Would competition between air transport and high-speed rail benefit environment and social welfare?

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Abstract

We develop a duopoly model to analyze the impact of air transport and high-speed rail (HSR) competition on the environment and social welfare. We show that the introduction of HSR may have a net negative effect on the environment, since it may result in additional demand, i.e., there is a trade-off between the *substitution effect* and the *traffic generation effect.* Furthermore, if environmental externalities are taken into account when assessing social welfare, the surplus measure may be higher when only air transport serves the market than when the two modes compete. When the airline and the HSR operator decide frequencies, the airline reduces the aircraft size in order to keep load factors high while offering lower frequency and carrying fewer passengers. In these circumstances, the introduction of HSR may be beneficial to the environment on a per seat basis only if the market size is large enough. When the HSR operator decides speed, it has incentive to keep it at the maximum level in order to reduce travel time. When the increase in the emissions of HSR due to the increase in the speed of the train is sufficiently high, the overall level of emissions grows after the introduction of HSR. Therefore, there can be a trade-off between the attractiveness of the service due to reduced travel time and the effects on the environment.

Keywords

High-speed rail, Airlines, Competition, Environment, Frequency, Speed

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1. Introduction

Air transport and high-speed rail (HSR) substitution has been supported by many for environmental reasons (EC, 2011; TRB, 2013; US DOT, 2002), due to the projected increase in demand for air transport[1]. One of the main statements to justify policies for modal shift from air transport to rail relates to the claimed *greenness* of HSR on a per seat basis. The European Commission, for instance, while deciding on benchmarks for achieving the 60% greenhouse gases (GHGs) emissions reduction, stated that the majority of medium-distance passenger transport should go by rail by 2050, with the length of the existing high-speed rail network to be tripled by 2030 (EC, 2011). Similarly, in the US the National Environmental Policy Act (NEPA) underlines the importance of mechanisms for comparing the environmental impact of alternative modes.

In fact, some empirical evidence shows that the per seat impact on Local Air Pollution (LAP) and climate change due to airline emissions is higher than that due to HSR (Givoni and Banister, 2006; Janic, 2003, 2011)[2]. For instance, Givoni and Banister (2006), based on the London Heathrow-Paris Charles De Gaulle route, report that the toxicity factor of LAP emissions is 9,760 units for air and 5,882 units for HSR (per seat supplied on the route). On the same route, NO_x (CO_2) emissions are 192.55 (43,265) grams for air transport and 17.57 (7,194) grams for HSR (per seat supplied on the route). Overall speaking, the environmental impact of aircraft operations on LAP and climate change depends on flying time, aircraft seat capacity, height of the mixing zone, modal share on the journey to/from the airport, and distance of the airport from the city center. The impact of HSR operations depends mainly on the mix of sources used to generate the electricity, the route distance, the energy consumption and the train capacity (Givoni, 2007; Janic, 2003).

Nevertheless, the introduction of HSR services does not necessarily lead to environmental advantages. The net environmental effect can be negative since the introduction of a new transport mode often results in additional demand. In other words, there is a trade-off between the *substitution effect* - how many passengers using the HSR are shifted from air transport - and the *traffic generation*

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[1] Evidence shows that several large airports in the EU are currently operating at full capacity. According to Eurocontrol, as much as 12% of the demand for air transport will not be met in 2035 because of a shortage of airport capacity (Avenali et al., 2014).

[2] LAP pollutants include hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and particulates (PM). Impact on climate change, instead, is mainly due to GHG emissions like carbon dioxide (CO_2). In general, HSR operations are not considered to contribute significantly to climate change due to lower emission rates of CO_2. Moreover, CO_2 emissions at high altitude affect climate change much more (by a factor higher than 100) than emissions at ground level (Archer, 1993; Dings et al., 2002). HSR contribution to LAP depends mainly on the level of SO_2, which is related to the share of coal used to generate the electricity employed to operate HSR. Finally, rail operations result in high levels of noise at high speeds (Brons et al., 2003). However, the impact (the actual noise heard and number of people exposed to it) is lower than could be expected since, in densely populated areas, speed is reduced when approaching the stations due to the distance required for the train to stop.

effect - how much new demand is generated by the HSR.

In this paper, we build a representative duopoly model to shed light on the basic mechanisms that regulate the impact of air transport and HSR competition on the environment and social welfare when new travel demand is induced.

Such an exercise is necessary from a policy perspective. On the one hand, the debate around HSR versus air transport, which has been typified with unsubstantiated claims of the *greenness* of HSR, may have led to a blatant bias amongst policy makers when considering future transport policy. On the other hand, HSR introduction can involve substantial investments, so a better understanding of its impact is necessary and timely. So far, developments indicate that partial substitution of short-haul flights for HSR services, through either modal competition or cooperation, has already taken place at Frankfurt Main, Paris Charles De Gaulle, Madrid Barajas or Amsterdam Schiphol airports, which are all connected to the Trans-European High-Speed-Rail Network. China, the United Kingdom, Italy, Belgium and South Korea are successfully launching HSR lines. Many others, like Brazil, India, Russia, Turkey and the US are evaluating the options of investing in HSR.

Our contribution is twofold. First, we show that, when HSR is introduced in the market and it is not sufficiently greener than the airline on a per seat basis, the gain from shifting former airline passengers to a cleaner mode of transport is not able to compensate the amount of pollution due to newly generated traffic. Moreover, if the impact on the environment is taken into account when assessing social welfare, the surplus measure may be lower in the competition case than in the monopoly case, when the attractiveness of HSR is sufficiently high. In this case, when HSR is owned by public and private sectors entities and maximizes a weighted sum of its profit and social surplus, the more HSR cares about social surplus, the more likely is HSR entry to induce an overall loss.

Second, we point out analytically that the choice of the frequency of flights (HSR rides) or of the speed of the HSR may affect the environment. On the one hand, when a new mode of transport is introduced in the market, we show that the airline reduces the size of the aircraft used in order to keep load factors high while offering lower frequency of services and carrying fewer passengers. Some analysis shows that decreasing aircraft size and adjusting the frequency of service to offer similar seating capacity will increase pollution (Givoni and Rietveld, 2010). In these circumstances, the introduction of HSR may be beneficial to the environment on a per seat basis only if the market size is large enough.

HSR may have incentive to raise the train speed, in order to reduce travel time and increase its own attractiveness to travelers when competing with air transport. This may affect the environment, since the HSR impact on LAP and climate change depends on the energy consumption, which, in turn, rises when the speed of the vehicle increases. When HSR decides the train speed, the operator will choose the maximum level of speed according to the technology available, legal requirements and number of stops on the HSR line. When the increase in the emissions of HSR due to the increase in the speed of the train is sufficiently high, the overall level of emissions after the introduction of the HSR will be higher than in the monopoly case.

To the best of our knowledge, the existing literature has mainly focused on the market equilibrium of airline-HSR competition (i.e., traffic and price levels) abstracting away from the environment, with empirical approaches (Albalate et al., 2014, Behrens and Pels, 2012; Dobruszkes, 2011; González-Savignat, 2004; Park and Ha, 2006), a game theory setting (Adler et al., 2010) or an analytical perspective (Yang and Zhang, 2012). Some contributions have examined airline-HSR cooperation and its potential benefits for the airlines and the society. Again, these are mainly empirical papers (Cokasova, 2006; Givoni and Banister, 2006), while few works have addressed this issue analytically (Jiang and Zhang, 2014; Socorro and Viecens, 2013). Some recent contributions investigate the long-term impacts of high-speed rail competition on air transport studying how the market coverage and the network choice of an airline would respond to HSR competition on origin-destination trunk routes (Jiang and Zhang, 2015)

The environmental impact of air-rail substitution has been mostly object of case studies on specific routes. Part of the debate has been concentrating on the assessment of the potential savings in pollution (per seat o per seat), which could be achieved by substituting some short-haul flights for equivalent HSR services on some routes. Janic (2011) compares quantities and related cost savings in airport congestion and delays, noise, and GHG emissions at London Heathrow. Givoni and Banister (2006) evaluate the environmental benefits from aircraft and HSR substitution for the London Heathrow-Paris Charles de Gaulle route and show, on a per seat basis, a clear and significant reduction in GHG impact and, though less significant, a reduction in LAP. Similar results have been obtained on the London-Manchester route (Miyoshi and Givoni, 2013). When air transport and HSR integrate and the runway capacity freed at the airport is used to accommodate more flights and to meet more demand, there are no environmental gains from mode substitution (Dobruszkes and Givoni, 2013; Givoni and Banister, 2006; Givoni and Dobruszkes, 2013; Givoni et al., 2012). Socorro and Viecens (2013) confirm, with a theoretical model, this prediction.

All these papers adopt a static perspective abstracting away from the effect on the environment of the demand induced by the introduction of a new mode of transport. Because of the criticality of ridership in environmental assessments, induced demand is often cited as a critical input for understanding future HSR performance (Behrens and Pels, 2012; Chester and Ryerson, 2014). Some studies explore the sensitivity of environmental performance to ridership, finding that ridership uncertainty can tip the balance to either mode (Chester and Horvath, 2012). While all the above-mentioned papers utilize empirical or survey data, to the best of our knowledge our paper is the first attempt in literature at developing an analytical framework to evaluate the impact of intermodal competition between air transport and HSR on the environment and social welfare while pointing out the effect of induced demand. Moreover, though flights (HSR rides) frequency and HSR speed have been cited as critical parameters – and formally modeled in a competition game between the two modes (Yang and Zhang, 2012) – their effects on the environment have never been addressed analytically and this paper bridges this gap.

An important feature of our analysis is that air transport and rail operators can have different objective functions. While the deregulation process in the airline industry makes it reasonable to assume that airlines maximize profit, the HSR decision maker may also take into account other objectives. Indeed, in some cases HSR operators are owned by the government or, even in cases in which they are private companies, like in Europe, the networks are often co-invested by public administrations due to huge capital requirements. Therefore, we assume that HSR maximizes a weighted sum of its profit and social surplus, taking into account the surplus of consumers and the surplus that the air transport operator brings about. This approach seems reasonable, since the companies serve the same population and the State cares about the productivity of the country and the travel possibilities of all inhabitants, and finds support in the literature developed to discuss the welfare consequences of partial privatization of a public firm in mixed oligopolies (Ishibashi and Kaneko, 2008; Matsumura, 1998). This makes our contribution different from literature, where Adler et al. (2010) and Socorro and Viecens (2013) considers a profit maximizing HSR and Yang and Zhang (2012) assume that the HSR operator maximizes his own profit plus a portion of the surplus of HSR passengers.

The structure of the paper is as follows. Section 2 presents the basic model and the main results on the effects of competition between air transport and HSR on the environment and social welfare. Section 3 describes some extensions of the basic model with respect to the frequency and the speed of service. Section 4 contains some concluding remarks.

2. The basic model

Consider a competition model between one airline and high-speed rail over a single origin (O) – destination (D) link[3]. Total journey time of transport mode i – with $i = A$ (air transport) or $i = H$ (HSR) – is:

$$T_i \coloneqq a_i + t_i \qquad (1)$$

where a_i is the sum of access and the egress time and t_i is the travel time of mode i[4]. Usually, air service results in a lower in-vehicle time for most of the routes, i.e., $t_A < t_H$, since the speed is different between the two modes. Moreover, trains do not follow the direct routes due to the orography of the territory. However, passengers need to spend a significant access/egress time for a flight, owing to the fact that airports are usually located far away from city centers (Adler et al., 2010; González-Savignat, 2004; Jiang and Zhang, 2014; Yang and Zhang, 2012)[5]. As a result, the total journey time may vary across the two modes.

González-Savignat (2004) estimates travelers' willingness to pay (WTP) in order to save time at different stages of the journey. He finds that individuals do not assign the same monetary value to the time spent in different phases of the journey. For instance, the WTP to save time is higher when a saving is produced in the travel time (55 €/hour) and is considerably lower when it is a saving in access time (22 €/hour). Following these considerations, we assign different values of time to different stages of the journey, i.e., we define the value of total travel time as follows: $\bar{T}_i = \nu_a a_i + \nu_t t_i$, where $\nu_a \geq 0$ represents the value of access/egress time and $\nu_t \geq 0$ the value of travel time. Let T denote the difference (positive or negative) between the value of total journey time between the two modes, i.e., $T = \bar{T}_A - \bar{T}_H$[6]. With these specifications, the full prices perceived by travelers are, respectively:

[3] Direct competition between the two modes usually takes place on distances in the range 300-1000 km (Janic, 1993; Rothengatter, 2011; Yang and Zhang, 2012). On routes of less than 300 km, evidence shows that the introduction of HSR services almost leads to a withdrawal of aircraft services (e.g., between Tokyo and Nagoya and between Bruxelles and Paris), while, on routes of around 1000 km and above, the HSR ceases to be a good substitute for the aircraft.

