The effects of competition between air transport and high speed rail on environment
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Abstract
We develop a duopoly model to analyse the impact of air transport and high speed rail (HSR) substitution on the environment and social welfare when intermodal competition takes place. We show that the introduction of HSR, even if greener than air transport on a per-passenger base, may have a net negative effect on environment, since it may result in additional demand, i.e., there is a trade-off between the substitution effect and the traffic generation effect. We incorporate into the model some specific engineering features: frequency and speed. When airlines and HSR decide on frequencies, there may be environmental disadvantages if load factors are not met, since the lower the load factor achieved, the higher the environmental cost per passenger from the operation of each mode. When HSR decides on speed, it has incentive to keep it at the maximum level in order to reduce travel time. This affects the environment, since pollution depends on the marginal energy consumption which is mainly proportional to cruising speed: the net effect on environment is negative if when the HSR marginal increase in emissions (per seat per kmh) is sufficiently high. Finally, when environmental externalities are taken into account into the social welfare function, we show that the introduction of HSR may be detrimental for society.

Keywords
High-speed rail, Airlines, Competition, Environment, Frequency, Speed, Social Welfare

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1. Introduction

Air transport and high speed rail (HSR) substitution has been encouraged by many for environmental reasons (ATAG, 1998; EC, 2001; 2010; ELPC, 2014; TRB, 2013; US DOT, 2002). One of the main statements to justify policies for modal shift relates to the claimed greenness of HSR on a per-passerenger base. The European Commission, for instance, while deciding on benchmarks for achieving the 60% greenhouse gases (GHG) emissions reduction, states 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). Developments so far indicate that partial substitution of short-haul flights with HSR services, either through modal competition or complementarity, has already taken place at Frankfurth Main, Paris CDG, Madrid Barajas or Amsterdam Schipol, which are all connected to the Trans-European High-Speed-Rail Network. Similarly, in the US the 2008 Passenger Rail Investment and Improvement Act (PRIIA) and the government environmental review process, in the form of National Environmental Policy Act (NEPA), underline the importance of mechanisms for comparing the environmental impact of alternative modes.

In fact, environmental benefits from modes substitution can be measured on a per passenger base through the impact on local air pollution (LAP), climate change and noise. Overall speaking, the environmental impact of aircraft operations 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. HST operations impact depends mainly on the mix of sources used to generate the electricity, the route distance, and the train capacity (Givoni, 2007). Some empirical evidences show that the per passenger impact on LAP and climate change due to airline emissions is higher than the impact due to HSR (Givoni, 2006; Givoni and Banister, 2006; Janic, 2003, 2011). For instance, Givoni and Banister (2006), based on the Heathrow-Paris route, report that the toxicity factor of LAP emission is 9,760 for air and 5,882 for HSR. On the same route, NOx (CO2) emissions are 192.55 (43,265) grams for air and 17.57 (7,194) for a HSR journey1.

The objective of this paper is to provide a simple framework for the analysis of the impact of air transport and high speed rail substitution on the environment and social welfare when intermodal competition takes place. Indeed, though HSR is greener than air on a per-passenger base, the introduction of HST services does not necessarily lead to environmental advantages, even if such

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1 Rail operations result in high levels of noise at high speeds (Brons et al., 2003; Ruijgrok, 2000). However, the impact (the actual noise heard and number of people exposed to it) is lower than can be expected. This happens since, in densely populated areas, speed is reduced far from the station due to the distance required for the train to stop.
introduction results in the increase of the HSR modal share and the decrease in the aircraft modal share. These advantages depend on the balance between the substitution effect (how many passengers using the high speed train are shifted from the aircraft and the car) and the traffic generation effect (how much new demand is generated by the HSR). In this direction, the debate has focused on the case of intermodal integration, where the net environmental effect depends on what happens with freed runway capacity at the airport. If this capacity is used to accommodate more flights and to meet more demand, there would be no environmental gains from mode substitution (Givoni and Dobruszkes, 2013a,b; Givoni and Banister, 2006). However, the net environmental effect can be negative even in the case of intermodal competition, since the introduction of the new transport mode often results in additional demand “generated”.

In view of these considerations, it would be useful to have an analytical framework that addresses environmental issues of mode substitution rigorously. Our contribution is threefold.

First, we build a very simple model to show out the basic mechanisms that regulate the trade-off between the substitution effect and the traffic generation effect affecting environment when modes competition takes place. While assuming that the airline is a private profit maximizer and the HSR is a public subject maximizing a weighted sum of profit and social welfare, we show that the introduction of HSR, even if greener of on a per-passenger base, may have a net negative effect on environment. The reason is that it may result in additional demand. We will make some accompanying simplifying assumptions (like linear demand functions or the absence of economies of density). Although this has some drawbacks in terms of generality, it has the advantage of making decisions of operators very explicit, and it allows for interpretable solutions and expressions.

Second, we incorporate into the model some specific engineering features of the two transport modes that are frequency and speed. Frequency is an important aspect to take into account since competition resulting from the introduction of HST services might induce airlines and HSR providers to increase service frequency in order to protect their market share. Evidence shows that this is detrimental for environment, since the lower the load factor achieved, the higher is the environmental cost per

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2 When air and rail integration takes place, airlines may try to achieve capacity releases by substituting short-haul flights by alternative short distance feeders with high speed trains. For instance, this is the case in Germany where Deutsche Bahn serves Lufthansa’s passengers on the routes from Frankfurt airport to Stuttgart and Cologne. This so called slot-substitution is especially important for airlines that operate at congested airports with capacity restrictions, since it allows them to use the freed up slots for new routes or operate with higher frequency on existing routes. This may also benefit airports: since short-haul flights are often replaced by medium- or long-haul flights, they may gain from higher overall passenger numbers and increased landing fees (Vesperman and Wald, 2011).
passenger from the operation of each mode (Givoni, 2007). On the other hand, airlines may tend to reduce the size of the aircraft used in order to keep load factors high while offering high frequency services. On short-haul routes, this phenomenon is even more apparent. Empirical evidence shows that decreasing aircraft size and adjusting the service frequency to offer similar seating capacity will increase the environmental impact (Givoni and Rietveld, 2010). Our model points out analytically these mechanisms and shows that, when airlines and HSR decide on frequencies, there may be environmental disadvantages if load factors are not met. Similarly, speed should reserve attention: since trains do not necessarily follow the direct route, HSR can have incentive to increase speed of HSTs in order to reduce travel time. This affects the environment, since its impact depends on the marginal energy consumption which is mainly proportional to cruising speed. In the scenario in which HSR decides on speed, we show that the net environmental impact of HSR introduction may be negative when the HSR marginal increase in emissions (per seat per kmh) is sufficiently high.

Third, we examine the effects of modes competition on social welfare when environmental externalities are taken into account and we show that the introduction of HSR may be detrimental for society.

To the best of our knowledge, the existing literature has mainly focused on the competition aspects of airline-HSR interaction, with an empirical approach (Behrens and Pels, 2012; Dobruskes, 2011; Gonzalez-Savignat, 2004; Park and Ha, 2006), a game theory setting (Adler et al., 2010) or an analytical perspective (Yang and Zhang, 2012). More recently, some contributions have examined the possibility of airline-HSR cooperation and its potential benefits for airlines and the society. Again, these are mainly empirical papers (Cokasova, 2006; Givoni and Banister, 2006; 2007), while only few works addressed such issue analytically (Jiang and Zhang, 2014; Socorro and Viciens, 2013). Besides, the environmental impact of air-rail substitution has been mostly object of empirical analysis based on case studies on specific routes. Janic (2011) deals with an assessment of the potential savings in the quantities and related costs of airport side congestion and delays, noise, and emissions of greenhouse gases, which could be achieved by substituting some short-haul flights with equivalent HSR services at London Heathrow. Givoni and Banister (2006) evaluate the environmental benefits from aircraft and HST substitution for the London Heathrow-Paris Charles de Gaulle route. Their evaluation shows, on a per passenger base, a clear and significant reduction in the effect of climate

3 The marginal energy consumption is lower during the accelerating/decelerating phase of a trip and higher - but reasonably constant - during cruising at a constant speed of about 250 km/h (Janic, 2011).
change and, though less significant, in local air pollution. Similar results have been later confirmed on the same route (Givoni, 2007) and on the London-Manchester route (Myoshi and Givoni, 2012). Because of the criticality of ridership in environmental assessments, induced demand is often cited as a critical input for understanding future HSR performance (Åkerman, 2011; Behrens and Pels, 2012, Cheng, 2010; Chester and Ryerson, 2014; Hensher, 1997; Hsu et al., 2010; Lynch, 1990; Wang and Sanders, 2011). In circumventing the need for ridership forecasts, ridership has been considered parametrically (Chester and Horvath, 2012, Jamin et al., 2004 and Ryerson and Hansen, 2010), or through assumptions. Other studies explore the sensitivity of environmental performance to ridership, finding that ridership uncertainty can tip the balance to either mode (Burgess, 2011, Chester and Horvath, 2012 and Sonnenberg, 2010). Socorro and Viciens (2013), with a theoretical model, examine the effects of HSR and airlines integration. When there are no capacity constraints, they found that integration reduces the level of pollution emitted by the aircraft if this allows the airline to reduce the number of passenger carried by the plane. However, when there are capacity constraints, the environmental benefits diminish if any freed runway capacity is used to meet more demand for air travel.

This brief survey of literature shows that the overall environmental benefits gained from substitution have been analyzed either from an empirical perspective or – if an analytical angle is adopted – within the scope of airline and HSR integration only. We move a step further, analyzing these issues when air and rail compete while including some important engineering aspects. Besides a theoretical perspective, such an exercise is necessary from a policy and managerial perspective. On one hand, the debate around rail versus air, which has been typified with unsubstantiated claims of the greenness of rail, may have led to a blatant bias amongst policy makers when considering future transport policy. On the other hand, airline-HSR cooperation can involve substantial investment in access/connecting facilities and management time and effort. A better understanding of its impact is necessary and timely given that many countries are successfully launching HSR lines, like China, Britain, France,

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4 Givoni et al. (2009) examine the environmental impact from rail transport and show how referring to rail as green has many limitations and can be misleading. Attention is focused on comparing different trains (e.g. diesel vs. electric, and in the latter examining how environmental impacts depend on the sources used to generate the electricity) and the scope for improving the environmental performance of rail through technical and operational measures. Nevertheless, some attention is also paid on comparing different modes (train vs. car and plane), so that the paper can be of interest to the reader in our context.

5 While the paper by Socorro and Viciens (2013) is the most relevant work to ours, we recognize that their results depend on strong assumptions about hub airport capacity and airlines’ priorities for different markets. In particular, they assumed that the airlines have a given order of importance for different markets, and fulfill all demands in one market before they consider the demands in another market.
Spain, Germany, Italy, Belgium, the Netherlands and South Korea. Many others, like Brazil, India, Russia, Turkey, the UK and the US are evaluating the options of investing in HSR (Fu et al., 2012).

The structure of the paper is as follows. Section 2 presents the basic model and main results with respect to the effects of competition between air and HSR on environment and social welfare. Section 3 describes some extensions of the basic model with respect to the frequency and the speed. Section 4 presents numerical simulation for all scenarios, while Section 5 contains some concluding remarks.

