Air transport and high-speed rail competition: environmental implications and mitigation strategies

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Abstract

We develop a duopoly model to analyse the environmental impact of high-speed rail (HSR) introduction in a market for travel served by air transport. We take into account the effects on the environment of induced demand, schedule frequency and HSR speed simultaneously, and we show that competition between the two modes may be detrimental to the environment depending on the *magnitude* of the pollution level of HSR relative to air transport. We conduct a simulation study based on the London–Paris market and we find that the introduction of HSR increases local air pollution (LAP) but decreases greenhouse gases (GHG) emissions. Moreover, we perform a sensitivity analysis of our results towards the level of HSR and air transport emissions. We find that modal competition is more likely to be detrimental to the environment when HSR emissions are not significantly lower than air transport emissions. Furthermore, we find that modal competition is more likely to be detrimental to the environment in the case of a fully private HSR, than in the case of a mixed public/private-owned HSR that takes into account the surplus of consumers and the surplus that the air transport operator brings about. Finally, we provide an interpretive discussion of the results with respect to the different mitigation strategies available to the two transport modes and the EU policy measures for the environment – which might affect HSR and air transport emissions.

Keywords

High-speed rail, Airlines, Competition, Environment, Mitigation Policies, London-Paris market.

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1. Introduction

Protecting the environment and preventing climate change is a strategic priority for the European Union (EU). By 2050, for instance, EU leaders have endorsed the objective of reducing Europe's Greenhouse Gas (GHG) emissions by 80-95% compared to 1990 levels. In this direction, the targets are: 20% GHG emissions reduction by 2020, 40% reduction by 2030 and 60% by 2040. The impact of aviation on the environment is of growing concern, mainly due to the projected increase in demand for air transport. The 37th International Civil Aviation Organization (ICAO) assembly reports a projected 4.7% growth in world revenue passenger kilometers (RPKs) flown between 2010 and 2030[1]. The Committee on Climate Change reports that, under a high growth scenario, the 2050 aviation CO_2 emissions will be 7–8 times the 1990 levels (Adler et al., 2013). The traffic increase will result in increasing emissions from aircrafts in spite of technological progresses (Socorro and Betancor, 2011). In fact, most studies foresee that the aviation sector will not able to reduce its emissions by more than 1% - 1.5% per kilometer flown per annum (Anger, 2010; Morrell, 2007; Scheelhaase and Grimme, 2007).

In this context, air transport and high-speed rail (HSR) substitution has been supported by many for environmental reasons. The EU, for instance, stated that the majority of medium-distance passenger transport should go by rail by 2050, with the length of the existing HSR network to be tripled by 2030 (EC, 2011)[2]. One of the main statements to justify policies for modal shift from air to rail relies on to the claimed *greenness* of HSR on a per-seat basis. In fact, some empirical evidences show that the (per-seat) Local Air Pollution (LAP) and GHG emissions (or their economic impact) of airlines is higher than that those of HSR (Givoni and Banister, 2006; Givoni, 2007; Janic, 2003, 2011). Nevertheless, the introduction of HSR services does not necessarily lead to overall environmental advantages (D'Alfonso et al., 2015). The net environmental effect can be negative since the introduction of the new transport mode often results in additional demand. In other words, there is a the trade-off between the *substitution effect* - how many passengers using the HSR are shifted from air transport - and the *traffic generation effect* - how much new demand is generated by the HSR.

The existing literature has mainly focused on the market equilibrium of airline-HSR competition (i.e., traffic and price levels) abstracting away from environmental considerations, with empirical approaches (Behrens and Pels, 2012; Dobruszkes, 2011; González-Savignat, 2004; Park and Ha,

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[1] Evidence shows that several large airports in the EU are currently operating at full capacity (Avenali et al., 2014).

[2] Similarly, outside the EU, the National Environmental Policy Act (NEPA) underlines the importance of comparing the environmental impact of alternative modes in the United States (US). As highlighted in the Passenger Rail Investment and Improvement Act (PRIIA), US rail plans are to address a broad spectrum of issues, including an analysis of rail environmental impacts compared to air in the US.

2006), game theory settings (Adler et al., 2010) or analytical perspectives (Yang and Zhang, 2012). 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), with only a few works addressing this issue analytically (Jiang and Zhang, 2014; Jiang et al., 2015; Socorro and Viecens, 2013). Some recent contributions have investigated the long-term impacts of high-speed rail competition on air transport studying how the market coverage and the network choice of an airline would respond to HSR competition on origin-destination trunk routes (Jiang and Zhang, 2015).

The environmental impact of air-rail substitution has been mostly object of case studies on specific routes. Part of the debate has been concentrating on the assessment of the potential per-seat savings in pollution (LAP or GHG emissions), which could be achieved by substituting some short-haul flights with HSR services (Janic, 2011; Givoni and Banister, 2006; Miyoshi and Givoni, 2013). However, all these papers have adopted a static perspective in abstracting away from the effect on environment of induced demand due to the introduction of a new mode of transport. D'Alfonso et al. (2015) is the first attempt in literature at deriving an analytical framework to evaluate the impact of modal competition between air transport and high-speed rail on the environment and social welfare while pointing out the effect of induced demand. Their results show that competition between the two modes may be detrimental to the environment depending on market expansion, modal shift, market size and modal heterogeneity on emission rates.

In this paper, we build a duopoly model to study the impact of air transport and HSR competition on the environment when new travel demand is induced. The operators decide simultaneously on the number of seats that they want to supply and the frequencies of service; furthermore, HSR is allowed to change train speed. We conduct a simulation study based on the London-Paris market, where HSR market share is 70% (Barrón et al., 2009). Such an exercise is necessary from a policy perspective. On the one hand, the debate around the impact of air-rail competition on environment, which has focused mainly on the *greenness* of HSR while ignoring the dynamic effects of its introduction, may have led to a bias amongst policy makers when considering future transport policies. On the other hand, HSR introduction can involve substantial investments, therefore a better understanding of its impact is necessary and timely. So far the partial substitution of short-haul flights with HSR services, either through modal competition or cooperation, has already taken place at major airports like Frankfurt Main, Paris CDG, Madrid Barajas or Amsterdam Schipol, which are all connected to the Trans-European High-Speed-Rail Network. China, the UK, Italy, Belgium and South Korea have

successfully launched HSR lines. Many others, like Brazil, India, Russia, Turkey and the US are evaluating the options of investing in HSR.

Our paper shows similarities with D'Alfonso et al. (2015) but clearly moves steps further that research.

First, we examine the effects on the environment of induced demand, schedule frequency and HSR speed simultaneously: we examine a single scenario in which air transport decides the traffic quantity and schedule frequency while HSR decides traffic quantity, schedule frequency as well as train speed. Conversely, D'Alfonso et al. (2015) build up three separate scenarios, each focusing on one aspect. In their first setting, the two operators only compete on quantities; in the second one, they compete on quantities and frequencies; in the third one, they build a two stage game: in the first stage, the HSR decides on train speed; in the second stage, both operators decide traffic quantities. What is missing in the framework of D'Alfonso et al. (2015) is that, when frequency and speed are both strategic variables for the HSR, the operator may have incentives to increase the speed of the vehicle and reduce the frequency accordingly, if this strategy is less costly than increasing the frequency of the service. On the one hand, this may be beneficial to the environment, since the number of HSR rides may reduce. On the other hand, this may be detrimental for the environment since pollution from HSR depends on the energy consumption of the rolling stock (CfIT, 2001), which increases with the speed of the train (Kemp, 2004; Garcia, 2010; Andersson and Lukaszewicz, 2006; Bousquet et al., 2013).

Second, through the numerical analysis, we measure the different implications of introducing HSR as a competitor of air transport on LAP and GHG, while no simulation study is present in D'Alfonso et al. (2015). In doing so, we are able to disentangle the impact of air transport/HSR competition on LAP and climate change. This simulation study is also a base for discussing different mitigation strategies available to the two transport modes and EU policy measures – which might jointly affect the ratio between HSR and air transport emissions.

We show that competition between the two modes may be detrimental to the environment depending on the *magnitude* of the environmental impact of HSR relative to air transport. In particular, we find that HSR always increases LAP but decreases GHG emissions. This is consistent with the general view that HSR operations do not contribute significantly to climate change due to lower emission rates of CO_2 (Archer, 1993; Dings et al., 2002). We examine the sensitivity of this result towards the relative values of the two modes' emissions. We find that the introduction of HSR increases neither LAP nor GHG emissions, when the ratio between HSR and air transport emissions is relatively low.