[4] Total journey time also includes schedule delay, which represents the time between the passenger desired departure time and the actual departure time. It was introduced by Douglas and Miller (1974) as the sum of two components: frequency delay and stochastic delay. The former is induced by the fact that flights do not leave at a passenger request but have a schedule. Stochastic delay has to do with the probability that a passenger cannot board her desired flight because it is overbooked. Overbooking arises in the presence of stochastic demands, which is not the case of our model. Instead, we will include frequency delay in Section 3.1.

[5] For instance, Adler et al. (2010), estimate that the access (and egress) time to (from) European hub airports and HSR stations are $a_A = 1h$ and $a_H = 0.5h$. Other than accessibility from main urban agglomerations, factors affecting ease of access/egress are parking availability, ease of transfer (baggage trolleys, ramps, escalators, design adaptation for disabled passengers), real time information on board, identification of staff and information service, baggage handling, check-in and security-check procedures (IATA, 2003; Janic, 2011).

[6] In this paper, we abstract away from the case of different value of time among passengers' type - e.g., leisure and business passengers - and price discrimination, since our focus is on the environment. In other words, we assume that the

$$\theta_A = p_A + T$$
$$\theta_H = p_H \quad (2)$$

where p_i is the ticket price of transport mode i and T is a parameter measuring quality differentiation between the two modes in a vertical sense. Other things being equal, as T increases, e.g., when the total journey time of HSR reduces relative to the total journey time of air transport, the attractiveness of HSR increases. This modeling allows assessing the importance of total journey time, in addition to the ticket price, in passengers' choice. Indeed, empirical evidence shows that this is the most important quality differentiator between the two modes (Adler et al., 2010; Behrens and Pels, 2012) and it accounts for 80% - 90% of the reasons for choosing to travel by air transport or HSR for given fares (Cokasova, 2006).

Travelers maximize a (strictly concave) quadratic utility function as proposed by Singh and Vives (1984). This approach has been used in transport literature (Flores-Fillol and Moner-Colonques, 2007; Oum and Fu, 2007; Socorro and Viecens, 2013). Let q_A and q_H be the number of passengers travelling by air transport or HSR, respectively. The utility function is:

$$U(q_A, q_H) = \alpha_A q_A + \alpha_H q_H - \frac{1}{2}(q_A^2 + q_H^2 + 2\beta q_A q_H) \quad (3)$$

The parameter $\alpha_i > 0$ denotes the gross benefit that the consumer derives from traveling from the origin *O* to the destination *D*, using transport mode i. The parameter α_i measures service quality in a vertical sense, on dimensions such as reliability, punctuality, safety, on board comfort, customer service (Cokasova, 2006; EC, 2006; IATA, 2003). For the sake of simplicity, we shall assume in what follows $\alpha_A = \alpha_H = \alpha$.

The parameter $\beta \geq 0$ measures the degree of substitutability between the two modes. Besides the travel time, different factors may affect mode substitutability: emotional associations may play a role (Bennett et al., 1957), as well as cultural/personal mode preferences (IATA, 2003). Habit may also form a significant barrier to mode shift, as past mode choices are a strong predictor of current mode choice (Blainey et al., 2012; Thøgersen, 2006). Larger values of β indicate more substitutable

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evaluation of time differs between stages of the journey, but for each stage, it is the same across the two modes and different types of passengers. However, the relative importance of price and time factors varies with the demand segment that is considered. Some empirical evidence shows that leisure passengers are more sensitive to ticket price than business travelers (who value more travel time) (Behrens and Pels, 2012; Cokasova, 2006). The reader may refer to Yang and Zhang (2012) for a competition model with passengers' different (gross) travel benefit and time value.

services: β is zero when the two modes are independent and it is equal to one when they are perfect substitutes.

In this setting, the representative consumer solves the following problem:

$$max_{q_A, q_H}\, U(q_A, q_H) - \theta_A q_A - \theta_H\, q_H \tag{4}$$

subject to the budget constraint $\theta_A\, q_A + \theta_H\, q_H \leq m$, where m denotes the income. First order conditions determining the inverse demand function for q_i are:

$$\theta_i(q_A, q_H) = \alpha - q_i - \beta \cdot q_{-i} \tag{5}$$

where $-i$ indicates the mode other than i, i.e., $-i = A$ if $i = H$ and $-i = H$ if $i = A$. From equations (2) and (5) it follows that:

$$\begin{gathered} p_A(q_A, q_H) = \alpha - T - q_A - \beta q_H \\ p_H(q_A, q_H) = \alpha - q_H - \beta q_A \end{gathered} \tag{6}$$

We now turn to the supply side. Let Q_A and Q_H be the total number of flights offered by the airline and the rides offered by the HSR operator, respectively. We have $q_i = Q_i \times Size_i \times LF_i$ where $Size_i$ represents the number of aircraft seats ($i = A$) or high-speed train seats ($i = H$) and LF_i represents the load factor of mode i. Each mode operates under a fixed-proportions relation such that load factor is 100% and the product between the size and load factor is constant for both modes[7]. With fixed load factors and sizes, prices per seat and per flight/HSR ride are equivalent and the profit of mode i can be written as:

$$\pi_i(q_A, q_H) = (p_i(q_A, q_H) - c_i)q_i \tag{7}$$

where c_i is the unit per seat variable cost of transport mode i and the fixed costs of operating a flight (HSR ride) are assumed to be zero. Finally in what follows, without loss of generality we normalize $\bar{T}_H = 0$. Thus, HSR operating costs c_H, and ticket price, p_H, are considered gross of $\bar{T}_H$.

While the deregulation process in the airline industry makes it is reasonable to assume that airlines maximize profit, the HSR operator may also take into account other objectives. Indeed, in some cases, HSR operators are owned by the government or, even if they are private companies, like in Europe,

[7] We shall relax this assumption in Section 3.1, when operators endogenously decide the schedule frequency.

the networks are often co-invested by public administrations due to the huge capital requirements[8]. In light of these considerations, we assume that the airline is a pure private firm, while HSR is a privatized firm that is jointly owned by public and private sectors. Thus, the airline maximizes its own profit and HSR maximizes a weighted sum of its profit and social surplus, taking into account the surplus of consumers and the surplus that the other transport operator brings about. This approach seems reasonable, since the companies serve the same population and the State cares about the productivity of the country and the travel possibilities of all inhabitants. The social surplus is[9]:

$$S(q_A, q_H) = U(q_A, q_H) - (c_A + T)q_A - c_H\, q_H \tag{8}$$

With these specifications, HSR objective function[10] is:

$$(1 - \delta)\pi_H(q_A, q_H) + \delta S(q_A, q_H) \tag{9}$$

The parameter $\delta = \delta(x)$ may be referred to as the "weight" of social surplus relative to profit, where $x \in [0,1]$ denotes the share of the HSR property owned by the public sector. The parameter $\delta(x)$ ranges from 0 to 1. If HSR is fully privatized (i.e., $x = 0$), δ is zero and HSR maximizes profit (Adler et al., 2010; Socorro and Viecens, 2013). If HSR is fully nationalized (i.e., $x = 1$), δ is one and HSR maximizes social surplus. If the amount of shares owned by the government increases, then δ increases. Formally, we assume that is $\delta(x)$ is continuous and non-decreasing in x, with $\delta(0) = 0$, and $\delta(1) = 1$. A similar approach has been proposed in the literature developed to discuss the welfare

[8] For instance, in China, all high-speed rails belong to China Railway Corporation, a state-owned company supervised directly by the Chinese Central Government. Similarly, in Italy, Trenitalia is 100% owned by FSI (Ferrovie dello Stato Italiane), which, in turn, has been transformed into a public company controlled by the Ministry of Economics and Finance since 1992.

[9] Whether non-economic benefits should also be factored into the assessment of social welfare is still an open question. On the one hand, widening the assessment framework to take into account non-economic externalities, such as environmental considerations, could allow competition authorities to identify and consider all the benefits of modal competition. On the other hand, the inclusion of non-economic benefits into the assessment of the social welfare function is likely to raise a number of challenges (Button, 1990). First, assigning a monetary value to non-economic benefits is likely to be complicated and may be arbitrary. Second, as non-economic benefits may spread over several generations, this might require the forecasting of various dynamic factors such as future capacity, prices and network development. Third, introducing non-economic benefits into the assessment framework may lead to conflicts between the different policy goals (e.g., economic efficiency and environmental targets) and a greater number of challenges to regulatory decisions. In this paper, we assume that the HSR transport operator only takes into account the surplus of consumers and the surplus that the other transport operator brings about. This seems reasonable, since, non-economic benefits are factored into the assessment of the objective function of the State or competition authorities, rather than of a (partial privatized) public firms. We will evaluate in Section 2.2 the effects of competition between HSR and air transport on social welfare, factoring the (per seat) environmental cost of damage due to two transport modes.

[10] This modeling differs from Yang and Zhang (2012). With use of a locational model to describe competition between air transport and HSR, they assume that the HSR operator maximizes his own profit plus a portion of the surplus of passengers taking HSR. The main difference between their paper and our work is in the fact that the surplus of all consumers (even those traveling by air transport) and the surplus that the other transport operator brings about are considered.

consequences of partial privatization of a public firm in mixed oligopolies (Ishibashi and Kaneko, 2008; Matsumura, 1998).

A glossary of variables with different notation and subscripts used in the basic model (as well as in the extensions of the model) can be found in Appendix 1.

2.1 Effects on the environment

In this section, we examine a basic case in which competition between the two modes takes place *à la Cournot*. Thus, the airline and the HSR operator compete on quantities and solve simultaneously the following decision problems[11]:

$$
\begin{aligned}
&max_{q_A}\ (p_A(q_A, q_H) - c_A)q_A \\
&max_{q_H}\ (1-\delta)(p_H(q_A, q_H)q_H - c_H) + \delta(U(q_A, q_H)\ - (c_A + T)q_A - \ c_H\ q_H)
\end{aligned}
\qquad (10)
$$

From first order conditions, it is straightforward to derive equilibria for the basic model (the superscript $*$ stands for equilibrium):

$$
\begin{aligned}
q_A^* &= \frac{\big(\alpha - (c_A + T)\big)(\delta - 2) + \beta(\alpha - c_H)}{2(\delta - 2) + \beta^2} \\
q_H^* &= \frac{\big(\alpha - (c_A + T)\big)\beta - 2(\alpha - c_H)}{2(\delta - 2) + \beta^2}
\end{aligned}
\qquad (11)
$$

where the parameters are assumed in the ranges where both q_A^* and q_H^* are non-negative[12]. In order to analyze the impact of competition between HSR and air transport on the environment we refer to the benchmark case of a monopoly airline serving the same O – D link.

Similarly to what described before, we assume linear demand function. Thus, the inverse demand with respect to full price in the market served by the monopoly airline is $\theta_M(q_M) = \alpha - q_M$ where

[11] Quantity competition may be the more appropriate choice in case of limited capacities, even if firms are price setters. Quinet and Vickerman (2004, p. 263) remark that this is the case found, for example, in rail. The main reason why high-speed rail capacity (i.e., tracks, train stations) is difficult to change (relative to the ease and rapidity of price adjustments) is that investments are lumpy, time-consuming and irreversible. Similarly, in the case of airports, physical expansion of infrastructure is strongly limited, being the result of tight budgets or political and environmental constraints, such as noise and air pollution externalities or land use restrictions (Starkie, 1998). Brander and Zhang (1990, 1993) and Oum et al. (1993) find some empirical evidence that rivalry between airlines is consistent with Cournot behavior. Cournot behavior has been assumed, among others, in Brueckner (2002), Jiang and Zhang (2014), Pels and Verhoef (2004) and Zhang and Zhang (2006). A technical appendix containing the analysis of price competition between the airline and the HSR is available upon request from the authors. However, we remark that results do not qualitatively change with respect to the case of Cournot competition presented in the manuscript.

[12] The second order conditions of problem (10), as well as for problems (are shown in Appendix 2.

α is the size of the market and q_M is the number of passengers (the subscript M stands for the monopoly case). If p_M denotes the air ticket price charged by the monopoly carrier, full price can be written as $\theta_M = p_M + T$, where $T = v_a\, a_A + v_t\, t_A$ measures the cost of total journey time for travelers when air is the only available transport mode. We easily obtain the inverse demand function with respect to air ticket price, that is $p_M(q_M) = \alpha - T - q_M$. While assuming that the fixed proportions and 100% load factor assumptions are maintained, the airline profit is $\pi_M(q_M) = (p_M(\,q_M) - c_A)\, q_M$. Maximization of profit with respect to quantity leads to the equilibrium:

$$q_M^* = \frac{\alpha - (c_A + T)}{2} \tag{12}$$

Lemma 1 The introduction of high-speed rail in the market for travel results in lower airline traffic compared to the monopoly case, i.e., $q_A^* < q_M^*$, and in additional traffic generated, i.e., $\Delta q = q_H^* + q_A^* - q_M^* > 0$.