2. The basic model

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

$$\tilde{T}_i := a_i + t_i + d_i$$  \hspace{1cm} (1)

where $a_i$ is the access time, $t_i$ is the travel time and $d_i$ is the expected schedule delay of transport mode $i$\textsuperscript{6,7}. Usually, air service results in a lower in-vehicle time for most of the routes, i.e. $t_A < t_H$, since trains do not follow the direct routes due to the orography of the territory. For example, distance as the crow flies (vs. HSR distance) are 481 km (621 km) between Madrid and Barcelona, 398 km (524 km) between Paris and Amsterdam and 435 km (621 km) between Munich and Cologne (according to OAG and Thomas Cook, 2011). However, passengers in general need to spend more access/egress time for a flight, owing to the fact that airports are usually located far away from city centers (Adler et al., 2010; Gonzales-Savignat, 2004; Jiang and Zhang, 2014; Yang and Zhang, 2012). As a result, the total journey time may vary across the two modes. Let $\delta$ denote the difference (positive or negative) between the total journey time between the two modes, i.e., $\delta = \tilde{T}_A - \tilde{T}_H$, and

\textsuperscript{6} Schedule delay represents the time between the passenger's desired departure time and the actual departure time. It was introduced by Douglas and Miller (1974) as the addition 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 here. Hence, our schedule delay corresponds only to frequency delay (see also Basso, 2008).

\textsuperscript{7} Without loss of generality, we let $a_i$ denote the sum of access and the egress time. 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 (ATAG, 1998; DCAG, 2009; EC, 2006; IATA, 2003; Janic, 2011; KITE, 2009).
\( \nu > 0 \) be the passenger value of time. With these specifications, the full prices perceived by travelers are, respectively:

\[
\begin{align*}
\theta_A &= p_A + T \\
\theta_H &= p_H
\end{align*}
\]  

(2)

where \( p_i \) is the ticket price of transport mode \( i \) and \( T = \nu T' \) is a parameter measuring some quality differentiation between the two modes in a vertical sense\(^8\). Other things equal, as \( T \) increases, e.g. when the total journey time of high speed rail reduces with respect to the total journey time of air, HSR becomes a more attractive transport mode. This modeling allows assessing the importance of total journey time, other than ticket price, in passenger choice. Indeed, empirical evidence show that this is the most important quality differentiators between the two modes (Adler et al., 2010; Behrens and Pels, 2012; DACG, 2009), accounting for 80% - 90% of the reasons for choosing to travel by air or high speed rail for given fares (Cokasova, 2006).

Facing this set of full prices, (homogeneous)\(^9\) travelers maximize a quadratic strictly concave utility function, as proposed by Singh and Vives (1984). This approach has been used transport literature (Clarks et al. 2009) and, in particular, in air transport literature (Oum and Fu, 2007; Flores-Fillol and Moner-Colonques, 2007; Socorro and Viciens, 2013; Clark et al., 2009, 2011). Let \( q_A \) and \( q_H \) be the number of passengers travelling by air or high-speed train, respectively. The utility function is of the type:

\[
U(q_A, q_T) = \alpha_A q_A + \alpha_H q_H - \frac{1}{2} (q_A^2 + q_H^2 + 2\beta q_A q_H)
\]  

(3)

The parameter \( \beta > 0 \) measures the degree of substitutability between the two modes evaluated on dimensions other than total journey time (which attain to vertical differentiation between the two modes). Indeed, some other factors may affect passengers’ choice. First, there are reliability, punctuality, safety, on board comfort and customer service (ATAG, 1998; IATA, 2003; Cokasova, 2006; EC, 2006; LINK, 2009). Cultural/personal mode preference (IATA, 2003; Grimme, 2007) or

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\(^8\) Without loss of generality, we normalize \( \nu T_H = 0 \). Thus, HSR operating costs, \( c_H \), and price, \( p_H \), are net of \( \nu T_H \). The approach also applies to the extensions of the basic model (see Section 3).

\(^9\) In this paper, we abstract away from the case of heterogeneous passengers and price discrimination, since our focus is on engineering aspects. However, a further note on time and price factors is that their importance varies with the demand segment that is considered. Some empirical evidence show that leisure passengers are more sensitive to travel price than business travelers (who pay more attention to travel time) (Behrens and Pels, 2012; Cokasova, 2006; AEROAVE, 2011). The reader may refer to Yang and Zhang (2012) for a competition model with heterogeneous passengers.
marketing (e.g., product awareness, Internet distribution, product positioning) (ATAG, 1998; IATA, 2003; EC, 2006; HERMES, 2010) may also play a role. Larger values of $\beta$ indicate more substitutable services: it ranges from zero, when the two modes are independent, to one when they are perfect substitutes. Besides, 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 $i$. For the sake of simplicity, we shall assume in what follows $\alpha_A = \alpha_H^{10}$.

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

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

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 $q_i$ is:

$$\theta_i = \alpha - q_i - \beta \cdot q_{-i}$$

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:

$$p_A = \alpha - T - q_A - \beta q_H$$

$$p_H = \alpha - q_H - \beta q_A$$

From (6), it is easy to see how this model, in a non-address setting, enables an assessment of the importance of (horizontal and vertical) differentiation in the demand for travel when two modes compete.

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 ($i = A$) seats or HST ($i = H$) seats 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$^{11}$ for both modes. With fixed load factors and sizes, prices per passenger and per flight/HST ride are equivalent and the profit of mode $i$ can be written as:

10 Note that $\alpha_i$ measures service quality in a vertical sense, so the case of the two modes being vertically differentiated on dimensions other than total journey time is abstracted away from the analysis.

11 We shall relax this assumption in Section 3.1, when operators endogenously decide the schedule frequency.
\[ \pi_i(q_A, q_H) = [p_i(q_A, q_H) - c_i] q_i \] 

where \( p_i(q_A, q_H) \) is the price per-passenger and \( c_i \) is the unit (per seat) variable cost of transport mode \( i \) and the fixed costs of operating a flight (HST ride) are assumed to be zero. Swan and Adler (2006) show that operating cost of a flight increases linearly over aircraft capacity for short and long haul flights. On the other hand, several researchers have found that HSR travelling at higher speeds would require higher per-seat cost (Bousquet et al., 2013; Kemp, 2004; Garcia, 2010). We will include this engineering specification in Section 3.2, where we examine the case in which the HSR operator endogenously decides the speed of the HST. For the sake of simplicity, instead, we shall assume that the unit (per seat) marginal cost is constant in the basic model (Jiang and Zhang, 2014).

Finally, it is commonly believed that the unit (per seat) variable cost of air transport is larger than that of HSR. For instance, Yang and Zhang (2012), report values of \( c_A = 200 \) and \( c_H = 150 \) (Chinese currency unit) based on their best estimates. Therefore, in what follows we shall assume constant marginal operating costs such that \( c_A > c_H \).

While the deregulation and privatization process in the airline industry makes it is reasonable to assume that airlines maximize profits, the HSR decision maker may also take into other objectives. Indeed, in some cases HSR operators are owned by government or, even in cases in which they are private companies, like Europe, the networks are often co-invested by public administrations due to the huge capital requirements. Moreover, different groups of owners, i.e. the State and the private company, are likely to put different weights on social welfare and profit since they pursue different goals. In light of these considerations, we assume that HSR is a privatized firm that is jointly owned by both public and private sectors, and the airline is a pure private firm. The public sector owns \( x \in [0,1] \) shares in HSR, which maximizes a weighted sum of his profit and social welfare, thus also taking into account the surplus of consumers and the surplus that the other transport operator brings about. The social welfare is:

\[ W(q_A, q_H) = U(q_A, q_H) - (c_A + T)q_A - c_H q_H \] (8)

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12 Note that, since we assume 100% load factor, aircraft capacity coincides with the total number of passengers served by the airline.

13 For instance, in China, they are owned by the Ministry of railways of Chinese Central Government. Similarly, in Italy, Trenitalia is 100% shareholded 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.
Thus, HSR objective function is:

\[(1 - \delta)\pi_H(q_H) + \delta W(q_A, q_H)\]  

(9)

where \(\delta = \delta(x)\) with 0 \(\leq \delta(x) \leq 1\) may be referred to as the “weight” on welfare relative to profits. If HSR is fully privatized (i.e., \(x = 0\)), \(\delta\) becomes zero and HSR maximizes profits (Adler et al., 2010). If HSR is fully nationalized (i.e., \(x = 1\)), \(\delta\) becomes one and HSR maximizes social welfare. If the shares owned by the government increase, then \(\delta\) increases. Formally we make the following assumption, that is \(\delta(x)\) is continuous, non-decreasing, with \(\delta(0) = 0\), and \(\delta(1) = 1\).

A similar approach has been proposed in the literature developed to discuss the welfare consequences of partial privatization of a public firm in mixed oligopolies (Ishibashi and Kaneko, 2008; Fujiwara, 2007; Matsumura, 1998; Saha, 2009).

2.1 Effects on environment

In this section, we examine a basic case in which the competition between the two modes is à la Cournot. Thus, the airline and the HSR operator decide quantities and solve simultaneously the following decision problems:

\[
\begin{align*}
\max_{q_A} \quad & (p_A(q_A, q_H) - c_A)q_A \\
\max_{q_H} \quad & (1 - \delta)[p_H(q_A, q_H)q_H - c_H] + \delta W(q_A, q_H)
\end{align*}
\]

(10)

where \(p_i(q_A, q_H)\) are prices per flight/train ride. It is straightforward to derive equilibrium solutions for the basic model (the superscript * stands for equilibrium):

\[
\begin{align*}
q_A^* &= \frac{[\alpha - (c_A + T)](\delta - 2) + \beta(\alpha - c_H)}{2(\delta - 2) + \beta^2} \\
q_H^* &= \frac{[\alpha - (c_A + T)]\beta + 2(c_H - \alpha)}{2(\delta - 2) + \beta^2}
\end{align*}
\]

(11)

In order to analyze the impact on environment of competition between HSR and airline 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 \(\theta_M = \alpha - q_M\) where \(\alpha\) 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 $T$ measures the value of time perceived by air travelers when air is the only available transport mode to travelers. We easily obtain that $p_M(Q_M) = \alpha - T - q_M$. 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:

$$q_M^* = \frac{\alpha - T - c_A}{2}$$  \hspace{1cm} (13)

**Lemma 1** The introduction of High Speed Rail in the market for travel results in lower air market share, i.e. $q_M^* > q_A^*$, and additional demand generated, i.e., $\Delta q = q_H^* + q_A^* - q_M^* > 0$.

