infrastructure marginal costs.

2.3. Results

In this section we provide some results with the comparison of fees and traffics under the different cases for the fully symmetric case $t_A = t_H = t_T = f_B = T$. It is shown that welfare maximizing fees are always the lowest ones, noting that for the local spoke airport it coincides with the marginal cost of providing the service while for the hub airport and the HSR station, the fees are smaller than marginal costs. Next, IM cooperation leads to a decrease in the access fee of the spoke airport up to the social maximizing level, i.e. $f_A^n > f_A^c = f_A^w = T$. Regarding the hub, cooperation implies an increase of the access fee with respect to independent profit maximization, i.e. $f_H^c > f_H^n > T > f_H^w$.[20] Finally, the degree of substitution (d) determines the ranking between the HSR fee chosen under competition and that under cooperation, as shown in the next result.

Result 1.

The ranking of the rail fees depends on the degree of substitution as follows.

a) *For low substitutability, $0 < d < 0.5431$, cooperation implies a lower fee than competition, $f_T^n > f_T^c > T > f_T^w$,*

b) *while for large substitutability $0.5431 < d < 1$, the ranking is reversed, $f_T^c > f_T^n > T > f_T^w$*

One wonders how robust are our results to the consideration of asymmetries in infrastructure marginal costs. To extend the above result and the next Result 2 and 3, we are going to consider a particular case where $t_A = t_H = f_B = T$, and to comply with our empirical application we assume that t_T is smaller than T. Under these conditions, Result 1 can be extended as follows. Firstly, both f_T^n and f_T^c are always larger than f_T^w. Secondly, we find the same pattern as in Result 1 when ranking f_T^n with f_T^c. In particular, for low substitutability cooperation implies a lower fee than competition, while for large substitutability is competition the one with the lowest fee. The unique modification is that the threshold on d partitioning the interval depends on the relation between T and t_T. It happens that this threshold is increasing in t_T being equal to 0.5431 when $t_T = T$. Regarding traffic in different markets, local airline traffic and connecting traffic that only travels by airplane follow the same pattern. Welfare maximizing fees induce the highest traffic airline volume, followed by that induced by cooperative fees with the lowest one being that induced by independent profit maximization, that is, $q_a^w > q_a^c > q_a^n$ and $x_a^w > x_a^c > x_a^n$. For the international market, it is the traffic induced by independent profit maximization the one closest to the welfare maximizing one, i.e. $q_i^w > q_i^n > q_i^c$. Finally, the ordering of HSR traffic is the content of the next result:

Result 2.

HSR traffic in each possible scenario is ranked depending on the degree of substitution as follows.

a) *Local market:*
$q_t^w > q_t^c > q_t^n$ *for* $0 < d < 0.4386$,
$q_t^w > q_t^n > q_t^c$ *for* $0.4386 < d < 0.9122$, *and.*
$q_t^n > q_t^w > q_t^c$ *for* $0.9122 < d < 1$.

b) *Connecting market:*
$x_t^w > x_t^c > x_t^n$ *for* $0 < d < 0.0319$,
$x_t^w > x_t^n > x_t^c$ *for* $0.0319 < d < 0.9113$, *and.*
$x_t^n > x_t^w > x_t^c$ *for* $0.9113 < d < 1$.

Result 2 can be extended to the case $t_T < T$ as follows. Firstly, both inequalities $q_t^w > q_t^c$ and $x_t^w > x_t^c$ hold. Besides, inequalities $q_t^w > q_t^n$ and $x_t^w > x_t^n$ are always satisfied. Finally, $q_t^c > q_t^n$ for $0 < d < d_{t_T}^-$ and for $d_{t_T}^+ < d < 1$, while $q_t^n > q_t^c$ otherwise. Note that both $d_{t_T}^-$ and $d_{t_T}^+$ increase in t_T, with $d_{t_T}^- = 0.4386$ and $d_{t_T}^+$ larger than one when $t_T = T$. The same changes occur when comparing x_t^n with x_t^c, with the only difference being that the corresponding thresholds for $x_t^n > x_t^c$ decrease in t_T. We are also interested in showing which upstream equilibrium case provides both the largest HSR market share in the local and connecting markets and also the largest number of connecting passengers.[21] First note that the welfare maximizing fees suppose larger differences in the local and connecting markets in favor of the HSR services than cooperative ones, i.e, $(q_t^w - q_a^w) > (q_t^c - q_a^c))$ and $(x_t^w - x_a^w) > (x_t^c - x_a^c))$ when the rail has a marginal infrastructure cost advantage, $t_A + t_H > 2t_T$. However, for the fully symmetric case both welfare maximizing and cooperative fees lead to the same number of passengers using each mode. Interestingly, the competition case implies larger HSR market shares in both markets even for the fully symmetric case. The reason is that indeed competition upstream is not symmetric since the rail infrastructure manager (RIM) controls the two HSR stations while each airport is managed separately, this meaning that the RIM exploits the complementarities of both HSR stations in setting the fee. Once cooperation or welfare maximization upstream is undertaken all the externalities in the whole infrastructure network are fully internalized and then the differences in traffics are only explained by differences in marginal infrastructure costs. Summarising, the main difference of high-

[19] Second order conditions for a maximum are satisfied.

[20] The proof of this ranking, that of the airport A fees and those for Results 1 to 3 are available from authors upon request.

[21] Using Eqs (34) and (35) in the Appendix, we reach the following expression for the total number of connecting passengers, $2(x_t^* + x_a^*) = \frac{2(3+d)(1+2d)(4a-2f_B-f_A-3f_H-2f_T)}{(1+3d)(8+9d-5d^2)}$.

Table 3
Sign of the marginal effects on welfare maximizing fees and traffics.

	Parameters				
	a	f_B	t_A	t_H	t_T
f_A^w	0	–	+	+	–
f_H^w	–	+	+	+	+
f_T^w	–	+	–	+ for $d < 0.2693$	+
$f_A^w + f_H^w$	–	+	+	+	–
$f_A^w + f_H^w - 2f_T^w$	0	0	+	+	–
q_a^w	+	0	–	–	+
q_t^w	+	0	+	+	–
q_i^w	+	–	0	–	0
x_a^w	+	–	–	–	+
x_t^w	+	–	+	+ for $d > 1/3$	–
$q_t^w - q_a^w = x_t^w - x_a^w$	0	0	+	+	–

speed rail and airline competition under full symmetry is that the effect of moving from competition to cooperation upstream is to reduce to zero the positive difference in market shares between HSR and airlines, which is present under competition upstream and explained by the fact that $f_A^n + f_H^n - 2f_T^n$ is positive and decreasing for all d.