The proof of lemma 1 is given in Appendix 2. Empirical evidence confirms theoretical predictions on the *traffic generation effect*. Although assessing induced traffic is difficult (Bonsall, 1996; Givoni and Dobruszkes, 2013; Mokhtarian et al., 2002), data collected after the launch of HSR in Asia and Europe suggest that induced traffic ranges from 6% to 37% of HSR ridership (Givoni and Dobruszkes, 2013). Some estimates relate to different periods - starting from 1980 – and indicate that additional traffic generated accounts for 29% of total HSR traffic on the Paris-Lyon route, 50% on the Madrid-Seville route, 20% on the Madrid-Barcelona route, 11% on the Paris-Bruxelles route and 20% on the London-Paris route (Preston, 2009).

In order to analyze the environmental impact of HSR introduction, we will focus on LAP and GHG emissions during the phase of operation. For each seat the aircraft level of emissions (LAP, or climate change or an equivalent aggregate of both) is denoted by e_A, while the HSR level of emissions is denoted by e_H. We assume that $e_A > e_H$, i.e., HSR is greener – per seat than air transport.

Let E denote the difference between the total level of pollution before and after the introduction of HSR. We define E as:

$$E(q_M, q_A, q_H) \coloneqq e_A q_M - (e_A q_A + e_H q_H) \tag{13}$$

If $E(q_M, q_A, q_H) > 0$, then competition between HSR and air transport is beneficial to the environment. Note that $E(q_M, q_A, q_H)$ can also be negative, that means that the introduction of HSR may result in an environmental damage.

Proposition 1 If high-speed rail is not sufficiently greener than air transport, i.e., if $e_H/e_A > \beta/2$, the introduction of high-speed rail will increase the environmental pollution.

The proof of Proposition 1 is in Appendix 2 but we provide some intuitions as follows. The introduction of a new mode of travel induces an increase in the total market size and HSR ridership is made up of former airline passengers who shift to the new mode and newly generated demand (e.g., people who did not travel before or people who shift from other transportation modes like traditional rail and automobile)[13]. If the level of pollution emitted by HSR is not sufficiently lower than that of the airline, the gain from shifting former air passengers to a cleaner mode of transport is not able to compensate the amount of pollution due to newly generated traffic. At the equilibrium, $e_H q_H^* > e_A(q_M^* - q_A^*)$ and competition from the new mode is detrimental to the environment, i.e., $E(q_M^*, q_A^*, q_H^*) < 0$.

Proposition 1 shows that it is not straightforward to say that the introduction of HSR is beneficial to the environment, and benefits depend on the environmental *friendliness* of the mode. In particular, the extent to which electric trains can be regarded as significantly more environment-friendly than air transport depends on the mix of energy sources used to generate the electricity. Generally speaking, the more renewable and nuclear energy is used to generate electricity, the more environment-friendly rail operations are. In fact, the generation mix for train electricity is heavily constrained by the country in which HSR operates – electricity sources available, topology of the electricity grid. Thus, energy

[13] In our analysis, we abstract away from road transport and conventional rail in order to focus on the environmental impact of competition between air transport and high-speed rail, which has received most attention in literature (Givoni, 2007; Givoni and Dobruszkes, 2013), and to get interpretable results. Empirical evidence shows that the case of routes in which HSR mainly diverts passengers from air transport is not rare. This is the case of the Paris-Lyon route in which most of the demand shifted to train is from aircrafts, rather than from conventional train, cars or coaches (Givoni, 2007). In the case of the routes from London to Paris, Lille Bruxelles, demand for HSR services as a percentage of passengers' mode of origin is 12% for rail, 49% for planes, 7% for cars and 12% for coaches (Givoni and Dobruszkes, 2013). As opposite, there are cases in which the modal shift from road and conventional rail is relevant, e.g., the Wuhan–Guangzhou route, on which 50% of the passengers using HSR have been diverted from conventional rail (Bullock et al., 2012). Barron et al. (2009) present data showing that in specific corridors the automobile share of travel decreased by an average of approximately 12% before and after HSR in France (Paris– Lyon), Spain (Madrid–Seville), and Germany (Hamburg–Frankfurt). Extending the analysis to a framework including road transport or conventional rail substitution would be an insightful future study.

efficiency technologies and strategies should be promoted in order to increase the *greenness* of HSR, e.g., aerodynamics and friction reduction, conversion losses reduction, regenerative braking and energy storage, reduction of energy consumption for comfort function, improvement load factors and use of flexible trains (UIC, 2003).

Proposition 1 also suggests that the higher the degree of substitutability between the two modes, the less likely is that the introduction of HSR is detrimental to environment. Indeed, the minimum ratio between the levels of pollution of the two modes required for HSR being beneficial to the environment, i.e., $\beta/2$, increases with the degree of substitutability β. This means that, when β is larger, it is harder for the constraint $e_H/e_A > \beta/2$ to be satisfied.

Proposition 2 There exists a value $\check{e} > 0$ such that, $\forall(e_A, e_H)$ with $e_H/e_A < \check{e}$, it results $\partial E(q_M^*, q_A^*, q_H^*)/\partial\beta > 0$, that is when high-speed rail is sufficiently greener than air transport the environmental benefit of high-speed rail introduction is increasing in the substitutability between the two modes of transport. Moreover, $\forall(e_A, e_H)$ such that $e_H/e_A < \beta/2 < \check{e}$, $E(q_M^*, q_A^*, q_H^*)$ is:

(a) increasing in the market size, α;
(b) increasing in the time-dimension differentiator, T;
(c) increasing in the weight on social surplus relative to profit for the HSR, δ.

The proof of Proposition 2 can be found in Appendix 2 but the intuition behind can be easily drawn as follows. It is easy to show that: (i) $\partial\Delta q^*/\partial\alpha > 0$ and (ii) $\partial q_H^*/\partial\alpha > 0$, $\partial q_A^*/\partial\alpha > 0$, $\partial(q_M^* - q_A^*)/\partial\alpha > 0$. Thus, the larger the market size, the larger the traffic induced by competition. Besides, the larger the market size the more passengers are diverted towards HSR: though both q_H^* and q_A^* increase with α, the quantity of air passengers increases proportionally less than what would have happened in absence of competition from HSR. Thus, if the airline is sufficiently more polluting than HSR, the increase in HSR emissions due to the newly generated demand is compensated by the increasing number of passengers that are diverted toward the cleaner mode of transport.

A similar argument applies to the effect of T. Other things being equal, as T increases, e.g., when the total journey time of HSR reduces compared to the total journey time of air transport, HSR becomes more attractive. Indeed, it results $\partial\Delta q^*/\partial T > 0$, $\partial q_H^*/\partial T > 0$ and $\partial q_A^*/\partial T < 0$. At the same time,

$\partial(q_M^* - q_A^*)/\partial T > 0$ and increasingly more passengers are diverted towards the greener transport mode.

It is easy to prove that $\partial\Delta q^*/\partial\delta > 0$, $\partial q_H^*/\partial\delta > 0$ and $\partial q_A^*/\partial\delta < 0$. Thus, when the weight of social surplus relative to profit for the HSR is higher, increasingly more passengers take HSR relative to air transport. The increase in HSR emissions due to the increased traffic is compensated by the decrease in the airline traffic when air transport is sufficiently more polluting.

β measures the degree of substitutability between the two modes: as β increases, it can be shown that the sign of $\partial q_H^*/\partial\beta$ and $\partial q_A^*/\partial\beta$ is not clear-cut while $\partial(q_A^* + q_H^*)/\partial\beta < 0$. Thus, at the equilibrium, the *traffic generation effect* decreases when the substitutability between the two modes becomes higher. If the HSR is sufficiently greener than air transport, the increase in total traffic due to the increase of the substitutability between the two modes is compensated by the fact that the newly generated demand goes to the greener mode and, at the equilibrium, after HSR introduction, the total pollution, i.e., $e_A q_A^* + e_H q_H^*$, decreases.

From Propositions 1 and 2, we can analyze the environmental impact of HSR introduction in three different scenarios. When $e_H/e_A < \beta/2$ the introduction of HSR is beneficial to the environment, i.e., $E(q_M^*, q_A^*, q_H^*) > 0$ and $\partial E(q_M^*, q_A^*, q_H^*)/\partial z > 0$ with $z \in Z \coloneqq \{\alpha, T, \delta, \beta\}$. In other word, the (positive) effect of HSR entry increases with the size of the market, the time differentiator, the HSR weight on social surplus relative to profit and the substitutability between the two travel products. On the other hand, when $\beta/2 < e_H/e_A < \check{e}$, the introduction of HSR is detrimental to the environment, i.e., $E(q_M^*, q_A^*, q_H^*) < 0$. It results, $\partial E(q_M^*, q_A^*, q_H^*)/\partial h < 0$, with $h \in Y \coloneqq \{\alpha, T, \delta\}$, while $\partial E(q_M^*, q_A^*, q_H^*)/\partial\beta > 0$. Thus, an increase in the size of the market, the time differentiator or the HSR weight of social surplus relative to profit exacerbates the environmental damage, while an increase in the degree of substitutability mitigates the negative effect on the environment. Finally, when $e_H/e_A > \check{e}$, the introduction of HSR is detrimental to the environment and $\partial E(q_M^*, q_A^*, q_H^*)/\partial z < 0$ with $z \in Z$, i.e., an increase in β exacerbates the environmental damage. The reason is that $\partial\Delta q^*/\partial\beta < 0$ while $\partial\Delta q^*/\partial h > 0$ with $h \in Y$. Thus HSR needs to be much more polluting to cause a decrease of the quantity $e_A q_M^* - (e_A q_A^* + e_H q_H^*) < 0$, when we look at the case in which this decrease is driven by the degree of substitutability between travel products[14].

[14] We remark that, tough we have considered competition between a single airline and a single HSR operator, in reality, more airlines may compete in the market for air travel. The analysis of an oligopolistic airlines market is available upon request from the authors. We find that the less fragmented the airline market is, the less the introduction of HSR is likely to be beneficial to the environment. However, results do not qualitatively change with respect to the case of a single airline presented in the manuscript.

2.2 Effects on social welfare

In this section, we seek to assess the effect of competition between HSR and air transport on social welfare, when the environmental impact matters for society. In particular, we define

$$W^c(q_A,q_H) = U(q_A,q_H) - (c_A+T)q_A - c_Hq_H - (\varepsilon_Aq_A+\varepsilon_Hq_H)$$
$$W^M(q_M) = U(q_M) - (c_A+T)q_M - (\varepsilon_Aq_M) \quad (14)$$

where $U(q_M) = q_M - (1/2)q_M^2$ and ε_i is the per seat environmental cost of damage due to mode i. The superscript C stands for the competition case, while the superscript (and subscript) M stands for the monopoly case. In particular, we assume that $\varepsilon_A > \varepsilon_H$, that is the per seat environmental cost of damage due to air transport is higher than the per seat environmental cost of damage due to HSR. For instance, based on the cost of damage due to LAP and climate change provided by Dings et al. (2002), Givoni and Banister (2006) estimate that on the London Heathrow - Paris Charles De Gaulle route the cost of the damage (per seat supplied on the route) from LAP is 0.91 € and 0.52 € for air transport and HSR, respectively. Similarly, they find that the cost of the damage from climate change is 2.07 € for air transport and 0.29 € for HSR.

Thus, we evaluate the overall effect caused by HSR entry on the society as $\Delta W(q_M,q_A,q_H) = W^M(q_M) - W^C(q_A,q_H)$. When $\Delta W(q_M,q_A,q_H) > 0$, then competition is detrimental to social welfare[15].

Proposition 3 When the attractiveness of high-speed rail is sufficiently high, i.e., $T > \tilde{T}$, there exists a value $\bar{\varepsilon} \geq 0$ such that $\forall(\varepsilon_A,\varepsilon_H)$ with $\varepsilon_A - (2/\beta)\varepsilon_H < \bar{\varepsilon}$, it results $\Delta W(q_M^*,q_A^*,q_H^*) > 0$, that is when the cost of environmental damage due to high-speed rail is not sufficiently lower than the cost of environmental damage due to air transport, the total social welfare is higher in the monopoly case than in the competition case.