**Proof**

At the equilibrium, it results:

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

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

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

Proof of Lemma 1 can be found in the Appendix. Empirical evidence confirms theoretical predictions on the traffic generation effect of standard IO literature. Although assessing induced traffic is difficult (Bonsall, 1996; Givoni and Dobruszkes, 2013a; Mokhtarian et al., 2002), data collected in the aftermath of HSR launches in Asia and Europe suggest that induced traffic ranges from 6% to 37% of HSR ridership (Givoni and Dobruszkes, 2013b). Estimates related to different periods starting from 1980 indicate that induced demand on the Paris-Lyon route accounted for 29% of total HSR traffic; in the Madrid-Seville route it was 50%, Madrid-Barcelona 20%, Paris-Brussels 11% and on the London-Paris it was 20% (Preston, 2009). The share of newly generated demand for the UK London-Midlands-North England HS2 project is expected to reach 32% for 2043 (IEA, 2011).
In order to analyse the environmental impact of HSR introduction, we will focus on LAP and climate change emissions during the phase of operation\textsuperscript{14}. In terms of LAP, the most significant emissions from commercial aircrafts comprise five air pollutants: hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO\textsubscript{x}), sulfur dioxide (SO\textsubscript{2}) and particulates (PM) (EPA, 1999; Seinfeld and Spyros, 2012). Let assume that for each passenger the aircraft emits an overall level of pollution (including LAP, or climate change or an equivalent aggregate of both of them\textsuperscript{15}) denoted by $e_A$, while the HST emits a level of pollution denoted by $e_H$. We shall assume that $e_A > e_H$. This assumption is justified. Measures of human toxicity factors for NO\textsubscript{2}, SO\textsubscript{2} and PM\textsubscript{10} when emitted to air show an advantage per passenger to the high speed train (HST) over the aircraft (Givoni and Banister, 2006; Huijbregts et al., 2000). The main gain relates to the level of SO\textsubscript{2} emissions related to HST operations, which depends mostly on the share of coal – or other energy sources – used to generate the electricity (Button, 1993). Usually, power plants are located away from densely populated areas, which means that the actual impact from HST operations on LAP is lower than suggested by the mix and amount emitted due to a relatively low number of people exposed to the emissions (Givoni, 2006). In terms of climate change, the impact of aircraft operations is higher than the impact of the HST due to higher emission rates of CO\textsubscript{2} and NO\textsubscript{x}. Moreover, NO\textsubscript{x} emissions at high altitude affects climate change much more than emissions at ground level (Archer, 1993; Rietveld et al., 2001; Schipper, 2004).

Let $E$ denote the overall environmental benefit of HSR introduction due to the traffic generation effect. We define $E$ as:

$$E(q_M, q_A, q_H) := e_A q_M - (e_A q_A + e_H q_H) \quad (14)$$

If $E(q_M, q_A, q_H) > 0$, then competition between HSR and air is beneficial for the environment.

\textsuperscript{14} In fact, phases other than operation in the life-cycle analysis of both modes need attention (ERA, 2011). These phases (construction/production, maintenance and disposal) can be responsible for significant environmental impact. The effects relating to the construction of rail infrastructure, for instance, include emissions from building a new line as well as land take, affecting landscape, townscape, biodiversity and heritage (Kageson, 2009; Westin and Kageson, 2012). Nevertheless, they are not considered to be significantly affected by aircraft and HST substitution (CfIT, 2001; Givoni et al., 2012), since mode substitution does not necessarily lead to changes in infrastructure and take place through the existing one.

\textsuperscript{15} Summing total emission across pollutants is meaningless since different pollutants have different nature and degree of impact.
**Proposition 1** If High Speed Rail is not sufficiently greener than air transport, i.e., if \( e_H/e_A > \beta/2 \), airline and HSR competition will increase the environmental pollution.

**Proof**

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

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

since \( q_H^* = \beta[\alpha - (c_A + T)]\beta + 2(c_H - \alpha)/[2(\delta - 2) + \beta^2] > 0 \), \( 0 < \beta < 1 \), \( 0 < \delta < 1 \). 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 \( e_H/e_A > \beta/2 \).

The intuition is as follows. The introduction of a new mode of travel involves 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 traditional rail passengers or people taking car)\(^{16}\). 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 demand. At the equilibrium, it result \( e_H q_H^* > e_A (q_M^* - q_A^*) \) and competition from the new mode is detrimental for the environment, i.e. \( E(q_M^*, q_A^*, q_H^*) < 0 \). As opposite, if the airline is much more pollutant than HSR, competition from the new mode is beneficial to the environment. The reason is that former airline passengers are shifted to a much cleaner mode of transport and the amount of pollution saved is higher than that due to newly generated demand. At the equilibrium, it results \( e_H q_H^* < e_A (q_M^* - q_A^*) \) and, thus, a positive benefit 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 for the environment. Since there is a traffic generation effect, this depends on the performance of the HST. For instance, the operation of electric trains – used on high speed and intercity routes – results

\(^{16}\) For instance, EC (1998) found that former airline passengers accounted for 42% of HSR ridership between Madrid and Seville, while Cascetta et al. (2011) found that traditional rail passengers accounted for 69% of HSR ridership between Rome and Naples.
in significantly less CO\textsubscript{2} emissions than diesel trains\textsuperscript{17}. However, the extent to which electric trains can be regarded as being significantly more climate friendly than other modes – like air – depends on the mix of energy sources used to generate the electricity (Givoni et al., 2013). Generally speaking, the more renewable and nuclear energy used to generate electricity, the more climate friendly rail operations would become. Some methods to reduce SO\textsubscript{2} and other gas emissions from power plants include switching to low-sulfur fuel oil, filtering stack emissions, and shifting to natural gas as an alternative fuel (Chaaban et al., 2004). Nevertheless, the generation mix for train electricity is heavily constrained from the country in which HSR operates – electricity sources available, dispatch merit rules, topology of the electricity grid. In this sense, the switch to greener energy is not as much a strategy of the rail operator but an exogenous factor.

From Proposition 1 we can observe that the higher the substitutability between the two modes, the less likely that the competition from HSR is detrimental for environment. Indeed, it is easy to see that 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 substitutability $\beta$. This means that the extent to which the constraint $e_H/e_A > \beta/2$ can be satisfied is more limited.

\textbf{Proposition 2} When HSR is sufficiently greener than air transport, i.e., $\forall(e_A,e_H)$ with $e_H/e_A < \hat{e}$ and $\hat{e} > 0$, the benefit on environment of competition between air and HSR, $E(q_M^*,q_A^*,q_H^*)$, is increasing in the substitutability between the two modes of transport, $\beta$. Moreover, $\forall(e_A,e_H)$ with $e_H/e_A < \beta/2 < \hat{e}$. $E(q_M^*,q_A^*,q_H^*)$:

(a) is increasing in the market size, $\alpha$;

(b) is increasing in the time-dimension differentiator, $T$;

(c) is increasing in the weight on welfare relative to profit for the HSR, $\delta$.

\textbf{Proof}

At the equilibrium, it results:

\textsuperscript{17}The difference is a result of greater technical efficiency for electric trains, different operating conditions (fewer stops i.e. less energy used for acceleration) and, crucially, the CO\textsubscript{2} content of electricity. For instance, the reader may refer to ATOC (2007) and DEFRA (2007) for some exercises on comparisons of CO\textsubscript{2} emissions from diesel and electric trains operations in the UK (operation data for 2006/2007).
\[
\frac{\partial E(q^*_M, q^*_A, q^*_H)}{\partial \beta} = \frac{e_h[(\alpha - (c_A + T))(4 + \beta^2 - 2\delta) - 4\beta(\alpha - c_H)]}{(-4 + \beta^2 + 2\delta)^2} + \frac{e_A[(\alpha - (c_A + T))(2\beta(-2 + \delta)) - ((4 + \beta^2 - 2\delta)(\alpha - c_H))]}{(-4 + \beta^2 + 2\delta)^2}
\]

Let denote \([((\alpha - (c_A + T))(4 + \beta^2 - 2\delta) - 4\beta(\alpha - c_H))] = \Gamma \) and \([((\alpha - (c_A + T))(2\beta(-2 + \delta)) - ((4 + \beta^2 - 2\delta)(\alpha - c_H)))] = \Theta\). It is easy to demonstrate that \(\Theta > 0\) when \(q^*_A > 0\) and \(q^*_H > 0\). Therefore, when \(\Gamma \geq 0\) \(\partial E(q^*_M, q^*_A, q^*_H)/\partial \beta > 0\) always holds. When \(\Gamma < 0\), \(\partial E(q^*_M, q^*_A, q^*_H)/\partial \beta > 0\) holds when \(-\Gamma e_H + \Theta e_A > 0\), that is when \(e_H/e_A < \Theta/\Gamma = \hat{e}\).

(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 \(e_H/e_A < \beta/2\). It follows \(\partial E(q^*_M, q^*_A, q^*_H)/\partial \alpha > 0\). It easy to demonstrate that when \(q^*_A > 0\) and \(q^*_H > 0\), \(\beta/2 < \hat{e}\).

(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 \(2e_H - \beta e_A < 0\), it follows \(\partial E(q^*_M, q^*_A, q^*_H)/\partial T > 0\).

(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 \(\partial E(q^*_M, q^*_A, q^*_H)/\partial \delta > 0\).

The intuition behind Proposition 2 can be easily drawn. It can be easily seen that: (i) \(d\Delta q/d\alpha > 0\) and (ii) \(dq^*_H/d\alpha > 0\), \(dq^*_A/d\alpha > 0\), \(d(q^*_M - q^*_A)/d\alpha > 0\). Thus, the higher the market size the higher is the traffic induced by competition. Besides, the higher the market size the more passengers
are diverted towards HSR: though both \( q_H^* \) and \( q_A^* \) increase with \( \alpha \), the quantity of passengers taking air increases proportionally less than what would have happened absent competition from HSR. Thus, if the airline is much more pollutant than HSR, the increase in HSR emissions due to the newly generated demand is compensated by the fact that increasingly more passengers are diverted toward the cleaner mode of transport. A quite similar argument can be applied to the effect of \( \beta \). Other things equal, as \( T \) increases, e.g. when the total journey time of HSR reduces with respect to the total journey time of air, HSR becomes more attractive. Indeed, it results \( dq/dT > 0 \) with \( dq_H/dT > 0 \) and \( dq_A/dT < 0 \). At the same time, \( d(q_M^* - q_A^*)/dT > 0 \) and increasingly more passengers are diverted towards the greener transport mode. Finally, it is easy to demonstrate that \( d\Delta q/d\delta \) with \( dq_H/d\delta > 0 \) and \( dq_A/d\delta < 0 \). Thus, when the weight on welfare relative to profit for the HSR is higher and higher, increasingly more passengers take HSR relative to air. The increase in HSR emissions due to its increased traffic is compensated by the decrease in the (very pollutant) airline traffic. \( \beta \) measures the substitutability between the two modes: as \( \beta \) increases, though the sign of \( dq_H/d\beta \) and \( dq_A/d\beta \) is not determined, it still holds \( d\Delta q/d\beta < 0 \). Thus, at the equilibrium, the traffic generation effect decreases when the substitutability between the two modes is higher and higher; if the airline is much more pollutant than HSR, the increase in total emissions is compensated by the fact that newly generated demand decreases.

We note that when \( e_H/e_A < \beta/2 \), airline and HSR competition is beneficial for 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 \( z \in \{\alpha, T, \delta, \beta\} \) that is the positive effect increases with the size of the market, the time differentiator, the HSR weight on welfare relative to profits and the substitutability between the two products. As opposite, when \( \beta/2 < e_H/e_A < \bar{e} \), airline and HSR competition is detrimental for the environment, i.e., \( E(q_M^*, q_A^*, q_H^*) < 0 \). Moreover, \( \partial E(q_M^*, q_A^*, q_H^*)/\partial z < 0 \) with \( z \in \{\alpha, \delta, \beta\} \) while \( \partial E(q_M^*, q_A^*, q_H^*)/\partial \beta > 0 \). Thus, an increase in in the size of the market, the time differentiator or the HSR weight on welfare relative to profits exacerbates the environmental damage, while an increase in the substitutability still mitigates it. Finally, when \( e_H/e_A > \bar{e} \), airline and HSR competition is still damaging for the environment and \( \partial E(q_M^*, q_A^*, q_H^*)/\partial h < 0 \) with \( h \in \{\alpha, T, \delta, \beta\} \), but even an increase in \( \beta \) starts exacerbating the environmental damage. The reason is that \( d\Delta q/d\beta < 0 \) and \( d\Delta q/d\delta > d\Delta q/dz \) with \( z \in \{\alpha, T, \delta\} \). In other words, the impact of \( \beta \) on the traffic generation effect is negative and lower than that one of \( \alpha, T \) and \( \delta \).