Regarding the connecting passengers ranking, the next result shows that it depends on the degree of differentiation as follows:

Result 3. *The welfare maximization case leads to the largest number of connecting passengers. The complete ranking depends on the degree of substitution as follows:*

a) *For low substitutability, $0 < d < 0.5639$, cooperation results in more connecting passengers than competition, $(x_t^n + x_a^n) < (x_t^c + x_a^c) < (x_t^w + x_a^w)$,*
b) *while for large substitutability $0.5639 < d < 1$, competition results in more connecting passengers, $(x_t^c + x_a^c) < (x_t^n + x_a^n) < (x_t^w + x_a^w)$.*

Result 3 can be extended as follows. Firstly, $(x_t^c + x_a^c))$ is always smaller than $(x_t^w + x_a^w)$ for all a, t_A, t_H, t_T, and f_B. Secondly, in case $t_T < \bar{T}$ then $(x_t^n + x_a^n) < (x_t^c + x_a^c)$ for $0 < d < d_{t_T}$ with the latter threshold increasing in t_T and equal to 0.5639 when $t_T = T$. Similarly, $(x_t^n + x_a^n) < (x_t^w + x_a^w)$ for all d when a is sufficiently large.

Before moving to the empirical application, it is instructive to discuss the case where the foreign airport B manager and the domestic IMs play a strategic game in setting the per-passenger fees. Profit functions are those in (19) to (21) and $B_B = (f_B - t_B)(Q_{i1} + Q_{i2})$, where t_B denotes airport B's marginal infrastructure costs. Note that airport B is providing a complement infrastructure to all the domestic infrastructures, both in the international and the connecting markets. Since IMs are competing in fees (prices) then f_T, f_A and f_H are strategic substitutes for airport B, which implies that any variation in the fees chosen by rivals will trigger a reaction in the opposite sense by airport B.

We are interested in the effect of cooperation upstream at a domestic level, thus it is important to check the reaction on f_B when moving from the competition to the cooperation scenario. Note that equilibrium fees under the competition scenario are implicitly defined now by the system of equations $\frac{\partial B_T}{\partial f_T} = 0$, $\frac{\partial B_A}{\partial f_A} = 0$, $\frac{\partial B_H}{\partial f_H} = 0$, and $\frac{\partial B_B}{\partial f_B} = 0$. Denote the solution to that system by f_j^N for $j = T, A, H, B$.[22] Cooperation upstream supposes that airport A decreases its fee, airport H increases it, while the HSR station decreases the fee only when the degree of substitution is low enough. Since fees are strategic substitutes for airport B, there is not a clear answer on the direction of the change in f_B.[23] Therefore, to check this change we compute f_B^C by substituting expressions (23) to (25) in airport B's reaction function and solve for f_B, where f_B^C captures the effect of cooperation on airport B's optimal behavior. In particular,

$$f_B^C = \frac{a(5+7d)(4+9d-d^2)}{3(14+53d+40d^2-11d^3)} - \frac{(3+d)(1+2d)(1+d)(t_A+2t_T)}{3(14+53d+40d^2-11d^3)} - \frac{(17+63d+49d^2-9d^3)t_H}{3(14+53d+40d^2-11d^3)} + \frac{2t_B}{3}. \quad (30)$$

Finally, assuming full symmetry in infrastructure marginal costs with $t_B = T$, we find that $f_B^C > f_B^N$ if and only if the degree of substitution is low enough, that is, for $d < 0.6649$. Thus, the consideration of an endogenous f_B can easily be introduced in the analysis. A numerical evaluation of its effects is offered at the end of Section 3.

A quantitative ex-ante assessment of the effects brought about by cooperation upstream is given in the numerical exercise provided in the next section. It allows us to abandon the symmetry assumed in illustrating the intuitions of the model while enabling us to quantify the impact of endogenous fees on passenger surplus, operators profits, HSR in particular, and welfare for an actual network.

Table 4
Data for the Valencia-Madrid-New York network, year 2016.

Local air traffic (pass. per day and direction)	548
HSR traffic point to point (pass. per day and direction)	2,445
International air traffic (pass. per day and direction)	1,164
% of train connecting users local leg	30
% of air connecting users local leg	60
Local air price (€)	110
HSR price (€)	90
International air price (€)	600

Source: own elaboration.

3. An empirical application

In this section we will follow the same calibration process developed in Álvarez-SanJaime et al. (2020b). We use data available for the network and values for price elasticities in order to recover the parameters of the utility functions. In particular, the data for traffic volumes and prices are the same as in Álvarez-SanJaime et al. (2020b) taken from statistics offered by AENA, the Spanish airport infrastructure manager, and RENFE, the Spanish passenger rail operator, and they are shown in Table 4. The Valencia-Madrid HSR line, started in December 2010, moved 2,100,000 passengers, of which 1,785,000 were point to point traffic, and hardly 400,000 passengers used the air transport in 2016. There is an important presence of connecting passengers in the link Madrid-Valencia, especially about air users, which suppose a percentage close to 60%. As for the international destination, we will consider the city of New York since it shows high traffic levels from Madrid and no direct flight connects Valencia to New York.

Parameters b_t, b_a, d_l, d_c and d_i are calibrated from values for elasticities (see Table 5), and the willingness to pay constants in the utility function are calibrated using the data for traffic in Table 4, considering that fees equal infrastructure marginal costs. And also to make the

[22] The precise expression for airport B's reaction function and f_B^N is in the Appendix.

[23] One may wonder which would be the reaction of airport B when the domestic IMs choose fees to maximize welfare. Strategic substitution and the fact that all fees are reduced with respect to the competition scenario leads us to conclude that airport B will definitively react by increasing its fee when domestic IM's have the same infrastructure marginal costs.

Table 5
Values for elasticities used in the calibration process.

	Own-price elasticity	Cross-price elasticity
HSR	– 0.75	0.2
Air	−1.2	0.2

Source: Ortega-Hortelano et al. (2016), and IATA IATA Annual Report, 2017.

Table 6
Calibration of the utility functions parameters.

Willingness to pay		Own and cross effects	
a_t	182.917	b_t	0.0455
a_a	158.093	b_a	0.0795
a_i	540.196	d_l	0.0146
a_{ct}	658.162	d_i	0.0219
a_{ca}	671.504	d_c	0.0182
a_{ci}	617.504		

Table 7
Operating and infrastructure costs per passenger.

	Valencia- Madrid- New York
HSR costs	51.42
Air local costs	83.33
Air international costs	499.98
HSR infrastructure marginal cost	4
Airport infrastructure marginal cost	8

Source: Campos and de Rus (2009) and Swan and Adler (2006).

simulation more realistic, we include an additional utility equation for connecting users that, coming from elsewhere and not having HSR direct connections, use the hub airport (Madrid in our case) to take either airline 1 or 2 in the second leg of our model.[24] All the calibrated parameters are shown in Table 6.[25] Finally, data for operating train and air costs and for airport and HSR infrastructure fees were used in order to complete the simulation process. Values per passenger are reported in Table 7.[26]

The calibrated parameters are employed in the different simulation scenarios reported in Table 8, where fees are endogenously determined. In the first column, our benchmark case, the results are shown when both airports and the RIM set profit-maximizing fees in an independent way and the foreign airport follows a marginal cost-pricing rule, whereas HSR and airlines set also profit-maximizing prices, which corresponds to the competition upstream case above (subs. 2.2.1). The second column shows the results when there is collaboration between the three IMs involved in the network, as in the cooperation upstream case above (subs. 2.2.2). Relative to the theoretical analysis, three more cooperation scenarios are considered. In the third column we assume that the RIM collaborates with the hub airport in setting their fees. In the fourth column the collaboration is produced between the domestic airports, and finally the fifth column shows the results when collaboration comprises the RIM and the local airport.