[15] HSR entry, while expanding the catchment area and improving accessibility of areas served by stations, may actually induce some indirect benefits, like spatial labor market relocation effects, spatial labor market matching effects, international labor market effects or additional consumer benefits (Levinson, 2012). In our analysis, we abstract away from these positive externalities (and, therefore, we do not model in the social welfare function the extra-surplus that consumers may gain from these benefits). We concentrate on traffic relocation (and generation) effects over a specific route while any examination of an HSR line indirect benefits must consider a wider geographic area than just the origin and the destination nodes on the high-speed line. In such a scenario, integration between transport networks, especially between the high-speed and conventional rail, should be considered. This is out of the scope of this paper, and any examination of all positive and negative externalities on the overall welfare deserves attention in future developments.

The proof of Proposition 3 is in Appendix 2 but the intuition behind can be easily drawn as follows. From equation (14) it follows that $\Delta W(q_M^*, q_A^*, q_H^*) = W^M(q_M^*) - W^C(q_A^*, q_H^*) = U(q_M^*) - U(q_A^*, q_H^*) - (c_A + T)(q_M^* - q_A^*) + c_H q_H^* - \varepsilon(q_M^*, q_A^*, q_H^*)$, where $\varepsilon(q_M^*, q_A^*, q_H^*) = \varepsilon_A q_M^* - (\varepsilon_A q_A^* + \varepsilon_H q_H^*)$ is the monetary value of the environmental impact of HSR. Let, for instance, consider the case in which ε_i is proportional to e_i. The introduction of a new mode of transport induces an increase in the overall demand for travel, which is beneficial to the society. Thus, there is a gain $U(q_A^*, q_H^*) - U(q_M^*) - (c_A + T)(q_A^* - q_M^*) - c_H q_H^* = -(U(q_M^*) - U(q_A^*, q_H^*) - (c_A + T)(q_M^* - q_A^*) + c_H q_H^*) > 0$. On the other hand, according to Proposition 1, when high-speed rail is not sufficiently greener than air transport, i.e., when $e_A < (2/\beta)e_H$, $E(q_M^*, q_A^*, q_H^*) < 0$ and $\varepsilon(q_M^*, q_A^*, q_H^*) < 0$. According to Proposition 2, in this case, $E(q_M^*, q_A^*, q_H^*)$ is decreasing in T: the higher the attractiveness of HSR the higher, in absolute value, is $E(q_M^*, q_A^*, q_H^*)$ and, as a consequence, the higher, in absolute value, the environmental cost of damage $\varepsilon(q_M^*, q_A^*, q_H^*)$. Therefore, when T is sufficiently high, $\Delta W(q_M^*, q_A^*, q_H^*)$ becomes positive and competition from the new mode is detrimental to the environment. In other words, when HSR is not clean enough and its attractiveness is sufficiently high, the gain obtained from shifting former airline passengers to the HSR is not able to compensate the amount of extra pollution from newly generated demand.

From the proof of Proposition 3 it follows that $\partial\bar{\varepsilon}/\partial c_H \geq 0$ and $\partial\bar{\varepsilon}/\partial c_A \leq 0$, that is the higher the level of air transport operating costs is, the more likely is that HSR entry in the market is beneficial for social welfare. Conversely, higher levels of HSR operating costs are less likely to enhance social welfare. It also follows that, when the environmental impact of introducing a new mode of transport is taken into account, it may happen that competition between the two modes is detrimental to society whatever is the weight of social surplus relative to profit chosen by HSR. In fact, for each $\delta \in [0,1]$, there exists a $\bar{\varepsilon} \geq 0$ such that $\forall(\varepsilon_A, \varepsilon_H)$ with $\varepsilon_A - (2/\beta)\varepsilon_H < \bar{\varepsilon}$, it results $\Delta W(q_A^*, q_H^*, q_M^*) > 0$. In particular, the following corollary holds.

Corollary 1 When the attractiveness of high-speed rail is sufficiently high, i.e., $> \tilde{T}$, $\forall\delta \in [0,1]$, there exists a value $\bar{\varepsilon} \geq 0$ such that $\forall(\varepsilon_A, \varepsilon_H)$ with $\varepsilon_A - (2/\beta)\varepsilon_H < \bar{\varepsilon}$ and $\partial\bar{\varepsilon}/\partial\delta > 0$, i.e., the condition $\varepsilon_A - (2/\beta)\varepsilon_H < \bar{\varepsilon}$ is less stringent when δ increases.

Corollary 1 states that, when the attractiveness of high-speed rail is sufficiently high, the higher δ, that is the more HSR cares about social surplus, the more likely an overall loss caused by HSR entry, $\Delta W(q_A^*, q_H^*, q_M^*) > 0$, arises. Intuitively, the more HSR cares about social surplus, the more passengers will be served by the rail operator, i.e., $\partial q_H^*/\partial\delta > 0$. However, these additional travelers are those with lower WTP: while contributing to environmental detriment from pollution with the same amount of emissions, they contribute less to surplus.

Proposition 3 shows that it is not always true to say that the introduction of HSR is beneficial to the society. This depends on the scope of benefits included in the assessment framework. In particular, we show that if the impact on the environment matters for society, the surplus measure of the *traditional* approach (when environmental effects are not taken into account when assessing social welfare) may fall short of giving a true measure of total social surplus.

In this respect, it will be important for competition authorities to specify their approach towards ranking and weighting factors in the assessment of social welfare, if the incentive to modes competition is not to be chilled.

3. Extensions

In this section, we broaden the analysis to include some characteristics that may influence strategic decisions of operators. In particular, Section 3.1 presents results for the case in which both the airline and the HSR can adjust frequency of service. In Section 3.2, we examine the case in which the HSR operator decides the speed of the train.

3.1 Schedule frequency

In this section, we consider a model of full prices that includes both quantities and frequencies decisions. Service frequency affects passengers' modal choice and is an important dimension in the competition between air transport and HSR (Behrens and Pels, 2012; González-Savignat, 2004; Román et al., 2010; Yang and Zhang, 2012).

Passengers choose among alternative modes on the basis of the ticket price, the total trip time and the frequency, a proxy for the level of service (Adler et al., 2010). In particular, following Flores-Fillol (2009), we introduce frequencies additively in the full price functions, assuming that frequency of flights (HSR rides) offered by a particular airline (HSR operator) delivers higher value to passengers and, therefore, determines service quality as a measure of flight (HSR rides) flexibility. The full prices perceived by travelers are, respectively:

$$\theta_A = p_A - \gamma_f f_A + T \tag{15}$$

$$\theta_H = p_H - \gamma_f f_H$$

where f_i is the schedule frequency of transport mode i and γ_f is the benefit from frequency[16]. A similar formulation is also suggested by Heimer and Shy (2006). In addition to a reduced total journey time, benefits from higher frequency may also include more opportunities for passengers in terms of schedule coordination for multi-stops trips (Cokasova, 2006; Vespermann and Wald, 2011) or less apprehension over what happens in case of a missed connection due to low punctuality or reliability[17]. González-Savignat (2004), for instance, finds that the WTP to save time when a saving is produced by an improvement in the frequency of the service timetable is 17 €/hour[18]. From equations (5) and (15) it follows that:

$$\begin{aligned} p_A(q_A, q_H, f_A) &= \alpha - T - q_A - \beta\, q_H + f_A \\ p_H(q_A, q_H, f_H) &= \alpha - q_H - \beta\, q_A + f_H \end{aligned} \tag{16}$$

where γ_f has been normalized to 1.

Turning to the supply side, the cost of operating a flight (HSR ride) is given by $k_{ii} \times f_i - k_i + c_i \times Size_i$, where $Size_i$ measures the number of seats of the aircraft,$(i = A)$, or the train $(i = H)$, c_i is the unit (per aircraft/train seat) variable cost and $k_{ii} \times f_i - k_i$ is the cost per departure, with $k_i \geq 0$ and $k_{ii} \geq 0$. In the case of air transport, for instance, this cost consists of fuel for the duration of the flight, airport maintenance, renting the gate to board and disembark the passengers, landing and air traffic control fees. We follow Flores Fillol (2009) and Brueckner (2009) in assuming that the operating costs are quadratic. It is assumed that all seats are filled, so that load factor equals 100% and therefore $q_i = f_i \times Size_i$, i.e., aircraft (train) size can be determined residually dividing airline (HSR) total traffic on a route by the number of planes (trains)[19]. Under this specification, we can write the profit of mode i as follows:

$$\pi_i(q_A, q_H, f_i) = (\,p_i(q_A, q_H, f_i) - c_i)\, q_i - C_i(f_i) \tag{17}$$

[16] We assume that the benefit from frequency is the same across the two modes of transport available to the travelers.
[17] For instance, Behrens and Pels (2012) estimate the direct elasticity of passenger demand with respect to frequency for business and leisure passengers on the London-Paris route, when air transport and HSR competeIn our model, the direct elasticity of passenger demand with respect to frequency for mode $i = A, H$, that is $\varepsilon_f^i = (\partial q_i/\partial f_i)\,(f_i/q_i)$, is equal to $\left(\gamma_f/(1-\beta^2)\right)(f_i/q_i)$ so that we can indirectly derive the value of γ_f from the estimation of the elasticity.
[18] As in the basic model, without loss of generality, in what follows, we normalize $\overline{T}_H = 0$. Thus, HSR operating costs, c_H, and ticket price, p_H, are considered gross of $\nu_a a_H + \nu_t t_H$.
[19] In what follows, we assume that k_i is much smaller than k_{ii} such that the total cost per departure is increasing with the frequency of service $\forall f_i \geq 1$ (e.g., Flores-Fillol, 2009, and Brueckner, 2009). We note that this assumption assures that the cost per seat, that can be written as $(k_{ii} \times f_i - k_i)/Size_i + c_i$, visibly decreases with the size, capturing the presence of economies of traffic density (i.e., economies from operating a larger aircraft) that are unequivocal in the airline industry. While other papers consider a constant cost per flight, the assumption of non constant returns is needed to generate sensible results (Brueckner, 2009).

where $C_i(f_i) = f_i(k_{ii} \times f_i - k_i) + K_i$, with K_i being the fixed cost that the airline or the HSR bears in the case in which no flights (HSR rides) are operated.

We note that this formulation assumes that the vehicle size and frequency can be smoothly adjusted to suit the size of the market. In reality, such decisions involve indivisibilities such as minimum vehicle sizes and minimum viable frequencies, which may constrain actual choices (Brueckner and Zhang, 2010). Nevertheless, the size of the aircraft can be easily adjusted in the short run, since leasing practices are common. Gavazza (2011) shows, for instance, that the share of new narrow-body and wide-body aircrafts acquired by lessors and the coefficient of variation of carriers' fleet size are highly correlated. Moreover, since the 1970s when the deregulation took place in the US, the airline companies invested in new techniques of yield management in order to achieve high load factors by optimal allocation of the available resources (Ciancimino et al., 1999).

In the HSR industry, where leasing practices are less common[20], some operators rely on advanced scheduling and capacity management process as a key factor in increasing load factors and winning market share. For instance, Societè Nationale des Chemins de Fer Français (SNCF), in partnership with SABRE Technology Solutions, has implemented a set of comprehensive decision-support systems such as revenue management (*RailRev*), schedule planning (*RailPlus*), and capacity (seat control) management (*RailCap*)[21]. Some evidence shows that both French TGV and Eurostar services, between London, Paris and Bruxelles, with long non-stop runs, compulsory seat reservations and sophisticated yield management systems, claim load factors similar to the 70% shown for air transport (Nash, 2009).

Similar to the basic model, we assume that the airline maximizes its own profit while HSR maximizes a weighted sum of its own profit and the social surplus, that is:

[20] We acknowledge that some evidence of leasing practice in the airline industry exists. The Italian NTV (Nuovo Trasporto Viaggiatori) leased 25 AGV trains from Alstom, for a value of EUR 650 million. The contract includes the maintenance of trains for a period of 30 years and an option for 10 additional trains. Renfe, the Spanish public rail operator, has announced that 26 high-speed trains will be available for leasing to new entrants in the market. From May 2000 until December 2005, GNER leased Class 373 Regional Eurostars from Eurostar. These were used on services to York and later Leeds in the United Kingdom.