### 2.2 Effects on social welfare
In this section, we seek to assess the effects on social welfare of competition between HSR and air, when the environmental impact of introducing a new mode of traveling matters for society. In particular, let define

\[ W^C = U(q_A, q_H) - (c_A + T)q_A - c_H q_H - (\varepsilon_A q_A + \varepsilon_H q_H) \]
\[ W^M = U(q_M) - (c_A + T)q_M - (\varepsilon_A q_M) \]

where \( U(q_M) = q_M - (1/2)q_M^2 \) and \( \varepsilon_i = \varphi e_i \) is the (per-passenger) environmental cost of damage due to mode \( i \). The parameter \( \varepsilon_i \) is obtained by multiplying emissions, \( e_i \), of the relevant pollutants and gasses by the cost of damage, \( \varphi > 0 \), from LAP or climate change impacts. Cost estimates for \( \varphi \) are provided, for instance, by Dings et al. (2003) and a more detailed analysis can be found in Section 4 were simulation is provided for the model \(^{18}\). Here, we assume that \( \varepsilon_A > \varepsilon_H \), that is the environmental damage due to air is greater than the damage due to HSR.

Thus, we evaluate the overall loss caused by HSR introduction as \( \Delta W(q_A, q_H, q_M) = W^M(q_A, q_H, q_M) - W^C(q_A, q_H) \). When \( \Delta W(q_A, q_H, q_M) > 0 \), then competition is detrimental for social welfare\(^{19}\).

**Proposition 3** There exists a value \( \bar{e} > 0 \) such that \( \forall (e_A, e_H) \) with \( e_A - (2/\beta) e_H < \bar{e} \) it results \( \Delta W(q_A^*, q_H^*, q_M^*) > 0 \), that is when the airline is sufficiently low pollutant, the total social welfare is higher under the monopoly case rather than in the competition case.

**Proof**

\(^{18}\) Schipper et al. (2001) provides a useful discussion on the evaluation of environmental externalities in air transport markets and the problem of assigning a monetary value to the damage imposed.

\(^{19}\) HSR introduction, while expanding the catchment area and improving accessibility of areas served by stations, may actually induce some direct and indirect benefits, like spatial labor market relocation effects, spatial labor market size and matching effects, international labor market effects or additional consumer benefits (Elhorst and Oosterhaven, 2008; Melo et al. 2009; 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). Indeed, we concentrate on traffic relocation (and generation) effects over a specific route while any examination of an HSR line’s indirect benefits must consider a wider geographic area than just the cities on the line and, therefore, must consider integration between transport networks, especially between the high-speed and conventional rail (Martínez Sánchez-Mateos and Givoni, 2012). Any examination of all positive and negative externalities on the overall welfare, that is out of the scope of this paper, is actually needed and may reserve attention in future developments of this work.
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 $e_A$, that is it reduces when the (per passenger) environmental damage due to airline increases. Indeed,

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

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

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

In particular, it results $\bar{e} > 0$. Indeed:

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

Moreover, at the equilibrium – when $q_A^* > 0$, $q_H^* > 0$ and $q_M^* > 0$ – it’s easy to demonstrate that show that $\bar{e} > 0$ if $c_H = 0$. Therefore, $\bar{e} > 0 \ \forall c_H > 0$. Thus, $\forall (e_A, e_H)$ such that $e_A - (2/\beta)e_H < \bar{e}$, $\Delta W(q_A^*, q_H^*, q_M^*) > 0$.

The intuition behind Proposition 3 can be derived as follows. The introduction of a new mode of transport induces an increase in the overall demand for travel. This is beneficial for the society. Indeed, there is a gain $U(q_A, q_H^*) - U(q_M^*)(q_A^* - q_M^*) - c_H q_H^* > 0$. However, competition from the new mode may be detrimental for the environment: when the airline is sufficiently low pollutant, this gain – obtained from shifting former air passengers to the (not sufficiently much greener) HSR – is not able to compensate the amount of pollution due to newly generated demand. In this case, $E(q_M^*, q_A^*, q_H^*) < 0$. Thus, if environment matters for welfare, this causes a cost $\varphi E(q_M^*, q_A^*, q_H^*)$ that offsets the benefit for the society due to the traffic generation effect.

In particular, the following corollary holds.
Corollary 1 For each $\delta \in [0,1]$, there always exists a value $\bar{e} > 0$ such that $\forall (e_A, e_H)$ with $e_A - (2/\beta)e_H < \bar{e}$, that is when airline is sufficiently low pollutant, the total social welfare is higher under the monopoly case rather than in the competition case, i.e. $\Delta W(q^*_A, q^*_H, q^*_M) = W^M(q^*_A, q^*_H, q^*_M) - W^C(q^*_A, q^*_H) > 0$

Proof of Corollary 1 derives immediately from the proof of Proposition 3. Corollary 1 states that, when the environmental impact of introducing a new mode of transport matters, it may always happen that competition between the two modes is detrimental for society, whatever is the weight of welfare relative to profits chosen by HSR. Intuitively, the more HSR cares about social welfare, the more passengers will be served by the rail operator, i.e., $dq_H/d\delta > 0$. However, these additional travelers are those with lower willingness to pay: while contributing to pollution with the same amount of emissions, they contribute less to surplus. Thus, it is possible that the gain from shifting air passengers to HSR, i.e., $U(q^*_A, q^*_H) - U(q^*_M) - (c_A + T)(q^*_A - q^*_M) - c_H q^*_H > 0$, is not able to compensate the amount of pollution due to newly generated demand, i.e., $E(q^*_M, q^*_A, q^*_H)$. Analytically, it is easy to show that $\partial \bar{e}/\partial \delta > 0 \\forall c_H > 0$, that is the maximum difference between the levels of pollution of the two modes required for HSR being detrimental to the society, i.e., $\bar{e}$, increases with $\delta$: this means that the extent to which the constraint $e_A - (2/\beta)e_H < \bar{e}$ can be satisfied is less limited. Thus, the higher $\delta$, the more likely an overall loss caused by HSR introduction, $\Delta W(q^*_A, q^*_H, q^*_M) > 0$, arises.

Proposition 3 shows that it is not straightforward to say that the introduction of HSR is beneficial for the society. This depends on the scope of any benefit included in the assessment framework. Actually, whether the non-economic benefits should also be factored into the assessment is still an open question (Chiambaretto and Decker, 2012). On 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 intermodal competition (OFT, 2010). In this case, we show that if the impact on environment is taken into account when assessing social welfare, the surplus measure of the traditional approach will fall short of giving a true measure of total social surplus. 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 (Baumol and Oates, 1988; Bromley, D.W, 1995; 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 be 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 appeals and challenges to regulatory decisions from stakeholders.

In this respect, it will be important for competition authorities to specify their approach to ranking and weighting factors in assessments if the incentive to mode competitions is not to be chilled.

### 3. Extensions

In this section, we broaden the analysis to include some engineering 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 choose over frequency. In Section 3.2, we examine the case in which the HSR operator decides on speed.

#### 3.1 Schedule frequency

We will now consider a model of full prices that include both quantities and frequency decisions. Service frequency is an important dimension of the competition between air and HSR, since it affects both airlines choice after market deregulation (Adler et al., 2001) and HSR choice (Chang et al., 2000). In particular, following Flores-Fillol (2009), we assume that frequency of flights offered by a particular airline delivers higher value to passengers and, therefore, determines service quality as a measure of flight flexibility. Following a similar approach for frequency of rides offered by HSR, the full prices perceived by travelers are, respectively:

\[
\theta_A = p_A - \gamma_f f_A + T \\
\theta_H = p_H - \gamma_f f_H
\]

where \(f_i\) is the schedule frequency of transport mode \(i\) and \(\gamma_f\) is the benefit from high frequency\(^{20}\). Introducing frequencies additively in the utility function simplifies the analysis, where higher frequencies reduce the cost of schedule delay. A similar formulation for the airlines industry is also suggested in Heimer and Shy (2006).

We note that the expected schedule delay of transport mode \(i\) becomes now endogenous. This raises an additional argument against a common practice such as applying a single value of time regardless

---

20 We assume that the benefit from high frequency is the same across the two modes of transport available to the travelers.
of which attribute produces the saving, due to the lack of additional information. Gonzalez-Savignat (2004), for instance, finds that the willingness to pay is higher when a saving is produced in the travel time (55 €/hour), and considerably lower when it is a saving in access time (22 €/hour) or an improvement in the frequency of the service timetable (17 €/hour). Following these results, assignment must be avoided of a single value to the total time saved on the journey, as this supposes a simplification that may cause an incorrect evaluation of the social benefits derived from an investment in transport. Following this logic, for the sake of notation, in what follows we shall refer to \( \tilde{T}_i = a_i + t_i \) and \( T = v_a(a_A - a_H) + v_t(t_A - t_H) \), where \( v_a \) represents the willingness to pay when a saving is produced in access/egress time and \( v_t \) when it is a saving in travel time. The willingness to pay when a saving is produced in an improvement in the frequency of the service timetable is now captured by \( \gamma_f \) which, indeed, measures the benefits from higher frequency. In addition to a reduced overall journey time, these benefits may also include increasing choice/travel opportunity 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\(^{21}\).

From equations (5) and (9) it follows that:

\[
\begin{align*}
    p_A(q_A, q_H, f_A) &= \alpha - T - q_A - \beta q_H + f_A \\
    p_H(q_A, q_H, f_H) &= \alpha - q_H - \beta q_A + f_H
\end{align*}
\]

(10)

where \( \gamma_f \) has been normalized to 1 (an assumption that will be further relaxed in Section 4 where simulation of the theoretical model will be run).