However, when such ratio increases, i.e., when HSR becomes increasingly more polluting than the airline (both from a LAP and GHG emissions perspective), the impact of HSR introduction on the environment might be negative. In particular, we assume that HSR maximizes a weighted sum of its profit and social welfare and we analyse the sensitivity of the environmental impact of modal competition towards the weight of welfare relative to profits. We find that HSR impact on the environment is more likely to be positive for high values of this weight. Overall, modal competition is less likely to be detrimental to the environment in the case of a fully private HSR.

Third, we provide an interpretive discussion of results with respect to the scope of the mitigation strategies available to the two modes and to the policy measures for emissions reduction, which will affect the level of pollution of the two modes differently.

The structure of the paper is as follows. Section 2 and 3 present an overview of air transport and HSR competition in Europe and a comparison between the environmental impacts of the two modes. Section 4 builds the model while in Section 5 we conduct the simulation study. Section 6 contains a discussion of results with respect to mitigation strategies and policy measures. Section 7 contains some concluding remarks.

2. Air transport and high-speed rail competition in Europe

As train become faster, HSR is likely to impose significant competitive pressures on air transport. Janic (1993) argues that HSR can compete with air transport over a range of distances of 400-2000 km. Rothengatter (2011) finds evidence that fierce competition between air transport and HSR may occur on routes with distance up to 1000 km, mostly likely between 400 and 800 km. Steer Davies Gleave (SDG, 2004) concludes that the threat imposed by HSR on air travel is the strongest in countries with a large market for travel over distances of around 200-800 km, and particularly in the range 300-600 km. HSR offers little benefits for journeys shorter than 150-200 km, and it is currently not competitive towards air transport for journeys longer than approximately 800-1000 km. Figure 1 shows an estimate of the potential demand for rail on the five biggest routes of at least 200 km in United Kingdom (UK) and four other European countries (SDG, 2004).

==Insert Figure 1 ==

In the case of the 620 km Madrid-Barcelona route, González-Savignat (2004) finds that HSR has a significant impact on the market share of air transport, with total journey time being the most important determinant of market share. On the same route, Román et al. (2010) analyse air transport–HSR competition based on a mixed set of revealed-preference and stated-preference data, and obtain

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different willingness-to-pay measures for service quality improvement due to lower access time or higher frequency. Dobruszkes (2011) studies HSR and air transport competition in Western Europe and examines empirically five city-pairs. He finds that, in addition to travel time frequencies and fares, variables such as airlines' hubs and the geographical structures of urban regions affect competition between the two modes. Behrens and Pels (2012) focuses on the London–Paris passenger market, and show that travel time and frequency are the two main determinants of travel behavior.

The impact of HSR introduction on air travel demand has been dramatic in some cases. On the Paris-Nantes route, the introduction of the TGV network decreased the air traffic by 30% (Dobruszkes, 2011). The same situation is observed in other routes like Paris-Rennes or Paris-Brest (Chi, 2004). According to the French rail operating company, Société Nationale des Chemins de fer Français (SNCF), the Train à Grande Vitesse (TGV) service has taken over 90% of the combined air/rail travel market in the Paris-Lyon route, which is characterized by a HSR travel time of less than two hours (AECOM Australia Pty Ltd, 2013). Generally speaking, the TGV market share is about 60% in corridors where the TGV travel time is around three hours (Logistics Design Management, 2014). Similarly, in Spain, before the HSR link was established between Madrid and Seville in the early 1990s, the mix of air/rail passengers was 67% and 33% respectively. After the introduction of HSR, the mix changed to 16% and 84%. These figures are forecasted to become 13% and 87% by 2020, according to Barrón et al. (2009). The introduction of HSR services severely affected the competitiveness of air transport in non-European countries. In the case of the link between Taipei and Kaohsiung in Taiwan, HSR has reportedly cut domestic air traffic by 50% by 2012 (Aerospace America, 2012). The opening of South Korea's first HSR line had significantly reduced airline demand in Korea domestic market (Park and Ha, 2006). In China, all the flights between Zhengzhou and Xi'an (505 km) were suspended in March 2010, 48 days after the opening of the HSR service, whereas daily flights on the Wuhan–Guangzhou route (1,069 km) were reduced from fifteen to nine, one year after the HSR entry (Fu et al., 2012)[3].

3. A comparison between the environmental impact of air transport and high-speed rail

Environmental benefits from modes substitution can be measured referring to the impact on LAP, climate change and noise. LAP is known to have a direct impact on human health, and it may lead to an increased risk of premature death (Dailey, 2012). Local air quality is directly affected by emission

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[3] Recent cases of air route cancellations also include a number of Chinese domestic markets such as Nanjing-Shanghai, Changsha-Guangzhou and Wuhan-Nanjing (Berdy, 2011). Deep cuts of airfares after the entry of HSR service are also very common. For example, the market between Wuhan and Xiamen, two Chinese cities recently linked by HSR, saw an 80% drop in air ticket price (Jiang and Zhang, 2014).

volumes and varies on a daily basis, while health impacts may take longer to emerge and tend to persist over time (Adler et al., 2013). LAP pollutants include hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), and particulates (PM). Impact on climate change is mainly due to GHG emissions like carbon dioxide (CO_2) (Seinfeld and Pandis, 2012). In general, HSR operations are not considered to contribute significantly to climate change due to lower emission rates of CO_2. Moreover, CO_2 emissions at high altitude affect climate change more than emissions at ground level, by a factor of more than 100 (Archer, 1993; Dings et al., 2002). With respect to human toxicity of NO_2, SO_2 and PM_{10}, HSR shows an advantage per-seat over the aircraft (Givoni, 2007). This is mainly due to low SO_2 emissions of HSR operations, which depends mostly on the share of coal – or other generation sources – used to generate the electricity (Button, 1993). Usually, power plants are located away from densely populated areas, which means that the actual impact of HSR operations on LAP is lower due to a relatively low number of people exposed to the emissions (Givoni, 2007). For instance, Givoni (2007), based on the London-Paris route, reports that the impact on LAP (toxicity factor based on estimates by Huijbregts et al., 2000) is 86.1 units for air and 32.2 units for HSR (per-seat supplied on the route). On the same route, NO_x (CO_2) emissions are 198.92 (44,095) grams for air and 17.57 (7,194) grams for HSR (per-seat supplied on the route). Finally, while engine emissions have both local and global impacts, noise has a direct impact on the community in the surrounding of airports (Marais and Waitz, 2009). Rail operations result in high levels of noise at high speeds (Brons et al., 2003). However, the impact (which depends on the actual noise heard and the number of people exposed to it) is lower than what can be expected since, in densely populated areas, speed is reduced when approaching the stations due to the distance required for the train to stop.

Overall, we can conclude that the environmental impact of aircraft operations on LAP and climate change depends on flying time, aircraft seat capacity, fuel consumption, height of the mixing zone[4], modal share in the journey to/from the airport, and distance of the airport from the city center. The impact of HSR operations depends mainly on the mix of the sources used to generate the electricity, the route distance and the energy consumption[5] (Givoni, 2007; Janic, 2003).

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[4] The mixing zone is the layer of the earth's atmosphere where chemical reactions of pollutants can ultimately affect ground level pollutant concentrations.
[5] The reader may refer to Pérez-Arriaga (2013, pag. 541-542) for the analysis of the environmental impact of electricity by fuel type. Direct energy consumption mostly includes the energy required to overcome the train resistance to movement. It also includes the energy lost due to inefficiencies in the traction system between pantograph and wheel, the energy used for on-board passenger comfort functions, the losses in the electrical supply system between the substation and pantograph. Direct energy consumption includes energy used for in-service maintenance of rail rolling stock (Network Rail, 2009).

In fact, phases other than operation in the life-cycle analysis of both modes also need attention (ERA, 2011). These phases (construction/production, maintenance and disposal) can be responsible for significant environmental impact. The effects related to the construction of rail infrastructure, for instance, include emissions from building a new line as well as land take, which affects landscape, townscape, biodiversity and heritage (Westin and Kageson, 2012)[6]. The International Union of Railways (Railway Handbook, 2012) reports that, on average, when taking the Well to Wheel (WTW) emissions[7] from the energy needed to propel the vehicle, HSR appears to be more efficient than air transport. Figure 2 shows a comparison of the average GHG emissions from WTW per passenger-km. It has been shown that including infrastructure manufacture and maintenance carbon emissions into the HSR carbon intensity would add an extra 5g CO_2/kpm, which would not drastically change the picture shown below.