[21] At SNCF, the major responsibilities of *RailCap* are to monitor the reservation activity for all trains, using the latest forecasts produced by the yield management system *RailRev*, and to proactively add capacity (train seats), called *forcements*. In particular, *RailCap* may suggest the following changes to TGV train capacity: (i) add a second train unit to single-unit trains; (ii) drop empty second train units or open them to reservations on double-unit trains; (iii) open an optional train to reservations and assign it an itinerary-compatible fleet type. Capacity adjustments can be suggested from 15 to 3 days before the train departure (Ben-Khedher et al., 1998)

$$S(q_A, q_H, f_A, f_H) = U(q_A, q_H) - (T + c_A)q_A - c_H q_H - f_A(k_{AA} \times f_A - k_A) - f_H(k_{HH} \times f_H - k_H) \tag{18}$$

The operators choose simultaneously the frequency of services and the quantity of passengers, i.e., they simultaneously solve the following decision problems[22]:

$$\begin{gathered} max_{q_A, f_A}\ (p_A(q_A, q_H, f_A) - c_A)\, q_A - C_A(f_A) \\ max_{q_H, f_H}(1-\delta)\left((p_H(q_A, q_H, f_H) - c_H)\, q_H - C_H(f_H)\right) \\ + \delta\big(U(q_A, q_H) - (T + c_A)q_A - c_H q_H - f_A(k_{AA} \times f_A - k_A) \\ - f_H(k_{HH} \times f_H - k_H)\big) \end{gathered} \tag{19}$$

where δ is the weight of social surplus relative to profit, as described in the basic model. From first order conditions, it is straightforward to derive equilibrium solutions for the quantities and frequencies (the superscript $*, f$ stands for equilibrium), which are given in Appendix 2.

In order to analyze the impact of competition between HSR and air transport on the environment, we refer to the benchmark case of a monopoly airline. Similarly to what described before, we assume a linear demand function. In particular, the inverse demand with respect to full price in the market served by the monopoly airline can be written as $\theta_M(q_M) = \alpha - q_M$. Full price is $\theta_M = p_M + T - \gamma_f f_M$, where $T = v_a a_A + v_t t_A$ measures the cost of access/egress and travel time for travelers when air is the only available transport mode. The inverse demand function with respect to the ticket price can be easily obtained: $p_M(q_M, f_M) = \alpha - T - q_M + \gamma_f f_M$, where γ_f is normalized to 1. The airline maximizes its profit, that is $\pi_M(q_M, f_M) = (p_M - c_A)\, q_M - C_A(f_M)$ with respect to quantity and frequency. Equilibrium results are

$$q_M^{*,f} = \frac{2k_{AA}\big(\alpha - (c_A + T)\big) + k_A}{4k_{AA} - 1} \tag{20}$$

$$f_M^{*,f} = \frac{2k_A + \big(\alpha - (c_A + T)\big)}{4k_{AA} - 1} \tag{21}$$

[22] It is reasonable to assume that the operators may choose contextually quantities and the frequency of service since frequency can be easily adjusted in the short run. Moreover, this is consistent with the instance of: (i) uncongested airports where slots are available; (ii) uncongested rail infrastructure (i.e., the tracks and train station) where, usually, a monopoly HSR serves the market. Moreover, this is a common assumption in literature investigating air transport and HSR competition (see Adler et al., 2010 and Yang and Zhang, 2012).

Lemma 2 The introduction of high-speed rail in the market for travel results in lower airline traffic and lower frequency, compared to the monopoly case, i.e., $q_A^{*,f} < q_M^{*,f}$ and $f_A^{*,f} < f_M^{*,f}$. Moreover, it results in the reduction of aircraft size, i.e., $q_M^{*,f}/f_M^{*,f} - q_A^{*,f}/f_A^{*,f} > 0$. If $\beta < (4k_{AA} - 1)/2k_{AA}$, competition between the two modes leads to market expansion, i.e., $q_M^{*,f} - q_H^{*,f} - q_A^{*,f} < 0$.

Lemma 2, which is proved in the Appendix 2, shows that competition between the two modes leads to market expansion, if the substitutability between the two modes is sufficiently low, i.e., if the two travel products are differentiated enough. Moreover, after the introduction of HSR in the market for travel, the airline carries fewer passengers and reduces the frequency of the service. When load factors are assumed to be 100%, the reduction of frequency may have an impact on the aircraft size, since $q_j^{*,f}/f_j^{*,f} = Size_j, j = A, M$, where $Size_M$ is the size of aircrafts used by the monopoly airline. In particular, Lemma 2 implies that the carrier reduces the size of the aircraft, i.e., $Size_A < Size_M$. In other words, with the entry of HSR the airline loses traffic, it reduces the frequency of service and it reduces the size of the aircraft used in order to keep load factors high while carrying less passengers. The results find empirical support. For instance, when the TGV Est began operations from Paris to Metz and Nancy, and provided attractive frequency (10 trains per day in each direction), flights between Paris and these two cities were completely eliminated (Dobruszkes, 2010). Similarly, in Spain, before the HSR link was established between Madrid and Seville at early 1990s, the mix of air/rail passengers was 67% and 33% respectively. After the introduction of HSR, the mix changed to 16% and 84%. In China, all the flights between Zhengzhou and Xi'an were suspended in March 2010, 48 days after the opening of the HSR service, whereas daily flights on the Wuhan–Guangzhou route were reduced from fifteen to nine, one year after the HSR entry (Fu et al., 2012). Recent cases of air route cancellations also include a number of Chinese domestic markets such as Nanjing-Shanghai, Changsha-Guangzhou and Wuhan-Nanjing (Berdy, 2011). Givoni and Rietveld (2009) investigate airlines' choice of aircraft size and claim that the stronger the competition the smaller the aircraft size one may expect given the importance of service frequency. In particular, they find that market concentration on certain routes leads to the choice of relatively large aircraft. Hence, in a highly concentrated market aircraft size tends to be larger. In the specific case of Paris-Nantes route, air traffic decreased by 30% after the introduction of the TGV network. Empirical evidence also shows that the reduction of aircraft size when adjusting frequency may have an impact on the environment. In general, literature suggests that environmental benefits can be expected from increasing aircraft size, i.e., large aircrafts have lower environmental per seat costs than small aircrafts

(Peeters et al., 2005). For instance, Givoni and Rietveld (2010) show that decreasing aircraft size, switching from a B747 (524 seats) fleet to an A320 (150 seats) fleet and adjusting the service frequency to offer similar seating capacity, would decrease LAP but increase the impact of climate change. When these impacts are monetized and aggregated, the analysis shows that an overall environmental detriment would follow.

Let E_i, with $i = A, H$ be the total level of emissions per flight or HSR ride, respectively, with $E_H < E_A$. In particular, we evaluate:

$$\hat{E}(\mathbf{q}, \mathbf{f}) := \frac{E_A \cdot f_M}{q_M} - \frac{(E_A \cdot f_A + E_H \cdot f_H)}{q_A + q_H} \tag{22}$$

where $\mathbf{q} = (q_A, q_H, q_M)$ and $\mathbf{f} = (f_A, f_H, f_M)$. $\hat{E}(\mathbf{q}, \mathbf{f})$ measures the difference between the per seat level of emissions observed in the case in which the market for travel is served by a monopoly airline and the case in which a new mode of transport is introduced. If $\hat{E}(\mathbf{q}, \mathbf{f}) > 0$, then competition between HSR and air transport is beneficial to the environment on a per seat basis. The following proposition holds:

Proposition 4 If the market size is small enough, that is if $\alpha < \bar{\alpha} = -2\, k_A + k_A\beta + T + c_A$, the introduction of the high-speed rail is always detrimental to the environment, i.e., $\hat{E}\left(q_A^{*,f}, q_H^{*,f}, q_M^{*,f}, f_A^{*,f}, f_H^{*,f}, f_M^{*,f}\right) < 0$. Otherwise, $\exists\, \tilde{e} > 0$ such that $\forall (e_A, e_H)$ with $e_A/e_H > \tilde{e}$ it results $\hat{E}\left(q_A^{*,f}, q_H^{*,f}, q_M^{*,f}, f_A^{*,f}, f_H^{*,f}, f_M^{*,f}\right) > 0$, that is if high-speed rail is sufficiently greener than air transport, competition between the two modes of transport is beneficial to the environment.

The proof of Proposition 4 is given in Appendix 2. Proposition 4 shows that it is not straightforward to assert that HSR is greener than air transport on a per seat basis. This depends on the market size when both modes of transport decide frequency. The final conclusion is that when HSR enters the market, the airline carries fewer passengers, lowers the frequency and, accordingly, decreases the size of the aircraft. Thus, there are some gains related to a reduced number of flights, i.e., a (positive) *frequency effect*, but these flights are supplied with small aircrafts, that are more polluting (Givoni and Rietveld, 2010), i.e., a (negative) *size effect*.

3.2 Speed

In this section, we turn back to the case in which the schedule frequency is exogenously given. We study the case in which the HSR operator may set the (maximum) train speed.

There are two reasons why it is interesting to look at this problem. First, while the aircraft speed can be considered as being constant, since it is close to the speed of sound and has been relatively stable, rail (maximum) speed can vary in practice. The maximum speed of HSR depends on the type of power car that is used to operate the train. For instance, maximum commercial speed is 360 km/h for the Italian Italo ETR 575 (used by NTV), 300 km/h for the Italian ETR 500 (used by Trenitalia) and the Eurostar BR Class 373, 250 km/h for the Spanish Alvia Class. Since HSR does not follow the direct routes, it may have incentive to increase the speed of the vehicle to reduce travel time: as train becomes faster, HSR is likely to impose a significant competitive pressure on air transport over a relatively large range of distances, due to the increase of its attractiveness toward travelers. Benefits from higher speed may also include the increase in the opportunities for passengers in terms of coordination with other transport modes or in the possibility to take advantage of some services when the departure time cannot be anticipated. Take the example of a traveler who is constrained to leave a city (e.g., Milan) not before a certain schedule (e.g., at the end of a business meeting) but has to reach a destination (e.g., Rome) as early as possible to take the last bus or a traditional rail ride back home (e.g., to a peripheral city). The traveler may not manage to catch these opportunities (e.g., he has to spend one more night in a hotel) if the train ride is not fast enough.

Second, the emissions from HSR depend on the energy consumption of the train (CfIT, 2001), which increases with the speed of the vehicle (Andersson and Lukaszewicz, 2006; Bousquet et al., 2013; Garcia, 2010; Kemp, 2004). Therefore, when HSR is able to decide on the speed of the vehicle, there can be a trade-off between the attractiveness of the service and the effects on the environment.

We first examine the demand side. In our formulation, we assume that higher train speed delivers higher value to HSR passengers and, therefore, determines higher service quality. Let $s_H > 0$ denote the commercial speed of HSR. In this framework, we model the full prices perceived by travelers as:

$$\begin{aligned} \theta_A &= p_A + T \\ \theta_H &= p_H - \gamma_s s_H \end{aligned} \tag{23}$$

The parameter γ_s measures the benefit for HSR passengers from train speed. The formulation is similar to the one adopted to model the impact of frequency on passengers' full prices. Introducing speed additively simplifies the analysis, where higher speed reduces the cost of travel time and increases travelers' WTP[23]. The WTP of HSR passengers for saving travel time is now captured by γ_s which includes the benefits from higher speed. From equations (5) and (23), it follows that:

$$
\begin{aligned}
p_A(q_A, q_H) &= \alpha - T - q_A - \beta\, q_H \\
p_H(q_A, q_H) &= \alpha + s_H - q_H - \beta\, q_A
\end{aligned}
\tag{24}
$$

where γ_s has been normalized to 1.

Turning to the supply side, the profit of the airline is $\pi_A(q_A, q_H) = (p_A(q_A, q_H) - c_A)\, q_A$, where c_A is the unit (per aircraft seat) variable cost. The profit of HSR is given by $\pi_H(q_A, q_H) = \big(p_H(q_A, q_H) - o_H - C_s(s_H)\big)\, q_H$, where o_H is the variable operating cost per train seat (other than the electricity cost per seat) and $C_s = C_s(s_H)$ is the electricity cost per km/h per seat (i.e., it is proportional to the energy consumption). We assume that $\partial C_s/\partial s_H > 0$, that is higher speed leads to higher unit electricity cost per km/h. This is confirmed by several empirical investigations (e.g., Andersson and Lukaszewicz, 2006; Bousquet et al., 2013; Garcia, 2010; Kemp, 2004) and adopted in a theoretical model by Yang and Zhang (2012). In particular, in this paper we assume that the unit electricity cost per km/h is constant, that is the electricity cost increases linearly with speed. Janic (2003) finds that HSR energy consumption is mainly proportional to the cruising speed: it is lower during the accelerating/decelerating phase of a trip and higher, but reasonably constant, during cruising at constant speed (of about 250 km/h). Lukaszewicz and Andersson (2009) estimations on the Swedish case show that the energy consumption increases by a power of 1.1–1.3 of the cruising speed for the trains running on the dedicated very-high-speed line. For example, if the speed is increased from 250 to 280 km/h (12%), energy consumption increases by 13–16%. Garcia (2010) reports the relationship between the output of each train (in kilowatts) and its maximum speed showing a curve that confirms the power of 1.3.