Turning to the supply side, the cost of operating a flight is given by \( k_A + c_A \times \text{Aircraft Size} \) where \( k_A \) is the aircraft fixed cost and \( c_A \) is the unit (per aircraft seat) variable cost (Brueckner, 2004; Brueckner and Flores-Fillol, 2007). Similarly, the cost of operating a train ride is given by \( k_H + c_H \times \text{HST Size} \) where \( k_H \) is the HST fixed cost and \( c_H \) is the unit (per train seat) variable cost. Profit of mode \( i \) is \( \pi_i = p_i q_i - f_i(k_i + c_i \times \text{Size}_i) \). Since \( q_i = f_i \times \text{Size}_i \times LF_i \), by assuming 100% load factor, we can write the profit of mode \( i \) is:

\[
\pi_i = (p_i - c_i) q_i - k_if_i
\]

(11)

\(^{21}\) Reliability is a measure of how often a service is subject to severe disruption, for example due to strikes or engineering works. Punctuality is a measure of the proportion of services which run on time, when the service does run (EC, 2006). EC (2006) compares, for instance, a few journeys where rail market share has increased due to these factors.
Similar to what described in the basic model, we assume that the airline maximizes his own profit while HSR a weighted sum of his own profit and consumer surplus, that is:

\[ W(q_A, q_H, f_A, f_H) = U(q_A, q_H) - (T + c_A)q_A - c_H q_H - k_A f_A - k_H f_H \]  

(12)

Thus, the operators solve simultaneously the following decision problems:

\[
\max_{q_A, f_A} (p_A(q_A, q_H, f_A) - c_A) q_A - k_A f_A
\]

\[
\max_{q_H, f_H} (1 - \delta) [(p_H(q_A, q_H, f_H) - c_H) q_H - k_H f_H] + \delta W(q_A, q_H, f_A, f_H)
\]

(13)

It is straightforward to derive equilibrium solutions for the quantities and frequency (* stands for equilibrium):

\[ q_A^* = k_A; \quad q_H^* = k_H; \]

\[ f_A^* = 2 k_A + \beta k_H - [\alpha - (c_A + T)]; \quad f_H^* = \beta k_A + k_H (2 - \delta) - (\alpha - c_H) \]

In order to analyze the impact on environment of competition between HSR and airline we refer to the benchmark case of a monopoly airline. Similarly to what described before, we assume linear demand function. If \( p_M \) denotes the ticket price charged by the monopoly airline, we have \( \theta_M = p_M + T + f_M \) and so \( p_M = \alpha - T - q_M - f_M \), where \( \gamma_f \) again is normalized to 1. The profit for the airline is \( \pi_M = (p_M - c_A) q_M - k_A f_M \); maximization with respect to quantity and frequency lead to \( q_M^* = k_A \) and \( f_M^* = 2 k_A - [\alpha - (c_A + T)] \). It’s easy to check that competition between the two modes leads to market expansion, i.e., \( q_M^* - q_H^* - q_A^* < 0 \). Since \( q_i = Q_i \times Size_i \times LF_i \), the strategic decision on frequency may have an impact on the size of the aircraft in order to meet load factor (or may have an impact on load factors, for given size). It is straightforward to prove Observation 1.

**Observation 1** When a new mode of transport is introduced, the airline increases its frequency, i.e. \( f_A^* > f_M^* \). Moreover, at the equilibrium \( q_M^* / f_M^* - q_A^* / f_A^* > 0 \).

When competition takes place, the airline increases its frequency in order to protect its market share, i.e., \( f_A^* > f_M^* \). This has an impact on load factors, since \( q_A^* / f_A^* = Size_A \times LF_A \). Thus, at the equilibrium, it results \( Size_M \times LF_M > Size_A \times LF_A \). Thus, two scenarios may apply: for a given fleet and aircraft size, load factor reduces after competition, i.e., \( LF_M > LF_A \) or, for a targeted load factor, the carrier may choose to adjust the size of the aircraft such that \( Size_M > Size_A \). In other words, when
a new mode of transport is introduced in the market, airlines may not manage to fill seating capacity or may tend to reduce the size of the aircraft used in order to keep load factors high while offering high frequency services.

Empirical evidence shows that effects on load factor and aircraft size when adjusting frequency may have an impact on environment. For instance, Givoni and Rietveld (2010), based on three case studies – Barcelona–Madrid (BCN–MAD), Sapporo–Tokyo (CTS–HND) and Los Angeles–Chicago (LAX–ORD) routes – show that decreasing aircraft size, switching from an A320 (150 seats) fleet to a B747 (524 seats) fleet and adjusting the service frequency to offer similar seating capacity, would decrease LAP but increase climate change impact. When these impacts are monetized and aggregated, the analysis shows that an overall environmental detriment will result. In addition, decreasing the aircraft size would also increase noise pollution around airports.

We thus measure the environmental impact of market expansion looking at the per-passenger level of emissions. In particular, we evaluate:

\[ \hat{E}(q, f) := \frac{e_A \cdot f_M}{q_M} - \frac{(e_A \cdot f_A^* + e_H \cdot f_H^*)}{q_A^* + q_H^*} \]  

(14)

where \( q = (q_A, q_H, q_M) \) and \( f = (f_A, f_H, f_M) \). \( \hat{E}(q, f) \) measures the difference between the per-passenger 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 \( \hat{E}(q, f) > 0 \), then competition between HSR and air is beneficial for the environment on a per passenger base.

**Proposition 4** If the market size is large enough, that is if \( \alpha > \bar{\alpha} = c_A + T + (2 - \beta) k_A \), competition between HSR and air is always detrimental for the environment, i.e., \( \hat{E}(q, f) < 0 \). Otherwise, it is possible to find a cut off point for the level of emissions, \( \bar{e} > 0 \), such that when \( e_H / e_A < \bar{e} \), that is when the HSR is much greener than air transport, competition between HSR and air is beneficial for the environment, i.e., \( \hat{E}(q, f) > 0 \).

**Proof**

In addition, the reduction in aircraft movements when upsizing aircraft fleet and adjusting service frequency can have two environmental benefits which were not accounted for in the above analysis. First, reduction in aircraft movements can reduce delays, on the ground and in the sky, and therefore reduce flight time leading to lower LAP and climate change impacts. Second, reduction in the number of movements means airport capacity can be maintained or increased without constructing new runways.
At the equilibrium, it results:

$$\frac{\partial \hat{E}(q, f)}{\partial e_A} = \frac{k_H (c_A + T + 2k_A - \alpha - k_A\beta)}{k_A (k_A + k_H)}$$

Thus, when $\alpha > c_A + T + 2k_A - k_A\beta$, then $\hat{E}(q, f)$ is decreasing in $e_A$. In particular, $\frac{\partial \hat{E}(q, f)}{\partial e_A} = 0$ when $e_H/e_A = \bar{e}$ with:

$$\bar{e} = \frac{k_H (c_A + T + 2k_A - \alpha - k_A\beta)}{k_A [c_H - \alpha + k_A\beta - k_H(2 - \delta)]}$$

where $(c_A + T + 2k_A - \alpha - k_A\beta) = f^*_H > 0$.

Hence, if $\alpha > c + T + 2k_A - k_A\beta$, then $\hat{E}(q, f)$ is decreasing in $e_A$ and $\bar{e} < 0$. In this case, $\hat{E}(q, f) < 0$ always holds. On the other hand, if $\alpha < c + T + 2k_A - k_A\beta$, then $\hat{E}(q, f)$ is increasing in $e_A$ and $\bar{e} > 0$. In this case, when $e_H/e_A < \bar{e}$, $\hat{E}(q, f) > 0$ holds.

Proposition 4 shows that it is not straightforward to assert that HSR is greener than air transport on a per passenger base. This depends on the market size and the capacity to meet load factor when both modes of transport decide on frequency. It’s easy to check that $\frac{\partial (q^*_M/f^*_M)}{\partial \alpha} > 0$ and $\frac{\partial (q^*_A/f^*_A)}{\partial \alpha} > 0$, but $\frac{\partial (q^*_M/f^*_M - q^*_A/f^*_A)}{\partial \alpha} > 0$: when the market size increases, the airline load factor rises but, in case of competition from HSR, it increases proportionally less than what would have happened absent competition. In other words, when a new mode of transport is introduced and the airline sets higher frequency there is a negative effect on load factors such that the airline may not manage to fill seating capacity as before competition. This negative effect is more severe as the market size increases since more passengers are diverted toward HSR. Thus, if the market size is not quite high, some constellations may occur such that negative effect on load factors is overcome by the fact that travelers have been choosing a greener mode of transport.

### 3.2 Speed

In this section, we turn back to the case in which the schedule frequency is assumed to be exogenously given but the HSR operator decides on speed. Indeed, as train become faster, HSR is likely to impose a significant competitive pressure on air transport over a relatively large range of distances. In general, on routes of around 300 km, evidence shows that the introduction of HST services almost leads to a withdrawal of aircraft services (e.g. between Tokyo and Nagoya and between Brussels and Paris), while on routes of around 1000 km and above, the HST ceases to be a good substitute for the aircraft.
In between these distances, there is usually direct competition between the modes (Janic, 1993; Givoni, 2006; Rothengatter, 2011; Yang and Zhang, 2012). In particular, let \( s_i \) denote the speed of transport mode \( i \). We consider \( s_A \) being constant, since it is close to the speed of sound and has been relatively stable. On the other hand, rail (maximum) speed can vary a lot and in practice and there are active debates on how fast HSR should be (Givoni, 2006). Since trains do not necessarily follow the direct route, HSR can have incentive to increase speed of HSTs in order to reduce travel time\(^{23}\). We assume that higher train speed delivers higher value to HSR passengers and, therefore, determines service quality. Intuitively, when the total journey time of HSR reduces with respect to the total journey time of air, HSR becomes a more attractive transport mode.

In addition, benefits from higher speed may also include increasing opportunities for passengers in terms of coordination with other transport modes or take advantage of some service 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 may wish to arrive at destination (e.g., Rome) as early as possible to take the last bus or traditional rail ride back home (e.g., to a peripheral city), or to do some ordinary shopping before shops close. 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. In some sense, the formulation is similar to the one adopted to model the impact of frequency on passengers’ full prices. In this framework, we model the full prices perceived by travelers as, respectively:

\[
\theta_A = p_A + T \\
\theta_H = p_H - \gamma_s s_H
\]

(15)

where \( 0 < s_H \leq \bar{s}_H \) and \( \bar{s}_H \) is the maximum train speed operable given the technology. The parameter \( \gamma_s \) measures the benefit for HSR passengers’ from high train speed. Introducing speed additively in the utility function simplifies the analysis, where higher speed reduce the cost of travel time and increases travelers’ willingness to pay.\(^{24}\) From equations (5) and (15), it follows that:

\(^{23}\) For instance, maximum commercial speed is 360 km/h for the Italian Italo ETR 575, 300 km/h for the Italian Trenitalia ETR 500, 250 km/h for the Spanish Alvia Class 120 (300 km/h for the AVE Class 100, 350 km/h for the AVE Class 103), 300 km/h for the Eurostar BR Class 373, 380 km/h for the Chinese CRH380 A&AL, 230 km/h for the Japanese Shinkansen 0 (300km/h for the Shinkansen 500). As far as unconventional rail, the Shanghai Maglev Train reaches 431 km/h during its daily service on its 30 km dedicated line, holding the speed record for commercial train service. Higher operating speeds seem commercially unfeasible at present due to noise problems, high operating costs and other technical problems (Givoni, 2006).

\(^{24}\) Following this logic, for the sake of notation, in what follows we shall refer to \( \tilde{T}_i = a_i + d_i \) and \( T = v[(a_A + t_A + d_A) - (a_H - t_H)] \) where \( v \) is the value of time. The willingness to pay when a saving is produced in an improvement in the travel time is now captured by \( \gamma_s \) which, indeed, includes the benefits from higher speed and thus
\[ p_A = \alpha - T - q_A - \beta q_H \]
\[ p_H = \alpha + s_H - q_H - \beta q_A \]

where \( \gamma_s \) has been normalized to 1 (an assumption that will be relaxed in Section 4).