== Insert Figure 2==

4. The model

Consider a competition model between air transport and high-speed rail over a single origin (O) – destination (D) link[8]. We assume that this route is served by one HSR operator and one airline[9]. Let $\tilde{T}_i := a_i + t_i$ be the total journey time of transport mode i – with $i = A$ (air transport) or $i = H$ (HSR), where a_i is the sum of access and egress time to and from the transport facility where transport mode i operates and t_i is the travel time by mode i. The total journey time may vary across the two modes. In general, passengers need to spend a significant access/egress time for a flight, i.e., $a_A > a_H$, owing to the fact that airports are usually located far away from city centers (Adler et al., 2010; González-Savignat, 2004)[10]. On the other hand, air service results in a lower in-vehicle time for most of the

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[6] 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 takes place through the existing one.

[7] Well-to-wheel is the specific life cycle assessment used for transport fuels. The analysis is often broken down into two stages entitled "well-to-station" and "station-to-wheel". The first stage incorporates the feedstock or fuel production, processing and fuel delivery or energy transmission; the second stage deals with vehicle operation itself.

[8] We abstract away from road transport and conventional rail, in order to focus on the environmental impact of competition between air transport and high speed rail, which has received most attention in the literature (Givoni, 2007; Givoni and Dobruszkes, 2013), and to get interpretable results. This approach might underestimate the benefits from HSR entry in the market therefore this modeling fits routes on which HSR mainly diverts passenger from air transport and mode substitution to HSR from other services appears modest. Empirical evidences shows that this is the case of the Paris-Lyon route on which most of the demand shifted from the train is from aircrafts (Givoni, 2007). Similarly, in the case of London to Paris, Lille and Brussels routes, such demand is 12% for rail, 49% for planes, 7% for cars and 12% for coaches (Givoni and Dobruszkes, 2013).

[9] This modeling is consistent with recent contributions investigating air transport-HSR substitution through competition (Yang and Zhang, 2012) or integration (Jiang and Zhang, 2014; Socorro and Viecens, 2013). Extending the analysis to a framework with more competitors would be an insightful future study. It is likely, however, that many of the conclusions would carry over to an oligopoly version of the model.

[10] 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

routes, i.e., $t_A < t_H$, since the speed is different between the two modes and trains do not follow direct routes from the origin to the destination due to the orography of the territory.

We assume that travelers maximize a (strictly concave) quadratic utility function, as proposed by Singh and Vives (1984). Let q_A and q_H be the number of passengers travelling by air or HSR, respectively. The utility function is:

$$U(q_A, q_H) = \alpha(q_A + q_H) - \frac{1}{2}(q_A^2 + q_H^2 + 2\beta q_A q_H) \tag{1}$$

where $\alpha > 0$ denotes the gross benefit that the consumer derives from traveling from the origin O to the destination D, using transport mode A or H, and the parameter $\beta > 0$ measures the degree of substitutability between the two modes. Larger values of β indicate more substitutable services: it ranges from zero, when the two modes are independent, to one when they are perfect substitutes[11]. Inverse demand functions for q_A and q_H are, respectively:

$$\theta_i(q_A, q_H) = \alpha - q_i - \beta \cdot q_{-i} \tag{2}$$

where $-i$ indicates the mode other than i, i.e., $-i = A$ if $i = H$ and $-i = H$ if $i = A$.

We now turn to the definition of the full prices perceived by travelers:

$$\theta_A = p_A - \gamma_f f_A + v\tilde{T}_A$$
$$\theta_H = p_H - \gamma_f f_H - \gamma_s s_H + v a_H \tag{3}$$

where p_i is the ticket price of transport mode i, v is the passenger value of time, f_i is the schedule frequency of transport mode i, s_H denotes the average operational speed of the HST, γ_f is the benefit from higher frequency and γ_s is the benefit for higher HSR passengers' from train speed[12]. The average operational speed of the HST differs from the maximum speed of the HST, since it depends on legal requirements, e.g., speed limits on the lines, and the number of stops on the HSR line (Givoni and Banister, 2012).

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information on board, identification of staff and information service, baggage handling, check-in and security-check procedures (IATA, 2003; Janic, 2011).

[11] The parameter β may be affected by different cultural/personal mode preference (IATA, 2003) or habits (Thøgersen, 2006).

[12] The value of HSR travel time is now captured through γ_s, which measures the willingness to pay for increased train speed, i.e., $s_H = l_H/t_H$ where l_H is the (constant) length of the HSR track route and t_H is the travel time by HSR. As opposite, the aircraft speed can be considered as being constant since it is close to the speed of sound.

The formulation in equation (3) introduces frequencies additively in the full price functions, following Flores-Fillol (2009). Higher frequency of flights/HSR rides offered by a particular airline/HSR delivers higher benefit to passengers and, therefore, determines service quality as a measure of flight/HSR ride flexibility (Adler et al., 2010; Behrens and Pels, 2012; González-Savignat, 2004; Román et al., 2010; Yang and Zhang, 2012). In addition to a reduced overall journey time, benefits from higher frequency may also include increasing choice/travel opportunities for passengers in terms of schedule coordination for multi-stops trips (Cokasova, 2006; Vespermann and Wald, 2011) or less apprehension over what happens in case of a missed connection due to low punctuality or reliability. Similarly, higher train speed reduces the travel time and increases travelers' willingness to pay, while delivering higher service quality. Other benefits from higher speed include the increase in the opportunities for passengers in terms of coordination with other transport modes or in the possibility to take advantage of some services when the departure time cannot be anticipated.

From equations (1) and (3) it follows that:

$$p_A(q_A, q_H, f_A) = \alpha - v\tilde{T}_A - q_A - \beta \, q_H + \gamma_f f_A \tag{4}$$

$$p_H(q_A, q_H, f_H, s_H) = \alpha - va_H - q_H - \beta \, q_A + \gamma_s s_H + \gamma_f f_H$$

Turning to the supply side, let $k_A + c_A \times q_A$ be the cost of operating a flight, where $k_A > 0$ is the fixed cost of operating a flight and $c_A > 0$ is the unit (per-passenger) variable cost. The airline profit may be written as follows:

$$\pi_A(q_A, q_H, f_A) = [\, p_A(q_A, q_H, f_A) - c_A \,] \, q_A - \, k_A f_A \tag{5}$$

We assume that the cost of operating a HSR ride is given by $k_H + [\, c_H + C_s(s_H) \,] \times q_H$, where $k_H > 0$ is the fixed cost of operating a train ride, $c_H > 0$ is the unit (per-passenger) variable cost and $C_s(s_H)$ is the per-passenger cost of electricity necessary to increase the average operational speed of the HST of 1 kph (kilometers per hours). We assume that $\partial C_s(s_H)/\partial s_H > 0$, that is higher speed leads to higher per-passenger cost of electricity. This is confirmed by several empirical researches (e.g., Kemp, 2004; Garcia, 2010; Andersson and Lukaszewicz, 2006; Bousquet et al., 2013) and adopted in a theoretical model by Yang and Zhang (2012). In particular, we assume that the per-passenger cost of electricity necessary to increase the average operational speed of the HST of 1 kph is

constant[13]– and we denote it with $\mu > 0$ – such that $C_s(s_H) = \mu s_H$. Under these assumptions, HSR profit may be written as:

$$\pi_H(q_A, q_H, f_H, s_H) = [\, p_H(q_A, q_H, f_H, s_H) - c_H - \mu s_H]q_H - k_H f_H \qquad (11)$$

In particular, following D'Alfonso et al. (2015), we assume that the airline is a pure private firm maximizing its profits, while the HSR maximizes a weighted sum of its profit and social welfare[14]. With these specifications, HSR objective function is:

$$(1 - \delta)\pi_H(q_A, q_H, f_H, s_H) + \delta W(q_A, q_H, f_A, f_H, s_H) \qquad (6)$$

where

$$W(q_A, q_H, f_A, f_H, s_H) \qquad (7)$$
$$= U(q_A, q_H) - [c_A + v(t_A + a_A)]q_A - (c_H + va_H + \mu s_H)q_H - k_A f_A$$
$$- k_H f_H$$

and δ is the weight of welfare relative to profits. The interaction between the airline and the HSR operator is modeled as a simultaneous game, i.e., we focus on the short run period in which the two operators decide on the operational aspects of their business. In particular, we assume that the airline decides the number of travelers to serve and the frequency of service, while HSR decides the number of travelers to serve, the frequency of service and the average operational speed of the HST[15]. Thus, the operators solve simultaneously the following decision problems:

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[13] Janic (2003) finds that HSR energy consumption (quantity of energy per unit of output - kWh/km) 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 kph). Lukaszewicz and Andersson (2009) estimations on the Swedish case show that the energy consumption increases by a power of 1.1–1.3 of the cruising speed for the trains running on the dedicated very-high-speed line. For example, if the speed is increased from 250 to 280 kph (12%), energy consumption increases by 13 – 16%. Garcia (2010) reports the relationship based on estimates on some Spanish routes, between each train vehicle's power output (in kilowatts) and its maximum speed showing a curve that confirms the power of 1.3.