Rows display the results obtained for prices, fees and traffic levels for the different types of users, the profits for the transport operators and IMs, the passenger surplus identifying the types of users and the aggregate total welfare. Since comparisons are drawn relative to the benchmark case, the tables incorporate the percentage variation in italics and small fonts below each figure. Regarding the scenario where all the IMs set a collaboration agreement, the fees in the hub and train infrastructure decrease by 17% and 2% (as predicted in Result 1, part a)[27] respectively, whereas fees at the local airport increase by 42.4%. These changes in fees provoke modifications in prices, increasing prices slightly in the local market for train and air transport, and reducing them for the international leg. These changes in prices reduce the local traffic level for HSR by 0.80% and by 25.4% for the local air traffic. However, all the connecting traffic, using HSR or air in the local leg, increases around 15%. This shows the robustness of Result 3 part a) above under asymmetries. Additionally, traffic in the international leg will increase by 22.8%. In terms of profits, all the operators are better off, with a 14.5% increase in the HSR profits. In terms of passenger surplus, except for the local users, the rest of users will experience an increase in their surplus, producing a total increase by 21%. Aggregating all the surpluses, total welfare increases by 10.4%.

The third column expresses the results under partial collaboration between the RIM and the hub airport leaving out the local airport. The changes in infrastructure fees are qualitatively similar to the previous scenario, but now the increase in the fee at the local airport is more moderate, leading to a slight fall in all prices, provoking an increase in all traffic levels for all types of users and improving the respective levels of passenger surplus. Also the profitability of operators and infrastructure managers increases, resulting in a total welfare increase by 11.11%.

The fourth column indicates partial collaboration between both airports, leaving alone the management of the RIM.[28] In this case, all infrastructure fees fall, especially the fee at the local airport by 16.4%. This implies a slight decrease in prices for all the transport services. In this case HSR traffic is hardly affected, while air local traffic and air connecting traffic would increase by 52.2% and 45.4%, respectively. International traffic will increase in a moderate way by 5.2%. Additionally, profits for the local airline increase by 114.3%. In terms of passenger surplus all users are better off with a global rise of 8.3%. Total welfare gains are 3.1% higher than under the benchmark scenario. Finally, the fifth column, where the RIM and local airport collaborate, shows a significant reduction in both passenger surplus and total welfare, as intuitively expected, due to the competing feature of both infrastructures in the local market.

Assume instead that airport B also chooses its profit maximizing per passenger fee. In this manner we can check the effect of strategic behavior involving all IMs in the network. Results are reported in Table 10. Comparing the competition scenarios (column 1 in Table 8 and in Table 10) we note that an endogenous f_B triggers a reduction by 27.3% of the fee at the hub airport, a slight increase in the fee at the local airport and also a slight decrease also in the fee for the rail infrastructure; a finding which is in agreement with Table 1 since the endogenization of f_B supposes an increase of that fee. Regarding the effect on

[24] The additional utility function reads, $U_{ci} = a_{ci}(q_{ci1} + q_{ci2}) - \frac{b_a}{2}(q_{ci1}^2 + q_{ci2}^2) - d_c q_{ci1} q_{ci2}$, where a_{ci} denotes the maximum willingness to pay for a traveler catching an international airline service in Madrid but coming from elsewhere. Note that those travelers have already spent some budget reaching Madrid from elsewhere, and we assume that the average price of such previous leg is equal to €80.

[25] Note, in particular, that there are asymmetries in the demand intercepts, which have a clear interpretation in terms of vertical differentiation between modes as put forward by Hackner (2000). These differences can be due to differences in access time, travel speed and connecting time (Xia and Zhang 2016) and capture the differences of HSR and airline competition.

[26] The utility functions considered here are i) the one appearing in (1) assuming different own effects for each mode as follows: $U_l = a_t q_t + a_a q_a - \frac{b_t}{2}q_t^2 - \frac{b_a}{2}q_a^2 - d_l q_t q_a$; ii) the one appearing in (3) as follows $U_c = a_{ct}(x_{t1} + x_{t2}) + a_{ca}(x_{a1} + x_{a2}) - \frac{b_t}{2}(x_{t1}^2 + x_{t2}^2) - \frac{b_t}{2}(x_{a1}^2 + x_{a2}^2) - d_c(x_{t1}x_{t2} + x_{t1}x_{a1} + x_{t1}x_{a2} + x_{t2}x_{a1}$ - $+ x_{t2}x_{a2} + x_{a1}x_{a2})$ and where a_{ct} and a_{ca} correspond to the connecting passengers' maximum willingness to pay for a bundle including a HSR service in the first leg and that for a bundle including an air transport service in the first leg, respectively. Regarding the own effect in (2), b_a is assumed.

[27] Our calibration assumes different degrees of substitution across markets, but in all cases the corresponding ratios (d/b) are relatively low which is consistent with a low d in the theoretical model.

[28] Note that AENA is in charge of the management of the whole Spanish airport network.

Table 8
Upstream collaboration.