Turning to the supply side, the profit of the airline is \( \pi_A(q_A, q_H) = [p_A(q_A, q_H) - c_A] q_A \), while the profit of HSR is given by \( \pi_H(q_A, q_H) = [p_H(q_A, q_H) - c_H - c_s(s_H)] q_H \), where \( C_s = C_s(s_H) \) is HSR’s unit (per seat) cost variable with speed. We assume that \( \partial C_s / \partial s_H > 0 \), that is higher speed leads to higher unit cost. This is confirmed by several empirical researches (e.g., Kemp, 2004; Garcia, 2010a,b; Lukaszewicz and Andersson, 2006; 2009; Bousquet et al., 2013) and adopted in a theoretical model by Jiang and Zhang (2012). In particular, in this paper we assume that unit (per seat) cost variable with speed (which is proportional to the energy consumption) is constant, that is it increases linearly with speed. Janic (2003) finds that HSR marginal energy consumption (quantity of energy per unit of output - kWh/pkm) is mainly proportional to 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)\(^{25} \) Lukaszewicz and Andersson (2009)’s estimations on the Swedish case show that the energy consumption increases by a power of 1.1–1.3 of the top speed for the trains running on the dedicated very-high-speed line. For example, if the top speed is increased from 250 to 280 km/h (12 %), energy consumption increases by 13 – 16%. Garcia (2010a,b) reports the relationship, based on estimates on some Spanish routes, between each train vehicle’s output (in kilowatts) and its maximum speed showing a curve that confirms the power of 1.3. Let \( \mu \) be the constant unit (per seat) variable cost with speed of HSR. The profit of HSR is given by:

\[ \pi_H(q_A, q_H) = [p_H(q_A, q_H) - c_H - \mu s_H] q_H \]

where \( \mu < \gamma_s = 1 \), that is the unit (per seat) cost of a marginal increase of speed is lower than the willingness to pay for a marginal increase of speed. Similar to what described in previous models, we assume that the airline maximizes his own profit while HSR a weighted sum of his own profit and social welfare, that is:

\[ W(q_A, q_H, s_H) = U(q_A, q_H) - (c_A + T)q_A - (c_H + \mu s_H)q_H \]

\(^{25}\) Some calculations and measurements (AEA, 2001) have shown that this constant consumption is about 0.19 kWh/pkm for the French TGV trains (Sud-Est, Atlantique, Reseau and Duplex, with an average train capacity is 430 seats/train), or 0.22 kWh/pkm for the German ICE train consumes the average train capacity is 380 seats/train).
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 in quantities. Indeed, deciding on speed actually means deciding on the rolling stock, which is most likely a sunk cost for the operator.\footnote{Once that the rolling stock has been acquired by the operator, leasing practices rarely appear in the HSR industry (as opposite to the airline industry).}

We solve the game by backward induction. In the second stage, the operators solve simultaneously the following decision problems:

\[
\max_{q_A} \ (p_A(q_A, q_H) - c_A) \ q_A
\]

\[
\max_{q_H} (1 - \delta) \ [(p_H(q_A, q_H, s_H) - c_H - \mu s_H) \ q_H] + \delta W (q_A, q_H, s_H)
\]

We thus find the best response functions for \(q_A(s_H)\) and \(q_H(s_H)\):

\[
q_A(s_H) = \frac{[c_H - s_H(1 - \mu)] \beta + (\delta - 2)(T + c_A - \alpha) - \alpha \beta}{\beta^2 + 2(\delta - 2)}
\]

\[
q_H(s_H) = \frac{\alpha (-2 + \beta) - 2s_H(1 - \mu) + 2c_H - (c_A + T) \beta}{\beta^2 + 2(\delta - 2)}
\]

As expected, \(\partial q_A^*/\partial s_H < 0\) while \(\partial q_H^*/\partial s_H > 0\).

In the first stage, the HSR operator maximizes its objective function with respect to the speed. The following decision problem results:

\[
\max_{s_H} (1 - \delta) \ [(p_H(q_A^*, q_H^*, s_H) - c_H - \mu s_H) q_H^*] + \delta W (q_A^*, q_H^*, s_H)
\]

In particular, it is easy to demonstrate \footnote{Indeed, it results \(\partial^2 ((1 - \delta) [(p_H(q_A^*, q_H^*, s_H) - c_H - \mu s_H) q_H^*] + \delta W (q_A^*, q_H^*, s_H)) / \partial s_H \partial \delta > 0\) in the feasible region and \(\lim_{\delta \rightarrow 0} \partial ((1 - \delta) [(p_H(q_A^*, q_H^*, s_H) - c_H - \mu s_H) q_H^*] + \delta W (q_A^*, q_H^*, s_H)) / \partial s_H) = 0\).} that \(\partial ((1 - \delta) [(p_H(q_A^*, q_H^*, s_H) - c_H - \mu s_H) q_H^*] + \delta W (q_A^*, q_H^*, s_H)) / \partial s_H > 0\). Thus, HSR has always incentive to raise its speed and, at the equilibrium, it results:

\(s_H^* = \bar{s}_H\)

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

In order to analyze the impact on environment of competition between air and HSR, we refer to the benchmark case of a monopoly airline. Equilibrium result for \(q_M\) is the same as in the basic case.
model, i.e., \( q^*_M = (\alpha - T - c_A)/2 \). Again, it is easy to check that competition between the two modes leads to market expansion, i.e., \( q^*_M - q^*_H - q^*_A < 0 \).

We shall consider the overall environmental impact of market expansion:

\[
\hat{E}(q^*_M, q^*_H, q^*_A, s^*_H) := e_A - \frac{(e_A q^*_A + e_H q^*_H + \vartheta s^*_H)}{q^*_A + q^*_H^2}
\]

where \( \vartheta \) is the marginal increase in emissions per seat per kmh, that can be expressed by the marginal increase in the level of emissions due to the energy consumption (per kmh per seat).

The following proposition hold.

**Proposition 6** There exists a value \( \vartheta > 0 \) such that \( \forall (e_A, e_H, \vartheta) \) with \( \vartheta > \frac{(e_A - e_H)}{\omega s_H} \) it results \( \hat{E}(q^*_A, q^*_H, q^*_M) < 0 \), that is when the HSR marginal increase in emissions (per seat per kmh) is sufficiently high, the overall level of emission in the competition case is always higher rather than in the monopoly airline case.

**Proof**

At the equilibrium, it results:

\[
\frac{\partial \hat{E}(q^*_M, q^*_H, q^*_A, s^*_H)}{\partial e_A} = \frac{\beta(c_A + T - \alpha) - 2s_H(1 + \mu) - 2(c_H - \alpha)}{(T + c_A + c_H + s_H(-1 + \mu) - 2\alpha)(\beta - 2) + (c_A + T - \alpha)\delta} > 0
\]

Indeed, \( \frac{\partial^2 \hat{E}(q^*_M, q^*_H, q^*_A, s^*_H)}{\partial e_A \partial c_H} = \frac{(c_A + T - \alpha)(\beta^2 - 4 + 2\delta)}{[(T + c_A + c_H + s_H(-1 + \mu) - 2\alpha)(\beta - 2) + (c_A + T - \alpha)\delta]^2} > 0 \)

since \( \alpha > c_A + T, 0 < \beta < 1 \) and \( \mu < 1 \).

Moreover, when \( c_H = 0 \) it results:

\[
\frac{\partial \hat{E}(q^*_M, q^*_H, q^*_A, s^*_H)}{\partial e_A} \bigg|_{c_H=0} = \frac{\alpha(2 - \beta) + 2s_H(1 - \mu) - 2c_H + (c_A + T)\beta}{(c_A + T - \alpha)(\delta - 2 + \beta) + (\beta - 2)(s_H(-1 + \mu) - \alpha)} > 0
\]

Thus, \( \hat{E}(q^*_A, q^*_H, q^*_M) \) is always increasing in \( e_A \). In particular, \( \hat{E}(q^*_A, q^*_H, q^*_M) = 0 \) when \( e_A = e_H + \vartheta s_H(\beta^2 - 4 + 2\delta)/\alpha(2 + \beta) - 2c_H(1 - \mu) + 2c_H - (c_A + T)\beta \), where \( \omega = (\beta^2 - 4 + 2\delta)/\alpha(2 + \beta) - 2c_H(1 - \mu) + 2c_H - (c_A + T)\beta > 0 \). Therefore, \( \forall (e_A, e_H, \vartheta) \) with \( e_A < e_H + \vartheta \omega s_H \), it results \( \hat{E}(q^*_A, q^*_H, q^*_M) < 0 \).
4. Numerical simulation and sensitivity analysis

In this section, we conduct a numerical simulation based on the theoretical models built so far. The numerical analysis is instrumental (i) to further illustrate the analytical results of our models; (ii) to perform sensitivity analyses\(^{28}\).

We assume as baseline case the London – Paris market\(^{29}\) and we test the sensitivity of the impact of HSR on the environment and social welfare toward per passenger emission levels, \(e_A\) and \(e_H\), and the size of the market, \(\alpha\). Following Givoni (2007), we distinguish between local air pollution (LAP) – per passenger emission referred to as \(e_A^{LAP}\) and \(e_H^{LAP}\) - and greenhouse gases (GHG) emissions – per passenger emission referred to as \(e_A^{GHG}\) and \(e_H^{GHG}\) - and we evaluate the environmental impact of passenger transport along these dimensions\(^{30}\). In the welfare analysis, we refer to the monetary value of environmental damage and we aggregate CHG and LAP.

We relax our assumptions on \(T_h\), i.e., \(T_h = 0\), and on the benefits derived from high frequency and speed, i.e., \(\gamma_f = 1\) and \(\gamma_s = 1\).

Parameters’ estimations are presented in Table 1. They are derived from literature and official websites, as described in the appendix.

***Table1 about here***

We choose three different weights of social welfare in HSR objective function: \(\delta \in \{0, 1/2, 1\}\). We solve the basic model and its extensions under non-negativity constraints of decision variables and prices together with an upper bound on the frequency of the modes: \(f_{MAX}\).

*** Table 2 about here ***

\(^{28}\) Comparative statics and analytical comparisons would not be conclusive for all relevant parameters constellations in the theoretical analysis.

\(^{29}\) The HSR across the English Channel was opened 1994. The distance between the two cities is 457 km, that is within the range of fierce competition distances between the two modes (Janic, 1993; Rothengatter, 2011). This makes the market prone to mode substitution. In this sense, it represents a suitable example for our numerical simulation.

\(^{30}\) The analysis incorporate the most significant LAP pollutants from commercial jet aircraft: hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), sulfur dioxide (SO2), and particulates (PM) (EPA, 1999; Givoni, 2007).
The results are shown in Table 2. They bring the following observations:

- In the three scenarios, HSR market share is increasing in $\delta$. Indeed, as the weight of social welfare in HSR objective function rises, the transport operator is more incentivized to set decision variables as to maximize consumer surplus. This moves passenger away from APT.

- When frequency of service is endogenous, airline frequency is decreasing in $\delta$ while HSR frequency increases in $\delta$. Indeed, higher frequency induces an increase in consumer surplus that compensates for the corresponding increase in operating costs in HSR objective function when $\delta > 0$, this in incentivizes rail operators to increase frequency. This finding is coherent with those of Yang and Zhang (2012).

- Product differentiation, i.e. $|f_A - f_M|$, is decreasing in $\delta$. Particularly when both carriers are pure profit maximizer, APT offers higher frequency than HSR, who suffers higher fixed costs. On the other side, when HSR is a pure welfare maximizer train offers higher frequency than APT. In this way, air transport creates value for passenger through frequency, while APT reduces per passenger costs and compete lowering prices.