[14] 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; Matsumura, 1998).

[15] There are some good reasons to believe that quantity competition may be more relevant for the present paper (see Brander and Zhang, 1990, 1993; Jiang and Zhang, 2014; Quinet and Vickerman, 2004). At the same time, it is reasonable to assume that the operators may choose contextually the frequency of service when focusing on the short run and on uncongested airport where slots are available, which is the case in our paper. This is a common assumption in the literature investigating air transport and HSR competition (see Adler et al., 2010 and Yang and Zhang, 2012). Finally, in the case of HSR, the operational speed operational speed can be easily adjusted in the short run, when the rolling stock has been acquired, deciding the number of stops.

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

$$\text{s.t. } q_A \geq 0$$

$$f_A \geq 0$$

$$f_A \leq f_A^{max}$$

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

$$\text{s.t. } q_H \geq 0$$

$$f_H \geq 0$$

$$f_H \leq f_H^{max}$$

$$s_H \geq 0$$

$$s_H \leq s_H^{max}$$

(8)

In problem (8), the constraints $f_i \leq f_i^{max}$, with $i = A, H$, imply that the frequency of flights (HSR rides) is bounded by the maximum feasible frequency of service during the day. Similarly, the constraint $s_H \leq s_H^{max}$ implies that the average operational speed of the HST is bounded by the maximum train speed which can be achieved given the best technology available and the percentage of the line on which the maximum speed can be operated in compliance with legal requirements[16].

In order to measure implications for the environment, we distinguish between LAP and GHG emissions, and we evaluate the environmental impact of air transport-HSR competition on the environment comparing the overall level of emissions that would occur in a benchmark case in which only air transport serves the market against the overall amount of emissions that occur at the equilibrium of our competition model[17]. The overall environmental benefit of HSR entry is measured as follows:

$$E^k(q_A^*, q_H^*, q_M^*) := e_A^k q_M^* - \left(e_A^k q_A^* + e_H^k q_H^* \right)$$

(9)

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[16] This formulation implicitly assumes that load factors are fixed for each mode. In particular, as described in section 5.1 an average load factor observed on the route is 48% for HSR (Givoni, 2003) and 70% for air transport (Nash, 2009) and we will use these values for our simulation study. We include in Section 6 some discussions on how changes in load factors may have an impact on the ratio between the emissions of two transport modes, and, as a consequence, how the impact of air transport – HSR competition on the environment may change in the long run.

[17] See Appendix 1 for the detailed description of the monopoly case.

$k = LAP, GHG$, where q_M^* represents the optimal level of passengers carried out by a monopoly carrier serving the O-D link, e_H^k stands for the level of emissions per-passenger of HSR and e_A^k denotes the amount of emissions per-passenger of air transport.

5. Simulation study

In this section, we conduct a simulation study in order to figure out the environmental implications of air transport-HSR competition. The baseline case used in the numerical study refers to the London-Paris market. The rail route between the two cities is operated by Eurostar International Limited and it had carried around 115 million passengers from 1994 to 2011. The flight distance between London and Paris is 380 km and this makes the two modes fiercely compete in the market for travel (Givoni, 2007; Janic, 1993; Rothengatter, 2011). In 2007, HSR had captured 70% of the market (Barrón et al., 2009) and it is suggested that the shift of passengers from short-haul air to HSR resulted in a combined passenger saving of 40,000 tons of CO_2. Nevertheless, the overall benefits of HSR on the environment should be carefully assessed, taking into account the overall emissions of the two modes of transport and the amount of new demand for travels generated by HSR.

In particular we assume that the origin and destination of passengers travelling between London and Paris is the city center. Indeed, though the origin and destination of journeys are usually dispersed over a large area, the city center is in many cases the location that attracts most passengers and it is reasonable to consider it as the geographical mean of passenger origins and destinations (Givoni, 2007).

In order to evaluate the environmental impact of HSR, following Givoni (2007), we distinguish between local air pollution (LAP) – per-passenger emissions referred to as e_A^{LAP} and e_H^{LAP} – and greenhouse gases (GHG) emissions – per-passenger emissions referred to as e_A^{GHG} and e_H^{GHG}. Furthermore, in the HSR objective function, we consider three different weights on social welfare relative to profits: $\delta \in \{0, 1/2, 1\}$, to examine the sensitivity of our results to different ownership structures.

5.1 Estimation of parameters

Estimates of relevant parameters of our numerical study are derived from literature and official websites and summarized in Table 1.

== Insert Table 1 about here ==

We first focus on the demand side. We incorporate estimations of the market size parameter and the substitutability parameter derived by Jiang and Zhang (2014) from Behrens and Pels (2012) analysis, i.e., $\alpha = 600$ and $\beta = 0.71$. We note that this β value is fairly large, which fits the London–Paris market well. In general, literature suggests that, while β may cover a wide range of values due to the diversity of market characteristics, it is more likely to be relatively large (Ivaldi and Vibes, 2008; Meunier and Quinet, 2012). Based on Adler et al. (2010), estimates of access time to European hub airports and HSR stations are $a_A = 1.5h$ and $a_H = 0.5h$[18]. The parameter a_A also incorporates air travelers' processing time at the airport, that is $pt_A = 1.28h$. This value is obtained as the average of processing times for business and leisure passengers, $pt_A^{business} = 1h$ and $pt_A^{leisure} = 2h$ (Adler et al., 2010), weighted on the number of business and leisure passengers on the London – Paris route, i.e., 28% and 72% respectively (Behrens and Pels, 2012). Air transport travel time is directly derived from transport operators websites, $t_A = 1,28h$[19]. The value of higher frequency for passenger, γ_f, is estimated from Behrens and Pels (2012). By mean of nested (and mixed) multinomial logit models, they estimate direct elasticity of passenger demand with respect to frequency for business and leisure passengers traveling on the London-Paris route. They refer to six airport-carrier pairs (Heathrow-Air France, Heathrow-British Airways, Heathrow-British Midland Airways, Gatwick-British Airways, Luton-EasyJet, and London City-Air France) and the HSR route operated by Eurostar. In our model, the direct elasticity of passenger demand with respect to frequency for mode $i = A, H$, that is $\varepsilon_f^i = (\partial q_i / \partial f_i)(f_i / q_i)$, is equal to $[\gamma_f / (1 - \beta^2)](f_i / q_i)$. Consequently, for each airport-carrier pair and the Eurostar, as well as for each type passenger, we are able to estimate γ_f from the values of elasticity, quantity and frequency in Behrens and Pels (2012). We average those values using the volume of business and leisure passengers as a weight. Finally we average the resulting γ_f values for each mode in order to obtain the final estimation of the value of schedule delay, $\gamma_f = 6$. We compute γ_s as the average (time) value of a unit increase of speed in the range $[250\ kph,\ 279\ kph]$[20]. In particular, γ_s is derived as follows: (i) we compute different values of travel times $v \cdot t_j = v \cdot 380km / s_j$, $\forall s_j \in [250\ kph,\ 279\ kph]$ where $s_{j+1} = s_j + 1$, $j = 1, \ldots, 28$ (ii) we then compute the

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increments of the value of travel times corresponding to a speed increment of 1 kph, i.e., $v\Delta t_j = v(t_{j+1} - t_j)$; (iii) we average the increments of the values of travel times, $v\Delta t_j$.