	Competition	All IM collaborat.	RIM & Hub collaborat.	Loc. Airp. & Hub collab.	RIM & Loc. Airp. collab.
HSR price p_t	141.95	142.50	140.88	141.67	144.04
		0.39%	*−0.75%*	*−0.20%*	*1.47%*
Local air price p_a	147.86	149.30	146.95	145.17	152.63
		0.97%	*−0.62%*	*−1.82%*	*3.23%*
Intern. air price p_{i1}	518.39	513.45	513.63	517.26	519.32
		−0.95%	*−0.92%*	*−0.22%*	*0.18%*
Intern. air price p_{i2}	518.39	513.45	513.63	517.26	516.84
		−0.95%	*−0.92%*	*−0.22%*	*−0.30%*
Fee RIM f_t	32.33	31.68	30.45	32.23	33.39
		−2.01%	*−5.82%*	*−0.31%*	*3.28%*
Fee Local airport f_A	21.09	30.04	25.00	17.64	30.85
		42.44%	*18.54%*	*−16.36%*	*46.28%*
Fee Hub airport f_H	45.57	37.84	38.81	43.45	43.92
		−16.96%	*−14.83%*	*−4.65%*	*−3.62%*
Local train passeng. q_t	879	872	900	874	851
		−0.80%	*2.39%*	*−0.57%*	*−3.19%*
Connect. train passeng. x_{t1}	392	454	465	392	344
		15.82%	*18.62%*	*0.00%*	*−12.24%*
Connect. train passeng. x_{t2}	392	454	467	392	435
		15.82%	*19.13%*	*0.00%*	*10.97%*
Local airl. passenger q_a	67	50	74	102	12
		−25.37%	*10.45%*	*52.24%*	*−82.09%*
Connect. passeng. airl. 1 x_{a1}	88	101	126	128	23
		14.77%	*43.18%*	*45.45%*	*−73.86%*
Connect. passeng. airl. 2 x_{a2}	88	101	119	128	64
		14.77%	*35.23%*	*45.45%*	*−27.27%*
Intern. airl. passeng. q_{i1}	215	264	262	226	196
		22.79%	*21.86%*	*5.12%*	*−8.84%*
Intern. airl. passeng. q_{i2}	215	264	263	226	240
		22.79%	*22.33%*	*5.12%*	*11.63%*
Intern. connecting airl. 1 q_{ci1}	229	280	277	241	212
		22.27%	*20.96%*	*5.24%*	*−7.42%*
Intern. connecting airl. 2 q_{ci2}	229	280	278	241	253
		22.27%	*21.40%*	*5.24%*	*10.48%*
HSR profits π_t	43704	50065	53113	43411	42803
		14.55%	*21.53%*	*−0.67%*	*−2.06%*
Local airline profits π_a	1509	1618	2606	3235	284
		7.22%	*72.70%*	*114.38%*	*−81.18%*
Intern. airline 1 profits π_{i1}	13694	19329	15551	15583	13505
		41.15%	*13.56%*	*13.79%*	*−1.38%*
Intern. airline 2 profits π_{i2}	13694	19329	15442	15583	14791
		41.15%	*12.76%*	*13.79%*	*8.01%*
Profits RIM B_T	94207			93575	
				−0.67%	
Profits Local airport B_A	3189		5445		
			70.74%		
Profits Hub airport B_H	69469				63468
					−8.64%
Profits RIM-Hub collabor.			166577		
Profits Hub-Local airp. collabor.				73363	
Profits RIM-Local airp. collabor.					98060
Profits RIM-Hub-Local airp. collab.		169627			
Local Passenger Surplus	18608	18047	19624	19079	16615
		−3.01%	*5.46%*	*2.53%*	*−10.71%*
International Passenger Surplus	4687	7054	6976	5187	4848
		50.50%	*48.84%*	*10.67%*	*3.44%*
Local Connecting Passenger Surplus	13072	17456	19287	15004	11178
		33.54%	*47.54%*	*14.78%*	*−14.49%*
Intern. Connecting Passeng. Surplus	5135	7651	7569	5668	5304
		49.00%	*47.40%*	*10.38%*	*3.29%*
Total Passenger Surplus	41502	50208	53456	44938	37945
		20.98%	*28.80%*	*8.28%*	*−8.57%*
Operators' profits	72601	90341	86712	77812	71383
		24.43%	*19.44%*	*7.18%*	*−1.68%*
Total IM profits	166865	169627	172022	166938	161528
		1.66%	*3.09%*	*0.04%*	*−3.20%*
Total welfare	280968	310176	312190	289688	270856
		10.40%	*11.11%*	*3.10%*	*−3.60%*

Table 9
Downstream collaboration.

	Competition	Rail-air collaborat.	Air-air collaborat.	Rail and local air coll.
HSR price p_t	141.95	144.19	141.80	143.73
		1.58%	*−0.11%*	*1.25%*
Local air price p_a	147.86	147.13	149.41	152.3
		−0.49%	*1.05%*	*3.00%*
Intern. air price p_{i1}	518.39	520.31	518.93	518.12
		0.37%	*0.10%*	*−0.05%*
Intern. air price p_{i2}	518.39	517.88	517.92	518.12
		−0.10%	*−0.09%*	*−0.05%*
Alliance price rail-air		652.94		
Alliance price air-air			661.38	
Fee RIM f_t	32.33	32.74	32.36	30.66
		1.27%	*0.09%*	*−5.17%*
Fee Local airport f_A	21.09	20.07	22.37	14.43
		−4.84%	*6.07%*	*−31.58%*
Fee Hub airport f_H	45.57	46.43	45.13	45.89
		1.89%	*−0.97%*	*0.70%*
Local train passeng. q_t	879	823	889	856
		−6.37%	*1.14%*	*−2.62%*
Connect. train passeng. x_{t1}	392	616	361	393
		57.14%	*−7.91%*	*0.26%*
Connect. train passeng. x_{t2}	392	281	399	393
		−28.32%	*1.79%*	*0.26%*
Local air passenger q_a	67	86	45	15
		28.36%	*−32.84%*	*−77.61%*
Connect. passeng. airl. 1 x_{a1}	88	48	161	45
		−45.45%	*82.95%*	*−48.86%*
Connect. passeng. airl. 2 x_{a2}	88	87	64	45
		−1.14%	*−27.27%*	*−48.86%*
Intern. air passeng. q_{i1}	215	187	206	218
		−13.02%	*−4.19%*	*1.40%*
Intern. air passeng. q_{i2}	215	229	223	218
		6.51%	*3.72%*	*1.40%*
Intern. connecting airl. 1 q_{ci1}	229	202	221	232
		−11.79%	*−3.49%*	*1.31%*
Intern. connecting airl. 2 q_{ci2}	229	242	237	232
		5.68%	*3.49%*	*1.31%*
HSR profits π_t	43704		43018	
			−1.57%	
Local airline profits π_a	1509	1246		
		−17.43%		
Intern. airline 1 profits π_{i1}	13694			12636
				−7.73%
Intern. airline 2 profits π_{i2}	13694	11283	13649	12636
		−17.61%	*−0.33%*	*−7.73%*
Profits RIM B_T	94207	98878	93550	87553
		4.96%	*−0.70%*	*−7.06%*
Profits Local airport B_A	3189	2672	3874	575
		−16.21%	*21.48%*	*−81.97%*
Profits Hub airport B_H	69469	72709	69480	67281
		4.66%	*0.02%*	*−3.15%*
Profits rail airl1 collabor.		57241		
Profits air-air collabor.			15738	
Profits rail and local airl. collabor				53491
Local Passenger Surplus	18608	16759	18657	16886
		−9.94%	*0.26%*	*−9.25%*
International Passenger Surplus	4687	4415	4676	4806
		−5.80%	*−0.23%*	*2.54%*
Local Connecting Passenger Surplus	13072	16249	13291	11338
		24.30%	*1.68%*	*−13.26%*
Intern. Connecting Passeng. Surplus	5135	4842	5123	5262
		−5.71%	*−0.23%*	*2.47%*
Total Passenger Surplus	41502	42265	41747	38292
		1.84%	*0.59%*	*−7.73%*
Operators' profits	72601	69770	72405	78763
		−3.90%	*−0.27%*	*8.49%*
Total IM profits	166865	174259	166904	155409
		4.43%	*0.02%*	*−6.87%*
Total welfare	280968	286294	281056	272464
		1.90%	*0.03%*	*−3.03%*

equilibrium prices, local market prices are lower, while international market prices increase as anticipated by the comparative statics of prices when f_B varies as proven in the theoretical section. Finally, an interesting welfare redistribution arises since local passengers are better off while the rest of passenger surpluses decline. On aggregate terms, total passenger surplus, profits and welfare decrease since now the operators' marginal costs of offering transport services in the international and connecting markets are higher due to the endogenization of f_B. Finally, we find that partial collaboration between the RIM and the hub airport leaving out the local airport is the collaboration scheme that reaches the largest increase in welfare and total passenger surplus, thus concluding that the endogenization of f_B does not affect the preferred collaboration scheme. As it occurs when f_B is exogenous, all agents are better off under the collaboration pattern mentioned above as compared to the competition scenario, being passengers those who benefit the most, followed by operators and noting that IMs barely increase profits. In general, the effect of an endogenous f_B is to mitigate the percentage variations in total welfare and total passenger surplus due to the different collaboration schemes with respect to the competition scenario.