- Transport operators always maximizes load factors. This is due to the structure of costs that exhibits high fixed costs and low variable costs.

- When HSR decide on speed, both rail passengers and prices are increasing in the maximum speed of trains. The reason is that higher speed increases passenger surplus (and thus willingness to pay) more than HSR unitary costs (this is also apparent from the decision to operate trains at maximum speed).

- HSR market share is higher when train operators are able to decide on the maximum speed to offer. In fact, raising speed, HSR is able to reduce APT competitive advantage on trip time. The tougher competition induced by lower product differentiation results in cheaper air ticket but might induce higher train ticket price because HSR costs are increasing in speed.

- In the three models, we find that HSR always induces market expansion, coherently with Proposition 1.

- In the basic model, HSR worsens LAP impact on the environment $\forall \delta \in \{0, 0.5, 1\}$. However, HSR increases CHG (greenhouse gases) impact only when both operators are pure profit maximizer. The reason is that the traffic generation effect decreases in $\delta$. We discuss the sensitivity of these results toward the level of emissions per passenger at the end of this section.
• In the frequency extension of our numerical example, HSR entry in the market does not increase the level of emission per passenger. The reason lies in the fact that transport operators always set frequency as to maximize load factors \(^{31}\). Within sensitivity analysis, we demonstrate that this result is not robust toward changes in estimation of market and pollution parameters.

• In the speed extension of our numerical example, HSR entry in the market does not increase the level of emission per passenger even if the train operator offers the maximum feasible speed and pollution is increasing in speed. Again, sensitivity analysis reveals that these results are not robust toward emission parameters estimation.

First, we test the sensitivity of the impact of HSR on social welfare toward the relative per passenger pollution degree of the two modes, i.e., \(e_H/e_A\), and the size of the market. In the basic model we find that, all other parameters being unchanged, there exist ranges of \(\alpha\) and \(e_H/e_A < 1\) such that HSR is detrimental for social welfare \(\forall \delta \in \{1, 1/2\}\) (see Figure 1). The effect is likely to occur for small values of \(\alpha\). The underlying reasons are that (i) the traffic generation effect is decreasing in the size of the market and (ii) the environmental damage resulting from the traffic generation decreases more slowly than the corresponding surplus increase.

***Figure 1 about here***

Second, we test the sensitivity of the environmental impact of HSR entry in the market toward the level of per passenger emission of the two modes, i.e., \(e_H\) and \(e_A\).

***Figure 2 about here***

In the basic model, \(\forall \delta \in \{1, 1/2, 0\}\), the environmental impact of HSR might be positive or negative, depending on the value of \(e_H/e_A < 1\) (see Figure 2). We observe that, the impact is more likely to be beneficial as \(\delta\) grows. Indeed HSR share of the market is increasing in \(\delta\) and HSR is greener on a per passenger base. Moreover Figure 2 shows that even small changes in \(e_H^{CHG}/e_A^{CHG}\) would change the sign of the environmental impact.

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\(^{31}\) This result depends on the structure of fixed/variable costs that comes from our estimations. For instance, if the ratio of per-passenger variable/fixed costs were 85% / 25% of fixed costs \(\delta \in \{0, 1/2\}\) then \(f_1 = f_{MAX}\) and \(f_2 = f_{MIN}\) (maximum product differentiation strategy) and APT load factor is lower than 100%.
When transport carriers decide on frequency, $\forall \delta \in \{1, 1/2\}$, the per-passenger impact of HSR might be positive or negative, depending on the value of $e_H/e_A < 1$ (see Figure 3). Again, the impact is more likely to be positive as $\delta$ decreases. In fact (i) APT is greener than HSR on a per vehicle basis; (ii) as $\delta$ increases HSR load factor reduces.

***Figure 3 about here***

When HSR decides on speed, there exist ranges of aviation CHG per passenger-emissions, $e_A^{\text{CHG}}$, and HSR per-kmh emissions per seat, $\vartheta$, such that HSR increases the overall level of emissions per passenger (see Figure 4). In particular, the effect realizes when $e_A$ is sufficiently small and $\vartheta$ is sufficiently high.

***Figure 4 about here***

Our sensitivity analysis suggests that (i) it is crucial to analyze HSR welfare and environmental implications on a case-by-case basis; (ii) within certain market size ranges, inaccurate estimation of the monetary value of environmental impact may lead to misleading results of the analysis of the impact of HSR on social welfare.; (iii) changes in the energy production mix, as well as the efficiency of aircraft or in the type of fuel used, might be determinant in this sense. Therefore, policy maker should carefully assess HSR implications taking into account (a) the perspective impact of policy targets for production from renewables and energy generation efficiency in each country; (b) the inclusion of APT in the emission trading scheme; (c) the impact of emergent resources for energy production, e.g. shale gas ; (d) reliability of the estimation of pollution monetary value; (e) APT and HSR efforts to reduce emissions.

We conclude with some observation related to point (e). APT and HSR have the opportunity to reduce their own environmental footprint through technological and operational efficiency improvements and use of alternative fuels (APT) or greener energy (HSR). With regard to efficiency improvements, mitigation strategies for air passenger transport relates both to airlines operations (e.g. friction and weight reduction) and to air traffic control operations (use of fuel minimizing routes and changes in the altitude of flights). On the other hand, HSR have not opportunities to change her, itinerary as

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32 HSR is greener on a per passenger basis, but the capacity of the train is significantly higher than that of aircrafts that operate on routes prone to HSR competition.

33 See Sgoudiris (2011) for an empirical assessment of the efficacy of APT mitigation strategies.
well as the impact of weight on train efficiency is less relevant than for airlines. With regard to changes in the source of propulsion energy, on one side airlines have the opportunity to switch to non-conventional jet fuels, e.g. biofuels, and this strategy is independent from the country in which the air carrier is based/operates. On the other side, the generation mix for train electricity is heavily constrained from the country in which HSR operates – electricity sources available, dispatch merit rules, topology of the electricity grid -, rail infrastructures within the country. In this sense, the switch to greener energy is not as much a strategy of the rail operator but an exogenous factor. Moreover, while use of biofuel entails higher costs, greener electricity generation mix is not necessary more expensive. Therefore different set of mitigation strategies available for transport operators should be carefully analysed both in term of efficacy and costs, in the design of environmental regulation.

5. Concluding remarks

In this paper, we propose a duopoly model to analyse the impact of air transport and high speed rail substitution on the environment and social welfare when intermodal competition takes place. Indeed, though HSR is greener than air on a per-passenger base, the introduction of HST services may not necessarily lead to environmental advantages, even if such introduction results in the increase of the HSR modal share and the decrease in the aircraft modal share. These advantages depend on the balance between the substitution effect (how many passengers using the high speed train are shifted from the aircraft and the car) and the traffic generation effect (how much new demand is generated by the HSR).

In particular, we show out that the introduction of HSR, even if greener of on a per-passenger base, may have a net negative effect on environment. The reason is that it may result in additional demand. Second, we incorporate into the model some specific engineering features of the two transport modes that are frequency and speed. When airlines and HSR decide on frequencies, there may be environmental disadvantages if load factors are not met, since the lower the load factor achieved, the higher the environmental cost per passenger from the operation of each mode. Similarly, since trains do not necessarily follow the direct route, HSR can have incentive to increase speed of HSTs in order to reduce travel time. This affects the environment, since its impact depends on the marginal energy

\[34\text{In principle, production from renewable technologies suffer lower marginal costs (e.g. the cost of sun or wind is null). However, electricity price may rise as RES penetrate the power sector because: (ii) generation from intermittent RES brings higher costs for ancillary services; (i) usually incentives scheme for renewables are socialized among users.}\]
consumption which is mainly proportional to cruising speed. In the scenario in which HSR decides on speed, we show that the net environmental impact of HSR introduction may be negative if the HSR marginal increase in emissions (per seat per kmh) is sufficiently high.

Finally, we examine the effects of modes competition on social welfare when environmental externalities are taken into account and we show that the introduction of HSR may be detrimental for society. Thus, it is not straightforward to say that the introduction of HSR is beneficial for the society. This depends on the scope of any benefit included in the assessment framework. On 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 of the benefits of intermodal competition (OFT, 2010). In this case, we show that if the impact on environment is taken into account when assessing social welfare, the surplus measure of the traditional approach will fall short of giving a true measure of total social surplus. 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 since assigning a monetary value to non-economic benefits is likely to be complicated and may be arbitrary.

The paper has also raised a number of issues and avenues for further research. First, we modeled airline-HSR rivalry as quantity competition as a direct consequence of our intention of examining a short-run model. In general, which model of competition is applicable to a particular market depends in large part on the production technology (in addition to time horizon). It would be interesting to compare our results with those obtained under price competition. Second, we considered the case of a single airline and a single HSR operator. In reality, with particular respect to the airline industry, more firms may compete in the market. Extending the analysis to a framework with more competitors would be a useful future study. Finally, phases other than operation in the life-cycle analysis of both modes need attention (ERA, 2011). These phases (construction/production, maintenance and disposal) can be responsible for significant environmental impact. 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. Further developments of this work may investigate the effect of modes competition and environment when capacity investments in building a new line are considered.

5. Concluding remarks
In this paper, we propose a duopoly model to analyse the impact of air transport and high speed rail substitution on the environment and social welfare when intermodal competition takes place. Indeed, though HSR is greener than air on a per-passenger base, the introduction of HST services may not necessarily lead to environmental advantages, even if such introduction results in the increase of the HSR modal share and the decrease in the aircraft modal share. These advantages depend on the balance between the substitution effect (how many passengers using the high speed train are shifted from the aircraft and the car) and the traffic generation effect (how much new demand is generated by the HSR).

In particular, we show out that the introduction of HSR, even if greener of on a per-passenger base, may have a net negative effect on environment. The reason is that it may result in additional demand. Second, we incorporate into the model some specific engineering features of the two transport modes that are frequency and speed. When airlines and HSR decide on frequencies, there may be environmental disadvantages if load factors are not met, since the lower the load factor achieved, the higher the environmental cost per passenger from the operation of each mode. Similarly, since trains do not necessarily follow the direct route, HSR can have incentive to increase speed of HSTs in order to reduce travel time. This affects the environment, since its impact depends on the marginal energy consumption which is mainly proportional to cruising speed. In the scenario in which HSR decides on speed, we show that the net environmental impact oh HSR introduction may be negative if the HSR marginal increase in emissions (per seat per kmh) is sufficiently high.

Finally, we examine the effects of modes competition on social welfare when environmental externalities are taken into account and we show that the introduction of HSR may be detrimental for society. Thus, it is not straightforward to say that the introduction of HSR is beneficial for the society. This depends on the scope of any benefit included in the assessment framework. On 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 of the benefits of intermodal competition (OFT, 2010). In this case, we show that if the impact on environment is taken into account when assessing social welfare, the surplus measure of the traditional approach will fall short of giving a true measure of total social surplus. 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 since assigning a monetary value to non-economic benefits is likely to be complicated and may be arbitrary.
The paper has also raised a number of issues and avenues for further research. First, we modeled airline-HSR rivalry as quantity competition as a direct consequence of our intention of examining a short-run model. In general, which model of competition is applicable to a particular market depends in large part on the production technology (in addition to time horizon). It would be interesting to compare our results with those obtained under price competition. Second, we considered the case of a single airline and a single HSR operator. In reality, with particular respect to the airline industry, more firms may compete in the market. Extending the analysis to a framework with more competitors would be a useful future study. Finally, phases other than operation in the life-cycle analysis of both modes need attention (ERA, 2011). These phases (construction/production, maintenance and disposal) can be responsible for significant environmental impact. 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. Further developments of this work may investigate the effect of modes competition and environment when capacity investments in building a new line are considered.