Turning to the supply side, we distinguish between fixed operating costs per flight (or HSR ride) and variable operating costs per-passenger. We do not have information regarding fixed and variable costs of operating a HSR ride or a flight. we take the expenditure for on board *passenger services and products* as a proxy of (constant) marginal costs per-passenger, that is 6.70% of total operating costs for air transport (Belobaba et al., 2009) and 12.70% for HSR (Shirocca Consulting, 2013) and we refer to the estimations of total operating costs per-seat.

Let us first focus on air transport, the level of airline variable costs per-seat is 40.62€/$seat$, which is derived from the adjusted cost per ASK (available seat per kilometer) reported by IATA (2006), i.e., 10.69c€/ASK, considering a flight travel distance between London and Paris of 380 km (Givoni, 2007). If we consider that the average load factor observed on the route is 70% (Nash, 2009), we obtain a level of airline variable cost per-passenger that is $c_A = (40.62 \cdot 0.067)/0.7 = 3.89$€/$pax$. Consequently, the level of fixed operating costs per vehicle, is $K_A = 40.62 \cdot (1 - 0.067) \cdot 150 = 5685$€/$flight$, where 150 is the average number of seats on the aircraft[21].

We now turn to HSR. First, we estimate the cost of electricity (per-passenger) necessary to increase the average operational speed of the HST of 1 kph, i.e., μ. In order to compute this value we: (i) derive the average energy consumption per kph per-passenger, that is $0.31 kWh/kph \cdot pax$, from Kemp (2004); (ii) refer to the average cost per kWh, 0.1 €/kwh, reported by Eurostat (2013). Under these assumptions, it results, $\mu = 0.031$€/$(kph \cdot pax)$. Second, we estimate the variable costs per-seat. Givoni (2003) provides an estimation of HSR total operating costs of 0.094€ per ASK. The length of the route is 410 km (Fröidh, 2008), therefore the total operating costs are 38.54€/$seat$. Considering that the average load factor observed on the route is 48% for HSR (Givoni, 2003), we obtain the variable costs per-passenger, i.e., $c_H = (38.54 \cdot 0.127)/0.48 = 10.20$€/$pax$. On the other hand, fixed operating costs per HST ride are $\widetilde{K}_H = 38.54 \cdot (1 - 0.127) \cdot 750 = 25234$€/$ride$, where 750 is number of seats in a HSR train on the route. This fixed cost includes electricity costs. Total electricity cost per HST ride is equal to 2790 €/$ride$, and it is derived from μ considering an an average speed on the route of 250 km/h, an average load factor of 48% and 750 seats per vehicle. Therefore fixed operating costs per HST ride net of electricity costs are equal to $K_H = 25234 - 2790 = 22444$€/$ride$

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[21] We refer to a reference number of seats derived from the seat counts for the airplane models used on the route, i.e., A319, A320 and A321, provided by Swan and Adler (2006).

Frequencies are capped by f_i^{max}, where $1 \leq f_i^{max} \leq 30$, with $i = A, H$. Furthermore, the results are provided as a function of s_H^{max}, where $200 \leq s_H^{max} \leq 350$.

Finally, the estimates of aircraft and HSR journey impact on LAP and GHG emissions are provided by Givoni (2007). They are referred to an average operational speed for HSR of 250 kph, and to a load factor of 70% for air transport and of 48% for HSR. We assume that HSR emissions increase linearly with speed, therefore the impact on LAP of the two transport modes – measured by the toxicity factor based on Huijbregts et al. (2000) - is $e_A^{LAP} = 123$ and $e_H^{LAP} = 67.1 \cdot s_H^*/250$. The impact on climate change, measured as CO_2 equivalent units per-passenger, is $e_A^{GHG} = 122084$ and $e_H^{GHG} = 15097 \cdot s_H^*/250$ [22].

5.2 Results and the effects on the environment

We solve decision problem (8) under non-negativity constraints of quantity, frequency, and HSR speed. Moreover, we set upper bounds on the frequencies of the two modes and the average operational speed of HSR. As noted in equation (9), we distinguish between LAP and GHG emissions. Numerical results are provided in Table 2.

=== *Insert Table 2 about here* ===

The results reveal that HSR has always incentive to raise its speed, since the per-passenger cost of electricity necessary to increase the average operational speed of the HST of 1 kph is lower than the passengers' willingness to pay for that marginal increase of speed, i.e., $\mu < \gamma_s$. For similar reason, as expected, the number of air travelers (the number of rail passengers) are decreasing (increasing) in the maximum speed of HSR. In fact, through raising speed, HSR is more attractive to passengers. Although the tougher competition induced by lower product differentiation results in cheaper air tickets, it induces higher train ticket prices, because HSR costs are increasing in speed. However, the negative effect on demand for HSR services due to the increase in prices is offset by the increase in

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[22] These estimations include the impact of the access/egress journeys to/from the airport, while do not account for access/egress for HSR. Heathrow and CDG airports are located at the outskirts of the cities, 24 and 22 km from the city center, respectively, while St. Pancras railway station in London and Gare-du-Nord in Paris (the origin and destination stations of the HST) is closer to the city center. We remark that we model an access time of $a_A = 1.5h$ for air transport and $a_H = 0.5h$ for HSR. Therefore some emissions might be produced when accessing the train station, that is our analysis suits situations in which the mode selected to access the train station produces low emissions (e.g., access by subway or walking). In the cases in which this hypothesis does not hold the environmental impact of HSR entry might be higher than in our analysis, in this sense our measure of the environmental impact of HSR is conservative.

consumers' surplus due to the reduction of the competitive advantage of air transport with respect to the total travel time. Moreover, HSR market share is increasing in δ. Indeed, other things being equal, the more HSR cares about the surplus of the agents in the market, i.e., as δ increases, the lower is the HSR ticket price and the more passengers are diverted from air transport.

Airline frequency is decreasing in δ while HSR frequency increases in δ, since higher frequency induces an increase in consumer surplus that compensates HSR for the corresponding increase in operating costs. Moreover, the frequency of flights (HSR rides) decreases (increases) in the HSR maximum speed, but such decrease (increase) due to s_H^{max} is lower as δ decreases. When HSR is a pure welfare maximizer, it offers higher frequencies (than the case in which it is a pure profit maximizer) and reduces prices in order to increase consumer surplus.

At the equilibrium, we find that HSR entry always induces market expansion, that is $q_M^* - (q_A^* + q_H^*) < 0$, and this effect is increasing in s_H^{max}. Indeed, as the speed increases, HSR is more attractive to passengers and air transport reacts lowering ticket price, which induces a higher number of air travelers. As noted, an increase in δ reduces HSR ticket price. The substitutability between the two travel products makes air transport react lowering p_A^* such that more and more individuals travel at the equilibrium. Empirical evidence confirms theoretical predictions on the traffic generation effect. Data collected after the launch of HSR in Asia and Europe suggest that induced traffic ranges from 6% to 37% of HSR ridership (Givoni and Dobruszkes, 2013). Some estimates related to different periods starting from 1980 indicate that additional traffic generated accounted for 20% on the London-Paris route (Preston, 2009). The share of newly generated demand for the London-Midlands-North UK HS2 project is expected to be 267% higher in 2043 than it is today (Aizlewood and Wellings, 2011).

Our results suggest that the introduction of HSR is always detrimental to LAP. On the contrary, HSR entry always reduces the level of GHG emissions[23]. This results hinges on the trade-off between the *substitution effect* - how many passengers using the HSR are shifted from air transport - and the *traffic generation effect* - how much new demand is generated by the HSR. The introduction of a new mode of travel induces an increase in the total market size and HSR ridership is made up of former airline passengers who shift to the new mode and newly generated demand (e.g., people who did not travel before or people who shift from other transportation modes like traditional rail and automobile)[24]. If

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[23] We refer to the level of maximum achievable average operational speed, $s_H^{max} = 279\ kph$

[24] 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. See also Footnote 8.

the level of pollution emitted by HSR is not sufficiently lower than that of the airline, the gain from shifting former air passengers to a cleaner mode of transport is not able to compensate the amount of pollution due to newly generated traffic. At the equilibrium, $e_H^k q_H^* > e_A^k(q_M^* - q_A^*)$ and competition from the new mode is detrimental to the environment, i.e., $E^k(q_A^*, q_H^*, q_M^*) < 0$.