Since the literature has examined the effects of cooperation at the downstream level, it is instructive to study how they compare to cooperation upstream. We take advantage of our setting to run simulations, shown in Table 9, where cooperation between transport operators is assumed. The first column reproduces the results of the benchmark scenario in the previous table. The second column shows the results when there is collaboration between the HSR operator and one of the international airlines. The third column stands for the situation where the local and one of the international airlines maximize their joint profits. The fourth column displays the results when the agreement is set between the HSR operator and the local airline. Note that in this type of horizontal agreements a bundle price is charged to those users travelling between A and B, which satisfies the non-arbitrage condition.

Regarding column two, RIM and hub fees increase slightly by 1.3% and 1.9% respectively, whereas the fee for the local airport decreases by 4.8%. These changes in fees run contrary to those above when cooperation happens at the upstream level, as in column two of Table 8. Individual prices for the HSR and for the international airline increase, while the prices for the local and the other international airline outside of the agreement decrease. Note that in this case the bundle price set by partners is lower than the sum of the individual prices set by non-collaborating operators. The effect on industry profitability is varied, increasing profits for the allied operators and reducing it for the non-allied ones. Passenger surplus is lower for all the users, except for the connecting users travelling from Valencia to New York. Aggregating all the surpluses, the total welfare increases by just 1.9%. The direction of these changes is qualitatively similar to that under exogenous fees, as presented in Álvarez-SanJaime et al. (2020b). At this stage it is interesting to compare the results under upstream and downstream cooperative agreements. In particular, an upstream agreement between the RIM and the hub airport is preferable in welfare terms to a downstream agreement between the HSR and one of the international airlines.

As for column three, the fee at the local airport increases by 6% producing an increase in local air price by 1.05%, a fall of local air traffic by 32.8% and a rise in the connecting air traffic by 83.0%. In terms or profits, the HSR operator and the RIM see their profits hardly reduced. In terms of passenger surplus the changes are small; only the surplus for connecting passengers increases by 1.7%. Aggregating all the surpluses, total welfare increases by just 0.03%. This is in contrast with the 3.1% rise in welfare produced when both airports collaborate, that meaning that an upstream agreement is preferred to a downstream one. Finally, the scenario shown in column four notably harms passengers and reduces total welfare as expected.

There is yet another interesting comment to highlight in our results. Note that the results in Table 9 are produced when fees are endogenous, while the results in Álvarez-SanJaime et al. (2020b) were obtained for given fees. The results for the same type of collaboration under exogenous or endogenous fees are qualitatively similar in prices. For instance, individual prices set by partners increase, but those set by non-allied companies fall. However, the higher prices levels lead to smaller gains in passenger surplus (especially for connecting users due to the bundle price) when fees are endogenous. The effect of endogenous fees is to alter the ranking on welfare of different collaborations, since now the cooperation between the HSR and one of the international airlines is better than cooperation between the local and one of the international airlines, the opposite of what happens with exogenous fees.[29]

4. Concluding remarks and policy implications

This paper has presented an integrated model of a transport network that exhibits complementarities and substitutabilities between different infrastructure providers. Our focus has been to examine the effects of upstream cooperation when fees are endogenously set. Formally, the model emphasizes the combinations and levels of access fees among infrastructures that determine modal traffic orderings in the local, international and connecting markets. Thus, for a sufficiently low degree of substitution, cooperation results in lower rail fees and higher rail traffic than under competition. Besides, it leads to more connecting passengers. Whether upstream cooperation is beneficial for users and welfare is determined by means of an empirical application to the Valencia-Madrid-New York network. Relative to competition, cooperation between all infrastructure managers and cooperation between the rail and the hub airport managers leads to gains in passenger surplus (in the range of 20.9–28.8%), in operators' profitability (19.4–24.4%) and in total welfare (10.4–11.1%). The received literature has shown that for-profit objectives at airports typically lead to higher fees and welfare reductions. We note differences once an intermodal integrated network is considered. In particular, coordination between infrastructures need not result in higher fees and may produce substantial welfare gains.

We believe that our setting can be employed to perform ex-ante simulation exercises that may advise informed transport policy. Our model throws a number of policy implications. First, transport authorities (at least in Europe) are favorable to the promotion of HSR because it is a more environmentally friendly mode while solving mobility problems and alleviating congestion on hubs and roads. The choice of access fees for the infrastructure network in a cooperative manner seems a sensible measure in this regard. This would be particularly useful in encouraging connecting traffic that involves rail travel in one of the links. Such coordination would improve the performance of HSR lines, which are very costly to build. Second, our results suggest that upstream cooperation is preferable to downstream cooperation. Users and operators are significantly better off with an upstream agreement provoking a notable increase in total welfare; this type of agreements do not show a conflict between private and social incentives, which would make them more easily acceptable from a policy viewpoint. Although we find examples of collaboration agreements between some HSR operators and airlines, policymakers should not disregard the option of exploring the joint determination of access fees that may lead to a more efficient working of transport closer to welfare maximizing objectives. Finally, it turns out that the most welfare improving agreements, whether at the upstream or the downstream level involve the HSR mode, emphasizing the importance of inter-modal collaborations. Further research should contemplate the benefits of HSR on environmental issues, time savings for connecting passengers and the introduction of competition in HSR lines.

[29] In the case of downstream collaboration when f_B is endogenously determined, results are similar to those obtained in Table 9, showing again that rail-air collaboration is preferable in terms of welfare to air-air collaboration.

Table 10
Upstream collaboration when f_B is endogenous.