Let μ be the constant unit electricity cost per km/h of HSR. The profit of HSR is given by:

$$
\pi_H(q_A, q_H) = (p_H(q_A, q_H) - o_H - \mu s_H)\, q_H \tag{25}
$$

where $\mu < \gamma_s$, that is the unit electricity cost of a marginal increase of speed is lower than the passengers' WTP for that marginal increase of speed. We constrain s_H as follows, $0 < s_H \leq \bar{s}_H$, where $\bar{s}_H > 0$ is the maximum train speed which can be achieved given the technology of the power

[23] For the sake of notation, in what follows we shall refer to $T_A = a_A + t_A$, $T_H = a_H$. We also note that s_A is assumed to be constant. Thus, $t_A = l_A/s_A$ with l_A being the length of the air route (as the crown flies), is constant and included, as $v_t\, t_A$, in T, i.e., and $T = v_a(a_A - a_H) + v_t\, t_A$. As in the basic model, without loss of generality, in what follows, we normalize $\bar{T}_H = 0$. Thus, HSR operating costs, c_H, and ticket price, p_H, are considered gross of $v_a a_H$.

car, legal requirements, e.g., the percentage of the line on which maximum speed can be operated, and the number of stops on the HSR line. For instance, each additional stop (station) may cost 5–10 min and often trains must slow-down in the proximity of the station, even if they are not stopping there (Givoni and Banister, 2012)[24].

Similar to previous sections, we assume that the airline maximizes his own profit while HSR a weighted sum of his own profit and social surplus, that is:

$$S(q_A, q_H, s_H) = U(q_A, q_H) - (c_A + T)q_A - (o_H + \mu s_H)q_H \tag{26}$$

The interaction between the airline and the HSR operator is modeled as a sequential game. In the first stage the HSR decides on speed. In the second stage, the two modes compete on quantities[25]. We solve the game by backward induction. In the second stage, the operators solve simultaneously the following decision problems:

$$\begin{gathered} max_{q_A}\ (p_A(q_A, q_H) - c_A)\ q_A \\ max_{q_H}(1-\delta)\left((p_H(q_A, q_H, s_H) - o_H - \mu s_H)\ q_H\right) \\ + \delta(U(q_A, q_H) - (c_A + T)q_A - (o_H + \mu s_H)q_H) \end{gathered} \tag{27}$$

where δ is the weight of social surplus relative to profit as defined in the basic model. In other words, the airline, first, observes the speed of HSR and, then, competes simultaneously with the HSR operator on quantities. We find the best response functions for $q_A(s_H)$ and $q_H(s_H)$:

$$\begin{gathered} q_A(s_H) = \frac{\left(\alpha - (c_A + T)\right)(\delta - 2) + \beta(\alpha + s_H(1-\mu) - o_H)}{\beta^2 + 2(\delta - 2)} \\ q_H(s_H) = \frac{\left(\alpha - (c_A + T)\right)\beta - 2(\alpha + s_H(1-\mu) - o_H)}{\beta^2 + 2(\delta - 2)} \end{gathered} \tag{28}$$

[24] For instance, from May 2000 until December 2005, the Class 373 Regional Eurostars used in the United Kingdom by GNER on services to York and later Leeds were restricted to 110 mph between Grantham and Doncaster because of problems with the overhead wire and pantograph interface. Due to gauging restrictions, they were not permitted to operate north of York to Newcastle, Glasgow or Edinburgh. In general, while maximum speed of 350 km/h is considered the new standard for HSR, most HSR services are provided at a much lower average speed. The world record for average speed of a commercial HSR service is 313 km/h, held by a non-stop service between Wuhan and Guangzhou in China. Since then, the speed on this route was reduced and a station added, reducing the average speed. Before that a French TGV service held the record with an average speed of 279 km/h (Givoni and Banister, 2012).

[25] As noted, leasing practices are much less common in the HSR industry than in the aviation industry, though some evidence exists. In most of the cases, HSR operators own their own fleet and, therefore, the decision on the type of the locomotive used to operate the service on a route implies a sunk cost in the short run. Consequently, the decision on the speed of the vehicle can be seen as a long run decision, since it cannot be easily adjusted in the short run once that the rolling stock, and so the power car, has been acquired. For instance, *Trenitalia* invested in 2013 approximately € 552 million, of which 56% was used to purchase new rolling stock (FSI, 2014). In particular, the investments involved the purchase of the new electric trains AV "Frecciarossa 1000". Similarly, in 2004 The European Investment Bank (EIB) granted a € 200 million loan to SNCF in order to purchase 18 Duplex (double-deck) trainsets.

In the first stage, the HSR operator chooses the speed of the vehicle in order to maximize its objective function. The decision problem is as follows:

$$max_{s_H}\ (1-\delta)\big((p_H(q_A(s_H),q_h(s_H),s_H)-o_H-\mu s_H)q_H(s_H)\big)+\delta S(q_A(s_H),q_h(s_H),s_H)$$

In particular, it is easy to demonstrate that

$$\partial\Big((1-\delta)\big((p_H(q_A(s_H),q_H(s_H),s_H)-o_H-\mu s_H)q_H(s_H)\big)(p_H(q_A(s_H),q_h(s_H),s_H)-o_H-\mu s_H)q_H(s_H)+\delta S(q_A(s_H),q_h(s_H),s_H)\Big)/\partial s_H>0$$

Thus, HSR has always incentive to raise its speed. It results (the superscript $*,s$ stands for equilibrium):

$$s_H^{*,s}=\bar{s}_H$$

Indeed, in the feasible region it results in $\partial^2\Big((1-\delta)\big((p_H(q_A(s_H),q_H(s_H),s_H)-o_H-\mu s_H)q_H(s_H)\big)+\delta S(q_A(s_H),q_h(s_H),s_H)\Big)/\partial s_H\partial\delta>0$. Moreover,

$$\lim_{\delta\to 0}\Big(\Big((1-\delta)\big((p_H(q_A(s_H),q_h(s_H),s_H)-o_H-\mu s_H)q_H(s_H)\big)\big((p_H(q_A(s_H),q_h(s_H),s_H)-o_H-\mu s_H)q_H(s_H)\big)+\delta S(q_A(s_H),q_h(s_H),s_H)\Big)/\partial s_H\partial\delta\Big)=0$$

Consequently, equilibrium quantities are found, i.e., $q_A^{*,s}=q_A(\bar{s}_H)$ and $q_H^{*,s}=q_H(\bar{s}_H)$.

In order to analyze the impact on the environment of competition between air transport and HSR, we refer to the benchmark case of a monopoly airline. Expression for the equilibrium value of q_M is the same as in the basic case model, i.e., $q_M^{*,s}=(\alpha-T-c_A)/2$. Again, it is easy to check that competition between the two modes leads to market expansion, i.e., $q_M^{*,s}-q_H^{*,s}-q_A^{*,s}<0$.

We shall consider the overall environmental impact of market expansion. In electrically powered high-speed trains, emissions mostly depend on the energy consumption (CfIT, 2010; Pérez-Arriaga, 2013, pg. 541-542). However, we can distinguish between direct and indirect energy consumption. The former mostly includes the energy required to overcome the train resistance to movement. It also includes the energy lost due to inefficiencies in the traction system between pantograph and wheel, or the energy used for on-board passenger comfort functions. The latter includes energy used for in-service maintenance of the rolling stock (Network Rail, 2009). In particular, emissions from indirect energy consumption do not increase with the speed as well as emissions from direct energy consumption for on-board passenger comfort functions[26]. Let e_H^f denote this type of emissions (the superscript f denotes *fixed* with respect to speed). Let e_H^v denote all emissions other than e_H^f, that is those which reasonably increase with the speed of the vehicle (the superscript v denotes *variable* with respect to speed). In other words, e_H^v is the marginal increase in the level of emissions due to the energy consumption per km/h, while e_H^f is the marginal increase in emissions per seat that is fixed per km/h.

Let $\breve{E}$ denote the difference between the total pollution before and after the introduction of HSR. We define $\breve{E}$ as:

$$\breve{E}(\boldsymbol{q}, s_H) \coloneqq e_A - \frac{\left(e_A\, q_A + e_H^f\, q_H + \, e_H^v\, s_H\right)}{q_A + q_H} \tag{29}$$

where $\boldsymbol{q} \coloneqq (q_A, q_H, q_M)$. The following proposition holds.

Proposition 5 There exists a value $e_H^v > 0$ such that, $\forall(e_A, e_H^f, e_H^v)$ with $e_H^v > \left(e_A - e_H^f\right)/(\omega \bar{s}_H)$, it results $\breve{E}(q_A^{*,S}, q_H^{*,S}, q_M^{*,S}, s_H^{*,S}) < 0$, that is when the increase in the emissions of high-speed rail due to the increase in the speed of the train is sufficiently high, the overall level of emissions after the introduction of the high-speed rail is always higher than the level of emissions in the monopoly case.

The proof of Proposition 5 is given in Appendix 2. When HSR is able to decide the speed of the vehicle, there can be a trade-off between the attractiveness of the service due to reduced travel time and the effects on the environment. Indeed, $\partial q_A^{*,S}/\partial s_H < 0$ while $\partial q_H^{*,S}/\partial s_H > 0$, that is the number of passengers traveling by air transport decreases as HSR become faster, while the number of passengers traveling by HSR increases. However, when HSR increases the speed of the vehicle and the subsequent increase in the emissions of HSR is sufficiently high, the competition between the two modes of transport may be detrimental to the environment. Thus, energy efficiency technologies and strategies should be promoted in order to increase the *greenness* of HSR when compared to air transport (UIC, 2003). Low energy consumption at increased speeds would require a new train

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[26] Comfort functions include lighting, heating and ventilating coaches for passenger comfort. Whilst this is mainly required during operation there is demand for cleaning and maintenance and to ensure a comfortable temperature when the train begins operation. Comfort function energy demand depends strongly on ambient temperature (Network rail, 2009). Evidence shows that such energy consumption accounts for the 22% of the direct energy consumption (Network Rail, 2009).

concept and design, using the most modern technologies and knowledge available. The Swedish research and development program “Gröna Tåget” (the Green Train) can be taken as an example in this sense. Environmental performance and energy efficiency is one of the major goals of the program together with reduced travel time and thus increased speed compared to recent trains (Lukaszewicz and Andersson, 2009).

4. Concluding remarks

In this paper, we propose a duopoly model to shed light on the impact of air transport and HSR competition on the environment and social welfare when new travel demand is induced. The net environmental effect depends on the balance between the *substitution effect* (how many passengers using HSR are shifted from the aircraft) and the *traffic generation effect* (how much new demand is generated by the HSR).

First, our findings show that, when the level of pollution emitted by HSR is not sufficiently lower than that of the airline, the gain from shifting former air passengers to a cleaner mode of transport is not able to compensate the amount of pollution due to newly generated traffic. Moreover, if the impact on the environment is taken into account when assessing social welfare, the surplus measure may be lower in the competition case than in the monopoly case, when the attractiveness of HSR is sufficiently high. In this case, when HSR is owned by public and private sectors and maximizes a weighted sum of its profit and social surplus, the more HSR cares about social surplus, the more likely an overall loss caused by HSR entry will arise.

Second, the choice of the frequency of flights (HSR rides) or of the speed of trains may affect the environment. On the one hand, when a new mode of transport is introduced in the market, we show that airlines may tend to reduce the size of the aircraft used in order to keep load factors high while offering lower frequency services and carrying fewer passengers. Decreasing aircraft size and adjusting the service frequency to offer similar seating capacity will increase the environmental impact. In particular, we show that reduced aircraft size may result in the introduction of HSR being beneficial to environment on a per seat basis only if the market size is large enough.

HSR may have incentive to increase the speed of trains, in order to reduce travel time and increase its attractiveness to travelers when competing with air transport. However, this affects the environment, since the HSR impact on LAP and climate change depends on the energy consumption, which rises when the speed of the vehicle increases. When HSR decides the train speed, the operator will choose the maximum level given the technology of the power car, legal requirements and the number of stops on the HSR line. When the increase in the emissions of HSR due to the increase in the speed of the train is sufficiently high, the overall level of emissions after the introduction of the HSR will be higher than in the monopoly case. Therefore, there can be a trade-off between the attractiveness of the service due to reduced travel time and the effects on the environment.

The paper has raised some important issues within the policy debate around HSR versus air transport. First, some recommendations, which have been typified with unsubstantiated claims of the *greenness* of HSR, may have led to a blatant bias amongst regulators when considering future transport policy. Indeed, it is not always true that the introduction of HSR is beneficial to the society. Though the inclusion of non-economic benefits into the assessment of the social welfare function is likely to raise a number of challenges, widening the assessment framework to take into account environmental considerations could allow competition authorities to identify and consider all of the benefits of intermodal competition. In this case, we show that the surplus measure of the *traditional* approach (that is when environmental effects are not taken into account in the assessment of social welfare) may fall short of giving a true measure of total social surplus.