Figures 3a and 3b show the impact of air transport and HSR competition on the environment for different levels of e_H^k and e_A^k, when $\delta = 1$ and the maximum level of achievable speed is $s_H^{max} = 279 \, kph$[25]. The gray area indicates the set of points (e_A^k, e_H^k) for which $E^k(q_A^*, q_H^*, q_M^*) > 0$, while the white area denotes the values (e_A^k, e_H^k) for whom $E^k(q_A^*, q_H^*, q_M^*) < 0$. The black/white points highlighted in the figures 3a and 3b indicate the reference level of (e_A^k, e_H^k) of our simulation, i.e., the level of e_A^k and e_H^k observed in the London-Paris market, for $L = LAP$ and $K = GHG$. We examine the sensitivity of our results towards the relative values of e_H^k and e_A^k, $k = LAP, GHG$. Figure 3, Panel (a), shows that $E^{LAP}(q_A^*, q_H^*, q_M^*) < 0$, but this result would easily reverse if e_H^{LAP} is mitigated relatively more than e_A^{LAP}. For instance, if e_A^{LAP} is not reduced compared to the reference level $e_A^{LAP} = 86.1$ and e_H^{LAP} is reduced by 46% or more, HSR entry in the market will reduce LAP. On the other hand, Figure 3, Panel (b), shows that $E^{GHG}(q_A^*, q_H^*, q_M^*) > 0$ and this result would reverse only if e_A^{GHG} is mitigated significantly more than e_H^{GHG}. For instance, if e_H^{GHG} is not mitigated, HSR entry in the market would increase GHG only if e_A^{GHG} were reduced by 61% or more.

Overall, our analysis suggests that that the introduction of HSR does not increase either LAP or GHG emissions, when the ratio e_H^k/e_A^k is relatively small. However, when e_H^k/e_A^k increases, that is when HSR becomes increasingly more polluting than the airline, the impact of HSR might be negative.

=== Insert Figure 3 ===

6. Mitigation Strategies and Environmental Policies

Our analysis shows that it is not straightforward to say that the introduction of HSR is beneficial to the environment: the benefits depend on the environmental *friendliness* of HSR. For instance, the operation of electric trains – used on high-speed lines – results in significantly less CO_2 emissions

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[25] When $\delta = 0$ and $\delta = 1/2$ the results of the sensitivity analysis are qualitatively the same. The only difference is that the line $E^k(q_A^*, q_H^*, q_M^*) = 0$ (that is the line that separates the white area from the gray area) slightly shifts, that is the set of values (e_A^k, e_H^k) for which $E^k(q_A^*, q_H^*, q_M^*) > 0$ slightly changes. Similarly if s_H^{MAX} increases (reduces) the main results of the analysis remain unchanged but the area $E^k(q_A^*, q_H^*, q_M^*) > 0$ reduces (expands). All the details of the sensitivity analysis are available at the authors.

than diesel trains, due to greater technical efficiency of electric trains, as well as different operating conditions (fewer stops, i.e., less energy used for acceleration)[26]. However, how much the electric trains are more climate friendly than aircrafts is less straightforward and depends on the scope of the mitigation strategies available to the two modes. Policy measures for emissions' reduction will also affect differently the level of pollution of the two modes. The following sections aim at analysing how these two aspects weigh on the ratio between the emissions of two transport modes and, as a consequence, how the impact of air transport – HSR competition on the environment may change in the long run.

6.1 A comparison between air transport and high-speed rail mitigation strategies

A mitigation strategy refers to a set of actions that limit, stop or reverse the magnitude and/or rate of long-term climate change and local air pollution. Airlines' opportunities to reduce their own environmental footprint include technological efficiency and operational improvements, as well as the use of alternative fuels (Capoccitti et al., 2010; Green, 2009; IPCC, 1999; Lawrence, 2009; Sgouridis et al., 2011; Winchester et al., 2013). In particular, technological efficiency improvements include measures related to the aircraft performance such as:

- improved engine design (e.g., 3D compressor blades);
- changes in propulsion and in-wings span;
- reduced aircraft empty weight through use of lightweight material (e.g., composites);
- reconfiguration of airplane interior.

Historically, engine and aerodynamic efficiency improvements reached 1.5% and 0.4% per year respectively (Lee et al. 2001). Operational efficiency improvements include:

- changes in airlines operations (e.g., use of alternative fuels, limiting the number and weight of baggage), optimization of fuel consumption (e.g., reduction of cruising speed, optimization of climb/descent paths), optimization of ground operations;
- maximization of load factor in order to fill up aircraft seat capacity;
- changes in air traffic control (ATC) operations, such as use of fuel minimizing routes, changes in the altitude of flights, reduction of delays.

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[26] As an example, the reader may refer to ATOC (2007) for some exercises on comparisons of CO_2 emissions from diesel and electric trains operations in the Britain.

Based on estimates from the Intergovernmental Panel on Climate Change (IPCC, 1999), operational efficiency improvements between 6% and 12% could be achieved. Alternative fuels are generally categorized into:

- synthetic fuel also called Fischer Tropsch (FT) fuels;
- biofuels derived from biomass[27].

Sgouridis et al. (2011), by assuming that the proportion of biofuels in total fuel consumption by commercial aviation has been 0.5% in 2009, find that, by 2024, it will rise to 15.5% in a "moderate" scenario, and to 30.5% in an "ambitious" scenario. Under these assumptions, the authors estimate that, by 2024, biofuels will reduce cumulative CO_2 emissions from aviation by between 5.5% and 9.5% relative to their reference case.

As far as HSR transport is concerned, there is general consensus that a potential saving in energy efficiency is achievable both in the short and long term through technological and operational efficiency improvements (Cucala and Cardador, 2011; Gunselmann, 2005; UIC, 2003; US DOT, 2014). HSR technological efficiency improvements include:

- mass reduction, which comprises concepts such as articulated trains with Jacob-type bogies as well as more innovative approaches such as curve-steered single-axle bogies or future suspension technologies based on mechatronics;
- reduction of conversion losses, regenerative braking and energy storage.
- aerodynamics and friction measures such as covering bogies with smooth fairings.

HSR operational efficiency improvements include:

- space utilization (e.g., use of both double-decked and wide-body trains, replacement of locomotive-hauled trains by multiple units so as to increase the number of seats per train length);
- reducing energy consumption for comfort functions, which includes energy used for in-service maintenance of rail rolling stock;

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[27] Biofuels comprise fuels from: (i) sugars, starches, oils or fats, that compete with food production and can have negative environmental impacts such as deforestation (first biofuel generation); (ii) sustainable sources of biomass such as forest residues, industry residues, municipal waste and sustainable grown biomass (second biofuel generation) and (iii) sustainable, non-food biomass sources such as algae, switch grass, jatropha, babassu and halophytes (third biofuel generation) (Capoccitti el al., 2010).

– energy efficient driving, such as reduced standing times in stations, driving advice systems[28], traffic fluidity[29];

– use of flexible trains as to maximize load factor[30];

– improvements in procurement strategies[31].

Though there is a scope for technological and operational efficiency improvements for both the transport modes, airlines have the opportunity to switch to non-conventional jet fuels – and this strategy is independent from the country in which the air carrier operates – while the generation mix for electricity is heavily constrained from the country in which HSR operates (e.g., the availability of electricity sources and dispatch merit rules). As a consequence, although there exist some methods to reduce SO_2 and other gas emissions from power plants – e.g., switching to low-sulfur fuel oil or shifting to natural gas (Chaaban et al., 2004) – the extent to which such strategies may be implemented by HSR is limited.

6.2 The role of environmental policy

The incentives of HSR and air transport to engage in environmental impact mitigation strategies are highly affected by the environmental policies of the countries in which they operate. Two key pieces of legislation for the achievement of the objectives defined within the EU climate and energy package are the EU ETS and the national targets for energy from renewable sources[32]. The EU ETS is a *cap*

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[28] As an example, Deutsche Bahn AG, the German railway company, developed a driving advice system called ESF (Energiesparende Fahrweise). The system gives coasting advices based on track and train data, timetable, position and time. A pilot on ICE 1 and 2 was realized in 2001. An average potential energy saving of over 5 % on German ICE has been confirmed by tests and calculations (UIC, 2003).