	Competition	All IM collaborat.	RIM & Hub collaborat.	Loc. Airp. & Hub collab.	RIM & Loc. Airp. collab.
HSR price p_t	137.13	139.59	136.37	136.99	139.95
		1.79%	*−0.55%*	*−0.10%*	*2.06%*
Local air price p_a	140.78	142.70	139.63	138.41	146.10
		1.36%	*−0.82%*	*−1.68%*	*3.78%*
Intern. air price p_{i1}	529.02	524.19	526.11	527.65	527.67
		−0.91%	*−0.55%*	*−0.26%*	*−0.26%*
Intern. air price p_{i2}	529.02	524.19	526.06	527.65	527.67
		−0.91%	*−0.56%*	*−0.26%*	*−0.26%*
Fee RIM f_t	30.68	31.89	33.94	30.64	32.43
		3.94%	*10.63%*	*−0.13%*	*5.70%*
Fee Local airport f_A	24.73	39.62	28.21	25.16	34.15
		60.21%	*14.07%*	*1.74%*	*38.09%*
Fee Hub airport f_H	33.13	19.53	26.76	27.63	32.6
		−41.05%	*−19.23%*	*−16.60%*	*−1.60%*
Fee Internat. aiport f_b	35.98	42.45	33.94	39.03	35.38
		17.98%	*−5.67%*	*8.48%*	*−1.67%*
Local Passenger Surplus	23778	21223	24681	24277	20537
		−10.75%	*3.80%*	*2.10%*	*−13.63%*
International Passenger Surplus	1231	2526	1963	1552	1546
		105.20%	*59.46%*	*26.08%*	*25.59%*
Local Connecting Passenger Surplus	8421	10479	11619	10117	7017
		24.44%	*37.98%*	*20.14%*	*−16.67%*
Intern. Connecting Passeng. Surplus	1418	2822	2215	1769	1762
		99.01%	*56.21%*	*24.75%*	*24.26%*
Total Passenger Surplus	34848	37050	40478	37715	30862
		6.32%	*16.16%*	*8.23%*	*−11.44%*
Operators' profits	53490	60364	63429	58140	49168
		12.85%	*18.58%*	*8.69%*	*−8.08%*
Total IM profits	119868	115699	120799	117382	120862
		−3.48%	*0.78%*	*−2.07%*	*0.83%*
Total welfare	208206	213113	224706	213237	200892
		2.36%	*7.92%*	*2.42%*	*−3.51%*

Appendix. : equilibrium expressions

Equilibrium prices and traffics

We first provide the expressions corresponding to the effects of each per passenger airport and rail fees on equilibrium prices. That is,

$$\Psi_t^A(d) = 2 + 30d + 83\ d^2 + 48\ d^3 - 19\ d^4 > 0$$

$$\Psi_t^B(d) = -2(1 - d^2)(6 + 19\ d + 11\ d^2) < 0$$

$$\Psi_t^H(d) = (-10 - 8d + 73\ d^2 + 86\ d^3 + 3d^4) > 0 \text{ for } d > 0.351659$$

$$\Psi_t^T(d) = 4(17 + 69d + 68\ d^2 - 3\ d^3 - 7\ d^4) > 0$$

$$\Psi_a^A(d) = \frac{1}{4}\Psi_t^T(d) > 0$$

$$\Psi_a^B(d) = \frac{1}{2}\Psi_t^B(d) < 0$$

$$\Psi_a^H(d) = (1 + 2\ d)(11 + 28\ d + 7\ d^2 + 2\ d^3) > 0$$

$$\Psi_a^T(d) = \Psi_t^A(d) > 0$$

$$\Psi_i^A(d) = -(1 - d^2) < 0$$

$$\Psi_i^B(d) = 3(2 + 3\ d - d^2) > 0$$

$$\Psi_i^H(d) = (1 + 2\ d)(5 - d) > 0$$

$$\Psi_i^T(d) = 2\Psi_i^A(d) < 0$$

$$\Omega(d) = \frac{(3 + d)(1 + 2\ d)}{(4 + 9\ d - d^2)(8 + 9\ d - 5\ d^2)} > 0$$

It is easily shown that:

$$\Psi_a^A(d) > \Psi_t^A(d) > 0 > \Psi_i^A(d),$$

$\Psi_i^B(d) > 0 > \Psi_t^B(d) > \Psi_a^B(d)$ and
$\Psi_t^T(d) > \Psi_a^T(d) > 0 > \Psi_i^T(d)$.

Finally,
$\Psi_i^H(d) > \Psi_a^H(d) > 0 > \Psi_t^H(d)$ for $0 < d < 0.351659$, while
$\Psi_i^H(d) > \Psi_a^H(d) > \Psi_t^H(d) > 0$ for $0.351659 < d < 1$.

The equilibrium traffics below are obtained by substitution of the equilibrium prices shown in Eqs. 16–18 in the corresponding demand functions, Eqs. (4)–(11).

Local and international markets

$$\begin{aligned} q_a^* = & \frac{a(3+d)(1+2\,d)}{(1+d)\left(8+9\,d-5\,d^2\right)} + \frac{2(3+d)(1+2\,d)(1-d)f_B}{\left(4+9\,d-d^2\right)\left(8+9\,d-5\,d^2\right)} \\ & - \frac{(3+d)(1+2\,d)(34+136\,d+106\,d^2-89\,d^3-62\,d^4+19\,d^5)f_A}{\left(4+9\,d-d^2\right)\left(1-d^2\right)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\ & - \frac{(3+d)(1+2\,d)(22+110\,d+134\,d^2-41\,d^3-78\,d^4-3\,d^5)f_H}{\left(4+9\,d-d^2\right)\left(1-d^2\right)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\ & - \frac{2(3+d)(1+2\,d)^2\left(2-8\,d-39\,d^2-10\,d^3+7\,d^4\right)f_T}{\left(4+9\,d-d^2\right)\left(1-d^2\right)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \end{aligned} \tag{31}$$

$$\begin{aligned} q_t^* = & \frac{a(3+d)(1+2\,d)}{(1+d)\left(8+9\,d-5\,d^2\right)} + \frac{2(3+d)(1+2\,d)(1-d)f_B}{\left(4+9\,d-d^2\right)\left(8+9\,d-5\,d^2\right)} \\ & - \frac{(3+d)(1+2\,d)^2(2-8\,d-39\,d^2-10\,d^3+7\,d^4)f_A}{\left(4+9\,d-d^2\right)\left(1-d^2\right)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\ & + \frac{(3+d)(1+2\,d)(10+30\,d+27\,d^2+40\,d^3+29\,d^4+8\,d^5)f_H}{\left(4+9\,d-d^2\right)\left(1-d^2\right)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\ & - \frac{2(3+d)(1+2\,d)\left(34+136\,d+106\,d^2-89\,d^3-62\,d^4+19\,d^5\right)f_T}{\left(4+9\,d-d^2\right)\left(1-d^2\right)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \end{aligned} \tag{32}$$

$$\begin{aligned} q_i^* = & q_{i1}^* = q_{i2}^* = \frac{a(3+d)(1+2\,d)}{(1+d)\left(8+9\,d-5\,d^2\right)} - \frac{(3+d)(1+2\,d)\left(6+9\,d-3\,d^2\right)f_B}{(1+d)\left(4+9\,d-d^2\right)\left(8+9\,d-5\,d^2\right)} \\ & + \frac{(3+d)(1+2\,d)\left(\left(1-d^2\right)(f_A+2f_T)-(5+9\,d-2\,d^2)f_H\right)}{(1+d)\left(4+9\,d-d^2\right)\left(8+9\,d-5\,d^2\right)} \end{aligned} \tag{33}$$