Second, our analysis suggests that it is crucial to analyze the implications of the introduction of HSR on social welfare and environment on a case-by-case basis, since benefits depend on the environmental *friendliness* of HSR relative to air transport. This, in turn, hinges on the mix of energy sources used to generate the electricity. Thus, policy makers should carefully assess the implications of HSR introduction in the market for travel, taking into account the perspective impact of policy targets for emergent (e.g., renewable) resources for energy production. In fact, whilst airlines have the opportunity to switch to non-conventional jet fuels, e.g., biofuels, in order to reduce their own environmental footprint, the generation mix for electricity is heavily constrained by the country in which HSR operates (e.g. due to the availability of electricity sources and the topology of the electricity grid). Consequently, the set of mitigation strategies that might be implemented by HSR is much more limited when compared to air transport. This is something that should be taken into account by policy makers in the design of environmental regulation.

The paper has also raised some avenues for further research. First, phases other than operation in the HSR life-cycle analysis (construction/production, maintenance and disposal) can be responsible for significant environmental impact (ERA, 2011). The effects relating to the construction of rail infrastructure, for instance, include emissions from building a new HSR line as well as land take, affecting landscape, townscape, biodiversity and heritage. For instance, using a panel data set from 1999 to 2007 for three Japanese railway companies and the Japanese air transport industry, Ha et al.

(2011) empirically investigate the environmental burden of HSR and air transport by taking into account the CO_2 emissions from both transport service provision and infrastructure construction. The aviation industry is shown to be efficient, whereas results for the railway industry are mixed. Further developments of our work may investigate the effects of modes competition on environment when capacity investments in building a new line are considered. Second, it can be interesting to include the environmental dimension in the analysis of demand (rather than of the supply side only). Its importance is suggested by some stylized facts. For instance, Trenitalia sponsored *EcoPassenger*, a tool developed by Union Internationale des Chemins de Fer (UIC) and approved by the European Environmental Agency and the European Commission, which calculates the energy consumption and emissions of the major atmospheric pollutants per seat travelling by plane or train and car. The aim of the system is to increase user awareness of the cost of their selected mode of transport, thanks to the possibility of comparing the energy consumption and emissions of modes of transport through information that is printed back to the train ticket.

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Appendix 1

Table 1. Summary of notation

Notation	Meaning
a_i	Access/egress time to transport terminals (airport, train station)
t_i	Travel time of mode i
T_i	Total journey time of mode i
v_a	Value of access/egress time
v_t	Value of travel time
γ_f	Benefit from frequency
γ_s	Benefit from HSR speed
$\bar{T}_i$	Value of total journey time of mode i
T	Time dimension-differentiator between the two modes
α	Gross benefit from traveling from the origin O to the destination D
β	Degree of substitutability between air transport and HSR
θ_i	Full price of transport mode i
p_i	Ticket price of transport mode i
p_M	Ticket price of the monopoly airline
q_i	Quantity of passengers carried by transport mode i
q_M	Quantity of passengers carried by the monopoly airline
f_i	Service frequency of transport mode i
f_M	Service frequency of the monopoly airline
s_H	Speed of the high-speed train
$\bar{s}_H$	Maximum train speed achievable by the available technology
c_i	Unit per seat variable cost of transport mode i
o_H	Unit per seat variable cost of HSR other than the electricity cost per km/h/ train seat
μ	Electricity cost per km/h/train seat
$k_{ii}xf_i - k_i$	Cost of operating a flight (HSR ride)
K_i	Fixed cost that transport mode i bears in the case in which no flights (HSR rides) are operated
e_i	Emissions per seat from mode i

e_H^f	Emissions from HSR which do not depend on the level of speed
e_H^v	Emissions from HSR which varies with the speed of service
ε_i	Cost of damage per seat due to pollution of mode i
E_i	Emissions per flight (HSR ride)
E	Difference between the total level of pollution before and after the introduction of HSR
$\hat{E}$	Difference between the per seat level of pollution before and after the introduction of HSR
$\check{E}$	Difference between the total level of pollution before and after the introduction of HSR when HSR emissions vary with the speed of the high-speed train
ΔW	Overall effect on the society caused by HSR entry when the environment matters for the society

Appendix 2

Second order conditions

Second order conditions for unconstrained optimization are satisfied:

- for problem (10). Indeed, $\partial^2\big(\pi_A(q_A, q_H)\big)/\partial {q_A}^2 = -2$ and $\partial^2\big((1-\delta)\pi_H(q_A, q_H) + \delta S(q_A, q_H)\big)/\partial {q_H}^2 = -2 + \delta$.

- for problem (19). Indeed, $\partial^2\big(\pi_A(q_A, q_H, f_A)\big)/\partial {q_A}^2 = -2$ and $\partial^2\big(\pi_A(q_A, q_H, f_A)\big)/\partial {q_A}^2 \cdot \partial^2\big(\pi_A(q_A, q_H, f_A)\big)/\partial {f_A}^2 - \partial^2\big(\pi_A(q_A, q_H, f_A)\big)/\partial q_A f_A \cdot \partial^2\big(\pi_A(q_A, q_H, f_A)\big)/\partial f_A q_A = 4k_{AA} - 1$ which is assumed to be positive. Similarly, $\partial^2\big((1-\delta)\pi_H(q_A, q_H, f_H) + \delta S(q_A, q_H, f_A, f_H)\big)/\partial {q_H}^2 = -2 + \delta$ and $\partial^2\big((1-\delta)\pi_H(q_A, q_H, f_H) + \delta S(q_A, q_H, f_A, f_H)\big)/\partial {q_H}^2 \cdot \partial^2\big((1-\delta)\pi_H(q_A, q_H, f_H) + \delta S(q_A, q_H, f_A, f_H)\big)/\partial {f_H}^2 - \partial^2\big((1-\delta)\pi_H(q_A, q_H, f_H) + \delta S(q_A, q_H, f_A, f_H)\big)/\partial q_H f_H \cdot \partial^2\big((1-\delta)\pi_H(q_A, q_H, f_H) + \delta S(q_A, q_H, f_A, f_H)\big)/\partial f_H q_H = -1 - 2k_{HH}(-2 + \delta)$, which is assumed to be positive. We remark that, at the equilibrium, it results $k_{ii} \times f_i^{*,f} - k_i > 0$, with $i = A, H$.

- for problem (27). Indeed, $\partial^2\big(\pi_A(q_A, q_H)\big)/\partial {q_A}^2 = -2$ and $\partial^2((1-\delta)\,\pi_H(q_A, q_H) + \delta S(q_A, q_H, s_H))/\partial {q_H}^2 = -2 + \delta$.

Proof of Lemma 1

At the equilibrium, it results:

$$q_M^* - q_A^* = \frac{\beta\left(\left(\alpha - (c_A + T)\right)\beta - 2(\alpha - c_H)\right)}{2(\beta^2 + 2\delta - 4)}$$

$$\Delta q = q_H^* + q_A^* - q_M^* = \frac{(2-\beta)\left(\left(\alpha - (c_A + T)\right)\beta - 2(\alpha - c_H)\right)}{2(\beta^2 + 2\delta - 4)}$$

where $\alpha - (c_A + T) > 0$ since $q_M^* > 0$ and $\left(\alpha - (c_A + T)\right)\beta - 2(\alpha - c_H) < 0$ since $q_H^* > 0$. The thesis follows immediately, given that $0 < \beta < 1$, $0 < \delta < 1$.

■

Proof of Proposition 1

At the equilibrium, it results $E(q_M^*, q_A^*, q_H^*) \coloneqq e_A q_M^* - (e_A q_A^* + e_H q_H^*)$ with:

$$\frac{\partial E(q_M^*, q_A^*, q_H^*)}{\partial e_A} = \frac{\beta\left(\left(\alpha - (c_A + T)\right)\beta - 2(\alpha - c_H)\right)}{2(\beta^2 + 2\delta - 4)} = q_M^* - q_A^* > 0$$

Thus, the overall environmental benefit of HSR introduction is increasing in the level of airline emissions, e_A. In particular, $E(q_M^*, q_A^*, q_H^*) = 0$ when $e_A = 2e_H/\beta$. It follows that $(e_A q_A^* + e_H q_H^*) > e_A q_M^*$, i.e., $E(q_M^*, q_A^*, q_H^*) < 0$, when $e_H/e_A > \beta/2$.

■

Proof of Proposition 2

At the equilibrium, it results:

$$\frac{\partial E(q_M^*, q_A^*, q_H^*)}{\partial \beta} =$$

$$= \frac{e_H\left(\left(\alpha - (c_A + T)\right)(4 + \beta^2 - 2\delta) - 4\beta(\alpha - c_H)\right)}{(-4 + \beta^2 + 2\delta)^2}$$

$$+ \frac{e_A\left(\left(\alpha - (c_A + T)\right)\left(2\beta(-2 + \delta)\right) + \left((4 + \beta^2 - 2\delta)\right)(\alpha - c_H)\right)}{(-4 + \beta^2 + 2\delta)^2}$$

Denote $\Gamma \coloneqq \left(\alpha - (c_A + T)\right)(4 + \beta^2 - 2\delta) - 4\beta(\alpha - c_H)$ and $\Theta := \left(\alpha - (c_A + T)\right)\left(2\beta(-2 + \delta)\right) - \left((4 + \beta^2 - 2\delta)\right)(\alpha - c_H)$. It is easy to demonstrate that $\Theta > 0$ when $q_A^* > 0$ and $q_H^* > 0$, while Γ can be either positive or negative. When $\Gamma \geq 0$, $\partial E(q_M^*, q_A^*, q_H^*)/\partial\beta > 0$ always holds. When $\Gamma < 0$ and $-|\Gamma|e_H + \Theta e_A > 0$, i.e., $e_H/e_A < \Theta/|\Gamma| = \check{e}$, $\partial E(q_M^*, q_A^*, q_H^*)/\partial\beta > 0$ holds.

(a) At the equilibrium, it results:

$$\frac{\partial E(q_M^*, q_A^*, q_H^*)}{\partial\alpha} = \frac{(-2+\beta)(-2e_H + \beta e_A)}{2(-4+\beta^2+2\delta)}$$

where $-2+\beta < 0$ and $-4+\beta^2+2\delta < 0$, since $0 < \beta < 1$ and $0 < \delta < 1$. Thus, when $-2e_H + \beta e_A > 0$, i.e., when $e_H/e_A < \beta/2$, $\partial E(q_M^*, q_A^*, q_H^*)/\partial\alpha > 0$. It easy to demonstrate that $\beta/2 < \check{e}$ when $q_A^* > 0$ and $q_H^* > 0$.

(b) At the equilibrium, it results:

$$\frac{\partial E(q_M^*, q_A^*, q_H^*)}{\partial T} = -\frac{\beta(-2e_H + \beta e_A)}{2(-4+\beta^2+2\delta)}$$

Thus, when $2e_H - \beta e_A < 0$, $\partial E(q_M^*, q_A^*, q_H^*)/\partial T > 0$.

(c) At the equilibrium, it results:

$$\frac{\partial E(q_M^*, q_A^*, q_H^*)}{\partial\delta} = \frac{(2e_H - \beta e_A)(2c_H + \alpha(-2+\beta) - (c_A+T)\beta)}{(-4+\beta^2+2\delta)^2}$$

where $(2c_H + \alpha(-2+\beta) - (c_A+T)\beta) < 0$ when $q_H^* > 0$. Thus, when $e_A > 2e_H/\beta$, it results $\partial E(q_M^*, q_A^*, q_H^*)/\partial\delta > 0$.