[29] A study made by ETH Zürich, Adtranz and SBB in 2000 revealed a considerable influence of traffic situation on energy consumption. Measurements realized on IC-2000 tilting trains running between Luzern and Zurich demonstrated that those trips affected by unexpected stops at signals showed an energy consumption 10 – 15 % higher than unimpeded trips (UIC, 2003).

[30] Growing modularity in German ICE generations provided an example. Whereas ICE 1 in typical formation is a long train with a locomotive ("Triebkopf") on each end, the ICE 2 is a so-called half train with a locomotive at one end and a small driving unit at the other end. Two half trains can be combined to a full train comparable in length to the ICE 1. To a certain extent this vehicle concept allows for an adaptation of train capacity to actual demand. For example on the service Berlin-Cologne the full train (2 half trains) is split up into two half trains which continue on different routes. Similarly, SNCF (Sociètè Nationale des Chemins de Fer Français) has implemented a set of comprehensive decision support systems such as revenue management (*RailRev*) and capacity (seat control) management (*RailCap*). In particular, *RailCap* may suggest the following changes to TGV train capacity: (i) add a second train unit to single-unit trains; (ii) drop empty second train units or open them to reservations on double-unit trains; (iii) open an optional train to reservations and assign it an itinerary-compatible fleet type. Capacity adjustments can be suggested from 15 to three days before the train departure (Ben-Khedher et al., 1998).

[31] For instance, Dutch NS Reizigers, the principal passenger railway operator in the Netherlands, reached an agreement with manufacturers fixing maximum weight as well as a bonus/penalty for each kg of weight reduction/increase beyond that target value. The amount of the bonus is based on the energy cost benefits NS Reizigers realizes as a consequence of the weight reduction (UIC, 2003).

[32] The EU climate and energy package consists of a range of measures adopted by the members of the EU to fight against climate change (EC, 2014a). The plan was launched in March 2007, and after months of tough negotiations between the member countries, it was adopted by the European Parliament on December 2008. The package focuses on emissions

and trade system for GHG emission[33]. The scheme covers more than 11,000 power stations and manufacturing plants in the 28 EU member states together with Iceland, Liechtenstein and Norway. Since 2013, auctioning is the main method used to allocate emission allowances to the sectors[34]. By associating, through the market, a financial value to each tonne of emissions, the scheme produces a twofold effect: on the one hand, it incentivizes power plants operators to invest in technologies that cut emissions; on the other hand, it makes the marginal cost of electricity generation from *green* sources relatively more competitive than that of carbon intensive technologies. This beneficial effect for the environment is further enhanced by reinvesting at least half of the funds raised from the emission allowance auctions in projects aiming to combat climate change.

The system does not directly cap emission from HSR, but it limits the emission of the electricity power sectors and, thus, indirectly affects HSR impact on the environment. In particular, EU countries have explicitly committed to targets for generation through renewable energy sources and have been promoting a *green shift* through incentive programs for renewables[35]. Overall, these measures are driving the reduction of emissions from the electricity power sector and this is resulting in HSR emission reduction. For instance, in the period 2001-2007 installed capacity for electricity generation from renewables grew by 96% in EU member states (Eurostat, 2013). Meanwhile, aviation has been directly included in the EU ETS since January 2012. The scheme covers flights operated on routes to and/or from the airports located in the 28 EU member states as well as Iceland, Liechtenstein and Norway but does not cover flights operated on routes to and/or from the airports located in non-European countries[36]. Participation in the EU ETS gives the airlines the option to comply with the emission cap in different ways: (i) reduce emission by themselves; (ii) buying additional allowances on the market from other sectors; (iii) investing in emission-reduction projects within the Kyoto

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cuts, renewables and energy efficiency and comprises two more (complementary) pieces of legislation: national targets for non-ETS emissions and a directive for the environmentally safe use of carbon capture and storage technologies.

[33] The EU ETS is a market-based measure for emission reduction that sets a EU-wide cap for the overall emissions from industry sectors included in the scheme. The cap is reduced every year. Within this cap, companies can buy and sell emission allowances as needed. It was launched in 2005 and it is now in its third phase, running from 2013 to 2020. The first phase covered the period 2005-2007 and the second phase the period 2008-2012. The GHGs covered by EU ETS are carbon dioxide emissions from power and heat generation, civil aviation, energy-intensive industry sectors like oil refineries, steel works and production of iron; nitrous emission from production of nitric, adipic, glyoxal and glyoxlic acids; perfluorocarbons from aluminium production.

[34] Auctioning should be the only method for emission allocation by 2027. The 2013 cap for emissions from power stations and other fixed installations has been set at 2,084,301,856 allowances and the total number of allowances allocated decreases by 1.74% each year.

[35] Directive 2009/28/EC on Renewable Energy requires Member States to submit national renewable energy Action Plans by 30 June 2010. Each Member State plan describes a roadmap to reach the 2020 targeted share of renewable energy of their final energy consumption. The most commonly used incentives are feed-in tariffs, feed-in premiums, quota obligations, tax exemptions, tenders, and investment aid. See EC (2013) and Kitzing et al. (2012) for further details on the evolution of support schemes for renewables.

[36] See Yuen and Zhang (2011) and Wan and Zhang (2010, 2012) for an analysis of the implications of regulating emission from the aviation sector within a scheme that is not implemented at global level.

protocol. In 2012, 7.9 billion allowances were traded with a total value of €56 billion, i.e., the average price for allowances was 7.09 € per tonne of CO_2 EC (2014,b).

In this context, it is important to note that the market price of allowances is expected to be lower than the price of fuel (especially biofuels), while it is higher than the cost of some power plants energy inputs. Furthermore, aviation costs for emission abatement are expected to be very high compared to other sectors included in the EU ETS. Thus, airlines may have incentive to buy allowances from other industries rather than to pursue an abatement effort in order to reduce its emissions (see Anger and Köhler, 2010).

This is a crucial argument to take into account when evaluating the environmental impact of air transport and HSR competition, since the allowances market may affect the input costs of the two modes of transport differently. On the aviation side, the price of allowances will increase airlines costs, whether they decide to pursue a mitigation strategy or to buy allowances from other industries, but that increment is not expected to be high[37]. Conversely, on the HSR side, the climate and energy package may result in lower cost of energy in the long run. Indeed, as the electricity generation technology shifts toward renewable resources, the average cost of input reduces (e.g., the marginal cost of electricity generation from photovoltaic or wind is close to zero) and the presence of power plants directly connected to the distribution grid (distributed generation) grows. As a consequence, reinforcements of existing networks might be deferred (distributed generation is located close to consumers, and the net demand to be supplied through electricity grid may decrease)[38]. Overall, the EU climate and energy package may result in a reduction of GHG emissions depending on the marginal cost of abatement in all the industries subject to ETS and the evolution of aviation cap and trade mechanisms in the future.

7. Conclusions

In this paper, we build a duopoly model to shed light on the environmental impact of introducing HSR as a competitor to air transport, capturing the effects of induced demand, schedule frequency

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[37] For estimations of the impact of ETS costs on airfares, see Anger and Köhler (2010) as well as Brueckner and Zhang (2010).

[38] The evaluation of the impact of renewables on the cost of electricity is actually controversial. In the short run, the cost of incentives to renewables and the need of investment in distribution networks to accommodate their entry push the price of the electricity upward. Similarly, generation from some renewables (e.g., wind and solar power) is tied to the availability of their resources, therefore their generation pattern is variable. The variability requires higher flexibility of despatchable power plants (that have to ensure that demand matches supply at any given time) and this can raise their operational cost as they do not run at their optimal efficiency level. Overall, the impact of renewables on the system depends on timing and coordination of production from renewables, the investment cycles in the grid and the regulatory framework (Cossent et al., 2009; IEA, 2013). Nevertheless, the investment deferral in network reinforcement and expansion and the lower cost of input might offset the cost increase in the long run.

and HSR speed simultaneously. We conduct a simulation study, based on the London-Paris market where HSR has served 70% of the market, in order to measure the environmental implications of air-rail competition on LAP and GHG emissions. We show that competition between the two modes may be detrimental to the environment depending on the *magnitude* of the environmental impact of HSR relative to air transport. In particular, we find that the introduction of HSR is detrimental to LAP, while it is beneficial to GHG emissions. We also examine the sensitivity of this result towards the ratio between HSR and air transport emissions and the weight of welfare relative to profits in the HRS objective function. We find that HSR entry increases neither LAP nor GHG emissions when the ratio between HSR and air transport emissions is relatively low. However, competition is more likely to be detrimental to the environment when such emissions ratio increases, or when the weight of the social welfare in HSR objective function is high.