Connecting market

$$\begin{aligned} x_a^* = & x_{a1}^* = x_{a2}^* = \frac{2a(3+d)(1+2\,d)}{(1+3d)\left(8+9\,d-5\,d^2\right)} - \frac{(3+d)(1+2\,d)f_B}{(1+3d)\left(8+9\,d-5\,d^2\right)} \\ & - \frac{(3+d)(1+2\,d)(7+23\,d+7\,d^2-13\,d^3)f_A}{(1-d)(1+3d)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\ & - \frac{(3+d)(1+2\,d)(1+d)(13+23\,d-24\,d^2)f_H}{(1-d)(1+3d)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\ & + \frac{2(3+d)(1+2\,d)^2(1+8\,d-d^2)f_T}{(1-d)(1+3d)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \end{aligned} \tag{34}$$

$$
\begin{aligned}
x_t^* &= x_{t1}^* = x_{t2}^* = \frac{2a(3+d)(1+2\,d)}{(1+3d)\left(8+9\,d-5\,d^2\right)} - \frac{(3+d)(1+2\,d)f_B}{(1+3d)\left(8+9\,d-5\,d^2\right)} \\
&+ \frac{(3+d)(1+2\,d)^2(1+8\,d-d^2)f_A}{(1-d)(1+3d)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\
&- \frac{(3+d)(1+2\,d)(5+3\,d-23\,d^2-9\,d^3)f_H}{(1-d)(1+3d)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)} \\
&- \frac{2(3+d)(1+2\,d)(7+23\,d+7\,d^2-13\,d^3)f_T}{(1-d)(1+3d)\left(8+9\,d-5\,d^2\right)\left(6+19\,d+11\,d^2\right)}
\end{aligned}
\tag{35}
$$

Infrastructure fees for the competition upstream case

Here, we provide the expressions corresponding to the profit maximizing equilibrium infrastructure fees, $f_A^n(a,f_B,t_A,t_H,t_T)$, $f_H^n(a,f_B,t_A,t_H,t_T)$ and $f_T^n(a,f_B,t_A,t_H,t_T)$.

The spoke airport infrastructure fee

$$f_A^n(a,f_B,t_A,t_H,t_T) = \frac{1}{2D(d)}\left(\Phi_a^A(d)a + \Phi_{f_B}^A(d)f_B + \Phi_{t_A}^A(d)t_A + \Phi_{t_H}^A(d)t_H + \Phi_{t_T}^A(d)t_T\right).$$

Where:

$$
\begin{aligned}
D(d) &= 9147600 + 178388352\,d + 1515301584\,d^2 + 7269040772\,d^3 + 21117628910\,d^4 \\
&+ 35722518870\,d^5 + 24716874776\,d^6 - 25527174859\,d^7 - 68605177509\,d^8 \\
&- 42984160545\,d^9 + 21413744241\,d^{10} + 39254504238\,d^{11} + 8412653956\,d^{12} \\
&- 9748246868\,d^{13} - 3758899470\,d^{14} + 1093174393\,d^{15} + 332359075\,d^{16} \\
&- 98167233\,d^{17} + 6050421\,d^{18} > 0
\end{aligned}
$$

$$
\begin{aligned}
\Phi_a^A(d) = &(1-d)(5+7d)\left(4+9d-d^2\right)\left(6+19d+11d^2\right)\left(57060+739428d+3863830d^2+10044708d^3+11862768d^4-426703d^5-15995394d^6-12880953d^7\right. \\
&\left.+1243088d^8+4427883d^9+423360d^{10}-413387d^{11}+40296d^{12}\right)>0
\end{aligned}
$$

$$
\begin{aligned}
\Phi_{f_B}^A(d) = &4(1-d)\left(6+19\,d+11\,d^2\right)\left(5850+183756\,d+1864699\,d^2+9096316\,d^3+23051552\,d^4+24928933\,d^5-12475006\,d^6-57695336\,d^7\right. \\
&\left.-31870473\,d^8+41745839\,d^9+50886904\,d^{10}+2153057\,d^{11}-14793221\,d^{12}-2407828\,d^{13}+1247327\,d^{14}-90561\,d^{15}\right)>0
\end{aligned}
$$

$$
\begin{aligned}
\Phi_{t_A}^A(d) = &F(d)\left(117900+1511640\,d+7800784\,d^2+19942768\,d^3+22816007\,d^4-2116878\,d^5-31681703\,d^6-23355760\,d^7\right. \\
&\left.+4653669\,d^8+9378418\,d^9+699143\,d^{10}-886684\,d^{11}+78648\,d^{12}\right)>0
\end{aligned}
$$

$$
\begin{aligned}
\Phi_{t_H}^A = &-(330+2000\,d+3554\,d^2+477\,d^3-3317\,d^4-1553\,d^5+237\,d^6)(22860+300252\,d+1602184\,d^2+4324914\,d^3+5615673\,d^4+1112864\,d^5 \\
&\left.-5718063\,d^6-5706762\,d^7-352459\,d^8+1586976\,d^9+316383\,d^{10}-125540\,d^{11}+6702\,d^{12}\right)<0
\end{aligned}
$$

$$
\begin{aligned}
\Phi_{t_T}^A(d) = &2(3+d)(1+2\,d)F(d)\left(2580+36828\,d+202214\,d^2+529176\,d^3+595040\,d^4\right. \\
&\left.-64955\,d^5-734425\,d^6-458198\,d^7+69426\,d^8+80269\,d^9-9123\,d^{10}\right)>0
\end{aligned}
$$

where $F(d) = 90 + 604\,d + 1280\,d^2 + 661\,d^3 - 601\,d^4 - 389\,d^5 + 83\,d^6 > 0$.

The hub airport infrastructure fee

$$f_H^n(a,f_B,t_A,t_H,t_T) = \frac{1}{2D(d)}\left(\Phi_a^H(d)a + \Phi_{f_B}^H(d)f_B + \Phi_{t_A}^H(d)t_A + \Phi_{t_H}^H(d)t_H + \Phi_{t_T}^H(d)t_T\right).$$

Where:

$$
\begin{aligned}
\Phi_a^H(d) = &(1-d)(5+7\,d)\left(4+9\,d-d^2\right)\left(6+19\,d+11\,d^2\right)\left(186+1312\,d+3023\,d^2\right. \\
&\left.+2107\,d^3-757\,d^4-815\,d^5+128\,d^6\right)\left(366+2416\,d+4834\,d^2+1671\,d^3\right. \\
&\left.-3271\,d^4-1411\,d^5+579\,d^6\right)>0
\end{aligned}
$$

$$
\begin{aligned}
\Phi_{f_B}^H(d) = &2(1-d)\left(6+19\,d+11\,d^2\right)\left(186+1312\,d+3023\,d^2+2107\,d^3-757\,d^4\right. \\
&\left.-815\,d^5+128\,d^6\right)\left(-1245-12741\,d-49496\,d^2-85502\,d^3-44677\,d^4\right. \\
&\left.+46078\,d^5+52790\,d^6-842\,d^7-8996\,d^8+951\,d^9\right)<0
\end{aligned}
$$

$$\Phi^{H}_{t_A}(d) = -F(d)\big(22860 + 300252\ d + 1602184\ d^2 + 4324914\ d^3 + 5615673\ d^4 + 1112864\ d^5 - 5718063\ d^6 - 5706762\ d^7 - 352459\ d^8 + 1586976\ d^9 + 316383\ d^{10} - 125540\ d^{11} + 6702\ d^{12}\big) < 0$$

$$\Phi^{H}_{t_H}(d) = 3(58 + 368\ d + 699\ d^2 + 179\ d^3 - 549\ d^4 - 247\ d^5 + 68\ d^6)(186 + 1312\ d + 3023\ d^2 + 2107\ d^3 - 757\ d^4 - 815\ d^5 + 128\ d^6)\big(330 + 2000\ d + 3554\ d^2 + 477\ d^3 - 3317\ d^4 - 1553\ d^5 + 237\ d^6\big) > 0$$

$$\Phi^{H}_{t_T}(d) = 2(3 + d)(1 + 2\ d)F(d)\big(- 2052 - 18904\ d - 59842\ d^2 - 52036\ d^3 + 104886\ d^4 + 247233\ d^5 + 129597\ d^6 - 50330\ d^7 - 49268\ d^8 - 1691\ d^9 + 1239\ d^{10}\big) \gtreqless 0$$

positive for $d > 0.653562$.