■

Proof of Proposition 3

We first show that the difference in social welfare between the monopoly case and the competition case, i.e., $\Delta W(q_A^*, q_H^*, q_M^*)$, is decreasing in ε_A, that is it reduces when the per seat environmental cost of damage due to air transport increases. Indeed:

$$\frac{\partial \Delta W(q_A^*, q_H^*, q_M^*)}{\partial\varepsilon_A} = -\frac{\beta\big(\alpha - (c_A+T)\big) - 2(\alpha - c_H)}{2(\beta^2+2\delta-4)} < 0$$

since $\beta\big(\alpha - (c_A+T)\big) - 2(\alpha - c_H) < 0$ when $q_H^* > 0$ and $\beta^2 + 2\delta - 4 < 0$. In particular, $\Delta W(q_A^*, q_H^*, q_M^*) = 0$ when $\varepsilon_A = \bar{\varepsilon} + (2/\beta)\varepsilon_H$ where

$\bar{\varepsilon}$:

$$= \frac{\beta(T + c_A)(20 - 3\beta^2 - 12\delta) + 2c_H(-12 + \beta^2 + 8\delta) + \alpha(24 + \beta(3\beta^2 + 12\delta - 20 - 2\beta) - 16\delta)}{4\beta(\beta^2 + 2\delta - 4)}$$

We note that there exists a range in which $\Delta W(q_A^*, q_H^*, q_M^*) \geq 0$ if and only if $\varepsilon_A = \bar{\varepsilon} + (2/\beta)\varepsilon_H \geq 0$. In particular, since $(2/\beta)\varepsilon_H \geq 0$, it is sufficient to prove that there exists a value $\bar{\varepsilon} \geq 0$. It results:

$$\frac{\partial \bar{\varepsilon}}{\partial \delta} = \frac{(3\beta^2 - 4)\left(\left(\alpha - (c_A + T)\right)\beta + 2(c_H - \alpha)\right)}{2\beta(\beta^2 + 2\delta - 4)^2} > 0$$

since, the numerator is positive because of non-negativity of q_H^*. Moreover, when $\delta = 0$, it results $\bar{\varepsilon} \geq 0$ when $T \geq \tilde{T}$, with:

$$\tilde{T} := (-24c_H + 24\alpha + 20c_A\beta - 20\alpha\beta + 2c_H\beta^2 - 2\alpha\beta^2 - 3c_A\beta^3 + 3\alpha\beta^3)/(-20\beta + 3\beta^3)$$

Thus, when $T \geq \tilde{T}$, there exists a value $\bar{\varepsilon} \geq 0$ $\forall\delta: 0 \leq \delta \leq 1$ such that $\forall(\varepsilon_A, \varepsilon_H)$ with $\varepsilon_A - (2/\beta)\varepsilon_H < \bar{\varepsilon}$, it results $\Delta W(q_A^*, q_H^*, q_M^*) > 0$.

■

Equilibrium results for the extension "Schedule frequency"

$$q_A^{*,f} = \frac{N_{qA}}{D}$$

$$q_H^{*,f} = \frac{N_{qH}}{D}$$

$$f_A^{*,f} = \frac{N_{fA}}{D}$$

$$f_H^{*,f} = \frac{N_{fH}}{D}$$

where:

$D := 1 + 2k_{HH}(-2 + \delta) - 4k_{AA}\left(1 + k_{HH}(-4 + \beta^2 + 2\delta)\right)$

$$N_{qA} \coloneqq 2k_{AA}\Big((2c_H k_{HH} - k_H - 2k_{HH}\alpha)\beta + (\alpha - T - c_A)\big(1 + 2k_{HH}(-2+\delta)\big)\Big)$$
$$- k_A\big(1 + 2k_{HH}(-2+\delta)\big)$$

$$N_{qH} \coloneqq (1 - 4k_{AA})(2c_H k_{HH} - k_H - 2k_{HH}\alpha) - 2k_{HH}\big(k_A - 2k_{AA}(T + c_A - \alpha)\big)\beta$$

$$N_{fA} \coloneqq -(\alpha - T - c_A)(1 + 2k_{HH}\delta) - 4Tk_{HH} - 4c_A k_{HH} + 4k_{HH}\alpha + 2c_H k_{HH}\beta - k_H\beta - 2k_{HH}\alpha\beta$$
$$- 2k_A\big(1 + k_{HH}(-4 + \beta^2 + 2\delta)\big)$$

$$N_{fH} \coloneqq -(\alpha - c_H) - k_A\beta + k_A(-2+\delta) - 2k_A(2c_H + \alpha(-2+\beta) - (T + c_A)\beta + k_H(-4 + \beta^2$$
$$+ 2\delta))$$

Proof of Lemma 2

At the equilibrium, it results:

$$q_A^{*,f} - q_M^{*,f} = \frac{2k_{AA}\beta\Big((1-4k_{AA})(2c_H k_{HH} - k_H - 2k_{HH}\alpha) - 2k_{HH}\big(k_A - 2k_{AA}(T + c_A - \alpha)\big)\beta\Big)}{-(4k_{AA}-1)\Big(1 + 2k_{HH}(-2+\delta) - 4k_{AA}\big(1 + k_{HH}(-4+\beta^2+2\delta)\big)\Big)}$$

$$f_A^{*,f} - f_M^{*,f} = \frac{\beta\Big((1-4k_{AA})(2c_H k_{HH} - k_H - 2k_{HH}\alpha) - 2k_{HH}\big(k_A - 2k_{AA}(T + c_A - \alpha)\big)\beta\Big)}{-(4k_{AA}-1)\Big(1 + 2k_{HH}(-2+\delta) - 4k_{AA}\big(1 + k_{HH}(-4+\beta^2+2\delta)\big)\Big)}$$

$$\frac{q_A^{*,f}}{f_A^{*,f}} - \frac{q_M^{*,f}}{f_M^{*,f}}$$
$$= \frac{k_A\beta\Big((1-4k_{AA})(2c_H k_{HH} - k_H - 2k_{HH}\alpha) - 2k_{HH}\big(k_A - 2k_{AA}(T + c_A - \alpha)\big)\beta\Big)}{(\alpha - T - c_A)(1 + 2k_{HH}\delta - 4k_{HH}) + (\alpha - c_H) + k_H\beta - 2k_A\big(1 + k_{HH}(-4+\beta^2+2\delta)\big)}$$
$$\cdot \frac{1}{\big(2k_A + (\alpha - T - c_A)\big)}$$

$$q_A^{*,f} + q_H^{*,f} - q_M^{*,f}$$
$$= \frac{(2k_{AA}(-2+\beta)+1)\Big((1-4k_{AA})(2c_H k_{HH} - k_H - 2k_{HH}\alpha) - 2k_{HH}\big(k_A - 2k_{AA}(T + c_A - \alpha)\big)\beta\Big)}{-(4k_{AA}-1)\Big(1 + 2k_{HH}(-2+\delta) - 4k_{AA}\big(1 + k_{HH}(-4+\beta^2+2\delta)\big)\Big)}$$

It is easy to note that:

$$q_A^{*,f} - q_M^{*,f} = \frac{2k_{AA}\beta N_{qH}}{(-4k_{AA}+1)D} \leq 0$$

Since, at the equilibrium, frequencies and quantities are non negative, N_{qA}, N_{qH}, N_{fA}, N_{fH} and D share the same sign. Thus, N_{qH}/D is positive. Moreover, $2k_{AA}\beta$ is positive while $(-4k_{AA}+1)$ is negative since, at the equilibrium the second order conditions are satisfied. Thus, the whole expression is negative. Following a similar argument, it follows that

$$f_A^{*,f} - f_M^{*,f} = \frac{\beta N_{qH}}{(-4k_{AA}+1)D} \leq 0$$

Moreover, it results

$$\frac{q_A^{*,f}}{f_A^{*,f}} - \frac{q_M^{*,f}}{f_M^{*,f}} = \frac{k_A \beta N_{qH}}{-N_{fA}} \cdot \frac{1}{2k_A + (\alpha - T - c_A)}$$

where $2k_A - (T + c_A - \alpha)$ is the numerator of $f_M^{*,f}$, which is positive since, at the equilibrium, $f_M^{*,f}$ is positive and $-N_{qH}/N_{fA}$ is negative since N_{qH} and N_{fA} share the same sign. Thus, the whole expression is negative. Finally, it results:

$$q_A^{*,f} + q_H^{*,f} - q_M^{*,f} = \frac{(2k_{AA}(-2+\beta)+1)N_{qH}}{(-4k_{AA}+1)D}$$

where $2k_{AA}(-2+\beta)+1$ can be positive or negative depending on β.

■

Proof of Proposition 4

At the equilibrium, it results:

$$\frac{\partial \hat{E}(\boldsymbol{q}, \boldsymbol{f})}{\partial e_A} = \frac{-\left(k_H(-2+\beta) + (c_A + T - \alpha)\right)N_{qH}}{-(2k_{AA}(T + c_A - \alpha) - k_A)\left(N_{qA} + N_{qH}\right)}$$

where $-2k_{AA}(T + c_A - \alpha) + k_A$ is the numerator of $q_M^{*,f}$, which is positive since, at the equilibrium, $q_M^{*,f}$ is positive and second order conditions are fulfilled. Since N_{qH}, N_{qA} share the same sign, the sign of the whole expression still depends on the sign of $k_H(-2+\beta) + (c_A + T - \alpha)$. If this is positive, i.e., $\alpha < k_H(-2+\beta) + (c_A + T)$, than $\hat{E}(\mathbf{q}, \mathbf{f})$ is decreasing in e_A. In particular, $\partial \hat{E}(\mathbf{q}, \mathbf{f})/\partial e_A = 0$ when $e_A/e_H = \tilde{e}$ with:

$$\tilde{e} = \frac{(2k_{AA}(T + c_A - \alpha) - k_A)N_{fH}}{\left(k_H(-2 + \beta) + (c_A + T - \alpha)\right)N_{qH}}$$

Thus, if $\alpha < k_H(-2 + \beta) + (c_A + T)$, $\hat{E}(\mathbf{q}, \mathbf{f})$ is decreasing in e_A, and $\check{e}$ is negative. In this case, $\hat{E}(\mathbf{q}, \mathbf{f}) < 0$ always holds and the introduction of the high-speed rail is always detrimental to the environment. As opposite, if $\alpha \geq k_H(-2 + \beta) + (c_A + T)$, $\hat{E}(\mathbf{q}, \mathbf{f})$ is increasing in e_A, and $\check{e}$ is positive. In this case, when $e_A/e_H > \tilde{e}$, $\hat{E}(\mathbf{q}, \mathbf{f}) > 0$ holds.

We remark that the definition of $\hat{E}(\mathbf{q}, \mathbf{f})$ implies that E_A, the total level of emissions per flight, is the same in the monopoly case and in the competition case, while the airline uses different types of aircrafts. In particular, let E_M denote the total level of emissions per flight in the monopoly case. We proved that when $E_M = E_A \cdot z$, with $z = 1$, there exists a $\tilde{e}$ such that $\forall\ e_A/e_H < \tilde{e}$ introducing HSR into the market will exacerbate the environmental impact on a per seat, as long as the market size is big enough. In fact, smaller aircrafts might be characterized by $z \neq 1$. Indeed, on the one side, they are characterized by lower weight (i.e., a lower number of seats) and, on the other side, they are less efficient. The larger z, the more likely HSR entry will harm the environment, since $\hat{E}(\mathbf{q}, \mathbf{f})$ is increasing in z. This translates into the fact that a larger z will induce and higher threshold $\tilde{e}$. The opposite occurs for values of z smaller than one.

∎

Proof of Proposition 5

At the equilibrium, $\check{E}(\boldsymbol{q}, s_H^*)$ is always increasing in e_A, that is:

$$\frac{\partial \check{E}(\boldsymbol{q}, s_H^*)}{\partial e_A} = \frac{\beta(c_A + T - \alpha) - 2\bar{s}_H(-1 + \mu) - 2(o_H - \alpha)}{(T + c_A + o_H + \bar{s}_H(-1 + \mu) - 2\alpha)(\beta - 2) + (c_A + T - \alpha)\delta} > 0$$

Indeed, $\partial \check{E}(q, s_H^*)/\partial e_A$ is always increasing in o_H:

$$\frac{\partial^2 \check{E}(\boldsymbol{q}, s_H^*)}{\partial e_A \partial o_H} = -\frac{(c_A + T - \alpha)(\beta^2 - 4 + 2\delta)}{\left((T + c_A + o_H + \bar{s}_H(-1 + \mu) - 2\alpha)(\beta - 2) + (c_A + T - \alpha)\delta\right)^2} > 0$$

since $\alpha > c_A + T$, $0 < \beta < 1$and $\mu < 1$. Moreover, when $o_H = 0$, it results:

$$\left.\frac{\partial \check{E}(q, s_H^*)}{\partial e_A}\right|_{o_H=0} = \frac{\alpha(2-\beta) + 2\bar{s}_H(1-\mu) + (c_A+T)\beta}{(c_A+T-\alpha)(\delta-2+\beta) + (\beta-2)(\bar{s}_H(-1+\mu)-\alpha)} > 0$$

where $\alpha(2-\beta) + 2\bar{s}_H(1-\mu) + (c_A+T)\beta$ is positive, since, at the equilibrium, $q_H^{*,S}$ is positive. In particular, $\check{E}(\boldsymbol{q}, s_H^*) = 0$ when:

$$e_A = e_H^f + e_H^v \bar{s}_H \omega$$

where $\omega := (\beta^2 - 4 + 2\delta)/(\alpha(-2+\beta) - 2s_H(1-\mu) + 2o_H - (c_A+T)\beta) > 0$. Therefore, $\forall(e_A, e_H^f, e_H^v)$ with $e_A < e_H^f + e_H^v \omega \bar{s}_H$, it results $\check{E}(\boldsymbol{q}, s_H^*) < 0$.

■