Acknowledgments

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Appendix – parameters estimation

**Basic Case**

We refer to Jiang and Zhang (2014) estimation of utility function parameters, $\alpha = 600$ and $\beta = 0.71$, that, in turn, are based on Beherens and Pels (2012) study of passengers behavior on the London-Paris route\(^{35}\).

We incorporate Adler et al. (2010) estimation of access time to European hub airports and HSR stations, $a_A = 1h$ and $a_H = 0.5h$\(^{36}\). Following Brueckner (2004) and Brueckner and Flores-Fillol (2007) we compute the expected schedule delay as $O_i/4f_i$, where $O_A = O_H = 16h$ is the number of operating hours (see Yang and Zhang, 2012) in a day and $f_A = 8.2$ and $f_H = 17$ (see Beherens and Pels, 2012) is the number of flights and trains operated within a day. Travel time values are directly derived from airlines websites\(^{37}\), $t_A = 1.28$ $h$ and $t_H = 2.43$ $h$. We incorporate in the simulation passengers’ processing time at the airport, $pt_A = 1.28h$. This value is obtained as the mean of Adler et al. (2010) processing times for business and leisure passengers, $pt_A^{business} = 1h$ and $pt_A^{leisure} = 2h$, weighted on the number of business and leisure passengers on the London – Paris route ( 22% and 88% respectively, cfr. Beherens and Pels, 2006). Finally, following Yang and Zhang (2012), we quantify passenger value of time as the average per capita GDP in Germany and United Kingdom: $v = 42,10\text{€}$ (source OECD, 2013). Turning to the transport operators side, airline operating costs estimation, $c_A = 40,62\text{€}$, is derived from the EU network airlines adjusted cost per ASK reported by IATA (2006), i.e., 10,19 € per ASK for European network airlines\(^{38}\), while the estimation of HSR operating costs on the London – Paris route, $c_H = 38,54\text{€}$, is provided by Givoni (2003).

With regard to emission levels we distinguish between transport modes’ impact on Local Air Pollution, $e_A^{LAP} = 86.1$ and $e_H^{LAP} = 32.2$, and greenhouse gas emission $e_A^{HAP} = 85459$ equal g of CO2 and $e_H^{HAP} = 7247$ equal g of CO2\(^{39}\).

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\(^{35}\) While Jiang and Zhang (2014) methodology of estimation of $\beta$ perfectly fits our model, the estimation of $\alpha$ might be biased as they do not refer to full prices. Nevertheless the estimated values of $T$ justifies the decision to refer to $\alpha = 600$. Furthermore our results hold when we run the simulation with slight different values of $\alpha$.

\(^{36}\) This value of the access time includes egress time as well.

\(^{37}\) The sample referred to for the estimation is made up by Air France and British Airways flights offered in the second week of April, 2014. Inclusion of other carriers in the sample, e.g. EasyJet, do not move the value of the mean significantly.

\(^{38}\) London – Paris flight travel distance is 380 km (Givoni, 2007).

\(^{39}\) Estimations are derived from Givoni (2007).
Extension: frequency

When frequencies are endogenous we distinguish between fixed operating costs per flight and marginal costs per seat. We do not have information regarding fixed and variable costs of operating a train or a flight. Therefore we take as a proxy of marginal costs per seat expenditures for on board passenger services and products, that is 6.70% of total operating costs for APT (Belobaba et al., 2009) and 12.70% for HSR (Shirocca Consulting, 2013) and we derive our estimation from basic case costs. The value of higher frequency for passenger, \( \gamma_f \), is estimated from Beherens and Pels (2012). They estimate direct elasticity of passenger demand with respect to frequency for business and leisure passenger with the nested multinomial logit and the mixed multinomial logit models on the London-Paris route. They refer to six airport-carriers pairs (Heathrow/ Air France, Heathrow/British Airways, Heathrow/British Midland Airways, Gatwick/British Airways, Luton/easyJet, and City/Air France) and Eurostar. For each model we refer to the average value of the direct elasticity weighted for the number of passengers in the sample for each city pair. In our model the direct elasticity of passenger demand with respect to frequency for mode \( i \), \( \varepsilon^i_f = \frac{\partial Q_i}{\partial f_i} \left( f_i/Q_i \right) \), is equal to \( \left[ \gamma_f / (1 - \beta^2) \right] (f_i/Q_i) \). Consequently, we are able to estimate \( \gamma_f \) from the values of elasticity, quantity and frequency in Beherens and Pels (2012). For each model, we obtain one value of \( \gamma_f \) for business passenger and one for leisure passengers per mode. We average those values using the volume of business and leisure passengers as a weight. Finally we average the resulting \( \gamma_f \) values for each mode in order to obtain the final estimation, \( \gamma_f = 6 \). \( T_A \) and \( T_H \) are equal to the corresponding values of the basic model net of the value of the schedule delays. Other parameters are the same as those of the basic model.

Extension: speed

We compute \( \gamma_s \) as the average value (of time) of a unit increase of speed in the range [250km/h; 300km/h]. We assume that HSR constant marginal cost per kmh, \( \mu \), is represented by the average electricity cost per kmh. In order to estimate this value we (i) derive the average energy consumption per kmh per seat, that is 0.15kWh/kmh * seat, from Kemp (2004); (ii) refer to the average cost per kWh, 0.096 €/kwh, reported by Eurostat (2013). Consequently, in this model, HSR operation costs per seat are all the basic model’s costs other than the electricity costs, i.e., \( c_h = 29.23 \text{ €/seat} \). Turning to the emission side, coherently with the assumption on \( \mu \), we suppose that only CO2 emissions varies with speed. Therefore, we estimate that the (constant) marginal increase in emissions
per kWh per seat, \( \varepsilon = 44.16 \text{ gCO2/kmh} \times \text{seat} \), as the number of CO2 grams emitted per seat per kwh of energy consumed, times the average energy consumption per kmh. Coherently \( e_{H}^{AP} \) entails NOx emissions only, that brings to \( e_{H}^{LAP} = 53 \text{ equal g of CO2}. \) \( T_{A} \) is equal to the corresponding values of the basic model and \( T_{H} \) corresponds to the corresponding values of the basic model net of the value of HSR travel time. All other parameters are set on the same value as those of the basic model.
### Figures

<table>
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Table 1 Parameter estimations for numerical analysis

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### Extension: frequency

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### Extension: speed

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<td>$\frac{898}{12.50} - \frac{2.00 s_{\text{MAX}}^2}{25.00}$</td>
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\[
\begin{array}{|c|c|c|}
\hline
q_h & 4(930.31 + 0.56s_{\text{MAX}}) \div 17.48 & 4(23.45 \cdot 10^2 + 1.13s_{\text{MAX}}) \div 27.48 & 13(544 + 0.22s_{\text{MAX}}) \div 12.50 \\
\hline
p_a & 41.56 \cdot 10^2 - 80.12s_{\text{MAX}} \div 17.48 & -13(-406.24 + 0.12s_{\text{MAX}}) \div 27.48 & -7(-401.79 + 0.29s_{\text{MAX}}) \div 25.00 \\
\hline
p_h & 10.80 \cdot 10^2 + 6.27s_{\text{MAX}} \div 43.6987500 & 51.89 + 4.02s_{\text{MAX}} \div 34.3493750 & -4.20 + 1.78s_{\text{MAX}} \div 25.00 \\
\hline
\pi_a & \frac{(86.15 \cdot 10^2 - 20.0291s_{\text{MAX}})^2}{19.10 \cdot 10^2} & \frac{4(52.06 \cdot 10^3 - 20.02s_{\text{MAX}})^2}{47.20 \cdot 10^2} & \frac{80.73 \cdot 10^3 - 179.95s_{\text{MAX}} + 0.40s_{\text{MAX}}^2}{15.63 - 15.63 + 62.50} \\
\hline
\pi_a + \delta W & \frac{1.6(930.49 + 0.56s_{\text{MAX}})^2}{30.55} & \frac{1}{47.19}(31(14.18 \cdot 10^{-8} + 91s2(13.32 + 35.27 \cdot 10^{-3}s_{\text{MAX}}))) & \frac{50.82 \cdot 10^2 + 38.10s_{\text{MAX}} + 35.84s_{\text{MAX}}^2}{31.25000 + 0.31 + 12.50 \cdot 10^2} \\
\hline
\hat{E}_{\text{CHG}} & \frac{25(71.17 \cdot 10^2 - 77.25 \cdot 10^4s_{\text{MAX}})}{258(12.32 \cdot 10^4 + 28.21s_{\text{MAX}})} & -180244.13 + \frac{1.09 \times 10^8}{440.61 + 0.11s_{\text{MAX}}} & -1600(-75.50 \cdot 10^5 + 21.64 \cdot 10^6s_{\text{MAX}}) \div 14.37 \cdot 10^4 + 36.39s_{\text{MAX}} \\
\hline
\hat{E}_{\text{LAP}} & \frac{2695(20.83 \cdot 10^2 + 11.28 \cdot 10^4s_{\text{MAX}})}{129(12.32 \cdot 10^4 + 28.21s_{\text{MAX}})} & \frac{2695(49.12 \cdot 10^2 + 2.26s_{\text{MAX}})}{30.27 \cdot 10^4 + 72.7818s_{\text{MAX}}} & \frac{14.01(54.40 \cdot 10^4 + 217s_{\text{MAX}})}{14.37 \cdot 10^4 + 36.3909s_{\text{MAX}}} \\
\hline
q^M - q_a - q_h & -169.22 - 0.083s_{\text{MAX}} & -246.07 - 0.11s_{\text{MAX}} & -380.39 - 0.15s_{\text{MAX}} \\
\hline
\end{array}
\]

Table 2 Results of the numerical analysis
Figure 1 Basic model: sensitivity analysis of the impact of HSR on social welfare when $\delta = 0.5$. In the shaded region this impact is negative.

Figure 2 Basic model: sensitivity analysis with respect to $e_H/e_A$ of the LAP environmental impact of HSR impact of HSR $\forall \delta \in \{0, 0.5, 1\}$. The dotted lines identify the value of $e_H/e_A$ for whom HSR is detrimental for LAP emissions. The vertical lines show the level of relative CHG and LAP impact of our numerical simulation.
Endogenous frequencies: sensitivity analysis with respect to $e_H/e_A$ of the environmental impact of HSR impact of HSR $\forall \delta \in \{0, 0.5, 1\}$. The dotted lines identify the value of $e_H/e_A$ for whom HSR is detrimental for emissions. The vertical lines show the level of relative CHG and LAP impact of our numerical simulation.

Endogenous HSR speed: sensitivity analysis with respect to $e_A$ and $\varepsilon$ of the CHG environmental impact of HSR impact of HSR $\forall \delta \in \{0, 0.5, 1\}$. In the shaded region this impact is negative.