The HSR infrastructure fee

$$f^{n}_{T}(a, f_B, t_A, t_H, t_T) = \frac{1}{4D(d)}(\Phi^{T}_{a}(d)a + \Phi^{T}_{f_B}(d)f_B + \Phi^{T}_{t_A}(d)t_A + \Phi^{T}_{t_H}(d)t_H + \Phi^{T}_{t_T}(d)t_T).$$

Where:

$$\Phi^{T}_{a}(d) = (1 - d)(5 + 7\ d)\big(4 + 9\ d - d^2\big)\big(6 + 19\ d + 11\ d^2\big)\big(92196 + 1230492\ d + 6676360\ d^2 + 18367920\ d^3 + 24593922\ d^4 + 6491678\ d^5 - 21990735\ d^6 - 21871500\ d^7 + 227939\ d^8 + 6953874\ d^9 + 786927\ d^{10} - 723536\ d^{11} + 66351\ d^{12}\big) > 0$$

$$\Phi^{T}_{f_B}(d) = -4(1 - d)(3 + d)(1 + 2\ d)\big(6 + 19\ d + 11\ d^2\big)\big(37890 + 551870\ d + 3379570\ d^2 + 11134049\ d^3 + 20525389\ d^4 + 18138770\ d^5 - 1607780\ d^6 - 18061169\ d^7 - 12277978\ d^8 + 1245613\ d^9 + 3682982\ d^{10} + 403048\ d^{11} - 302281\ d^{12} + 23883\ d^{13}\big) < 0$$

$$\Phi^{T}_{t_A}(d) = (3 + d)(1 + 2\ d)F(d)\big(2580 + 36828\ d + 202214\ d^2 + 529176\ d^3 + 595040\ d^4 - 64955\ d^5 - 734425\ d^6 - 458198\ d^7 + 69426\ d^8 + 80269\ d^9 - 9123\ d^{10}\big) > 0$$

$$\Phi^{T}_{t_H}(d) = (3 + d)(1 + 2\ d)(330 + 2000\ d + 3554\ d^2 + 477\ d^3 - 3317\ d^4 - 1553\ d^5 + 237\ d^6)\big(22860 + 300252\ d + 1602184\ d^2 + 4324914\ d^3 + 5615673\ d^4 + 1112864\ d^5 - 5718063\ d^6 - 5706762\ d^7 - 352459\ d^8 + 1586976\ d^9 + 316383\ d^{10} - 125540\ d^{11} + 6702\ d^{12}\big) \gtreqless 0$$

positive for $d > 0.653562$

$$\Phi^{T}_{t_T}(d) = 2F(d)\big(102924 + 1315176\ d + 6754636\ d^2 + 17129668\ d^3 + 19207976\ d^4 - 2652576\ d^5 - 27510437\ d^6 - 18977986\ d^7 + 5418657\ d^8 + 8495308\ d^9 + 433529\ d^{10} - 836086\ d^{11} + 77163\ d^{12}\big) > 0$$

Infrastructure fees for the competition upstream case when fB is strategically chosen

Here, we provide the expressions corresponding to the profit maximizing equilibrium infrastructure fees, $f^{N}_{A}(a, t_A, t_H, t_T, t_B)$, $f^{N}_{H}(a, t_A, t_H, t_T, t_B)$, $f^{N}_{T}(a, t_A, t_H, t_T, t_B)$ and $f^{N}_{B}(a, t_A, t_H, t_T, t_B)$, when f_B is also chosen to maximize airport B's profits.

Airport B's reaction function is,

$$\begin{aligned} f_B(f_A, f_T, f_H) &= \frac{1}{2R(d)}\big(a(5 + 7\ d)\big(4 + 9d - d^2\big) - (3 + d)(1 + 2\ d)(1 + d)(f_A + 2f_T) \\ &- \big(17 + 63d + 49d^2 - 9\ d^3\big)f_H + R(d)t_B\big), \end{aligned} \quad (36)$$

where $R(d) = 14 + 53d + 40d^2 - 11\ d^3 > 0$. Note that $f^{N}_{B}(a, t_A, t_H, t_T, t_B)$ is easily obtained by substituting the expressions for the remaining fees computed when f_B is parametric, f^{n}_{A}, f^{n}_{H} and f^{n}_{T} in (36) and solving for f_B. That is,

$$f^{N}_{B}(a, t_A, t_H, t_T, t_B) = \frac{1}{Z(d)}(\Omega^{B}_{a}(d)a + \Omega^{B}_{t_A}(d)t_A + \Omega^{B}_{t_H}(d)t_H + \Omega^{B}_{t_T}(d)t_T + \Omega^{B}_{t_B}(d)t_B).$$

Where:

$$\begin{aligned}
Z(d) &= 4D(d)R(d) + (1+d)(3+d)(1+2\,d)\left(\Phi^A_{f_B}(d) + 2\,\Phi^T_{f_B}(d)\right) \\
&\quad + \left(17 + 63d + 49d^2 - 9\,d^3\right)\Phi^H_{f_B}(d) > 0 \\
\Omega^B_a(d) &= 2(5+7\,d)\left(4+9d-d^2\right)D(d) - (1+d)(3+d)(1+2\,d)\left(\Phi^A_a(d) + 2\Phi^T_a(d)\right) \\
&\quad - \left(17 + 63d + 49d^2 - 9\,d^3\right)\Phi^H_a(d) > 0 \\
\Omega^B_{t_A}(d) &= -(1+d)(3+d)(1+2\,d)\left(\Phi^A_{t_A}(d) + 2\Phi^T_{t_A}(d)\right) \\
&\quad - \left(17 + 63d + 49d^2 - 9\,d^3\right)\Phi^H_{t_A}(d) > 0 \\
\Omega^B_k(d) &= -(1+d)(3+d)(1+2\,d)\left(\Phi^A_k(d) + 2\Phi^T_k(d)\right) \\
&\quad - \left(17 + 63d + 49d^2 - 9\,d^3\right)\Phi^H_k(d) < 0, \quad \text{for } k = t_T, t_H \\
\Omega^B_{t_B}(d) &= 2D(d)R(d) > 0
\end{aligned}$$

Finally, by evaluating f^n_A, f^n_H, and f^n_T at $f^N_B(a, t_A, t_H, t_T, t_B)$, we obtain f^N_A, f^N_H, and f^N_T.

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