The implication of this research on the transportation field is two-fold. First, some transport policy recommendations, which have focused mainly on the *greenness* of HSR, may have led to a bias amongst regulators when considering future transport policies. Our results show that competition between the two modes may be detrimental to the environment depending on market expansion, modal shift and market size, as well as on the magnitude of the environmental *friendliness* of HSR relative to air transport. Second, how much the electric trains are more environmental friendly than aircrafts is not straightforward and depends on the scope of the mitigation strategies available to the two modes and on the policy measures for emissions reduction, which will affect the pollution of the two modes differently. Since the magnitude of the environmental *friendliness* of HSR hinges on the mix of energy sources used to generate the electricity (which is heavily constrained by the country in which HSR operates), regulators should assess the implications of HSR entry taking into account the energy policy (e.g., targets for renewable energy sources) and efficiency technologies/mitigation strategies of transport modes.

The paper has some limitations that need to be taken into account when looking at policy implications. First, we assume homogenous customers. Second, the parameters of the model are estimated based on data that are specific to the London-Paris route. The paper has also raised some avenues for further research. First, we have considered the case of a single airline and a single HSR operator. In reality, with respect to the airline industry, more firms may compete in the market. Extending the analysis to a framework with more competitors would be an insightful future study. Second, phases other than operation in the HSR life-cycle analysis (construction/production, maintenance and disposal) can be responsible for significant environmental impact. The effects related 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 modal competition on environment when capacity investments in building a new line are considered.

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Appendix

In this section, we analyse a benchmark case of a monopoly airline serving the O-D link. Travelers maximize a (strictly concave) quadratic utility function, $U(q_M) = \alpha q_M - (1/2)q_M^2$, where α measures the willingness to pay for the travel and q_M is the number of air passengers (the subscript M stands for the monopoly case). The inverse demand with respect to the full price in the market served by the monopoly airline is $\theta_M(q_M) = \alpha - q_M$. Finally, let p_M denote the air ticket price charged by the monopoly carrier. The monopoly airline decided the number of travelers and the frequency of the service. Full price is $\theta_M = p_M - \gamma_f f_M + v\tilde{T}_A$, where f_M is the schedule frequency. The inverse demand function with respect to the airline ticket price can be easily obtained: $p_M(q_M, f_M) = \alpha - v\tilde{T}_A - q_M - \gamma_f f_M$. Turning to the supply side, the profit of the carrier can be written as $\pi_A(q_M, f_M) = [p_M(q_M, f_M) - c_A]q_M - k_A f_M$. The carrier decides on the level of passengers and the frequency of service and solves the following decision problem:

$$max_{q_M, f_M} \ \pi_M(q_M, f_M) = [p_M(q_M, f_M) - c_A]q_M - k_A f_M$$
$$\text{s.t. } q_M \geq 0$$
$$f_M \geq 0 \tag{a.1}$$
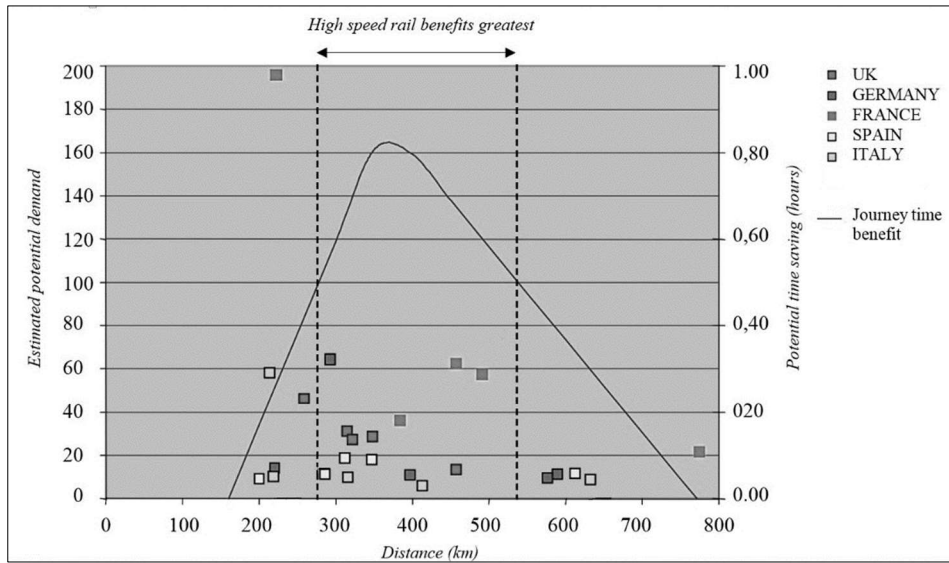$$f_M \leq f_A^{max}$$

List of Figures

Figure 1. The potential demand for and benefits of HSR. Source: adapted from SDG (2004).
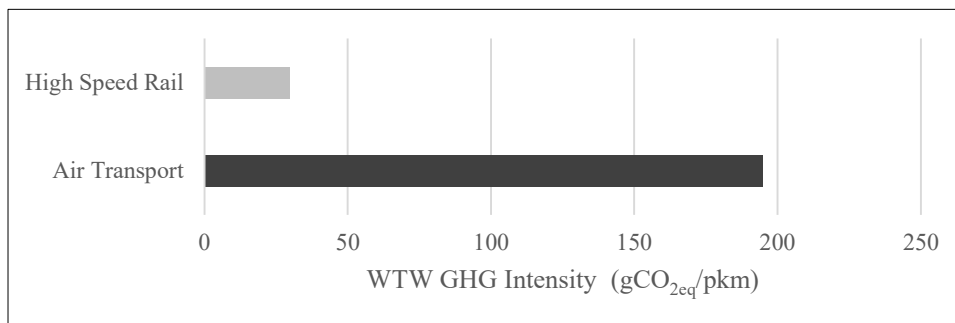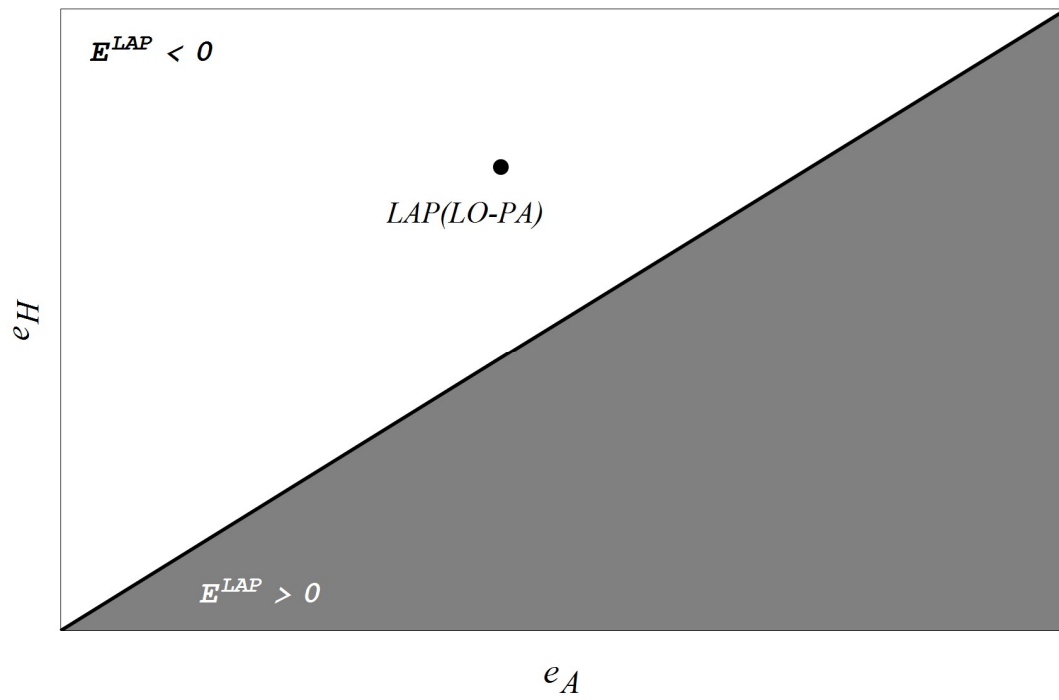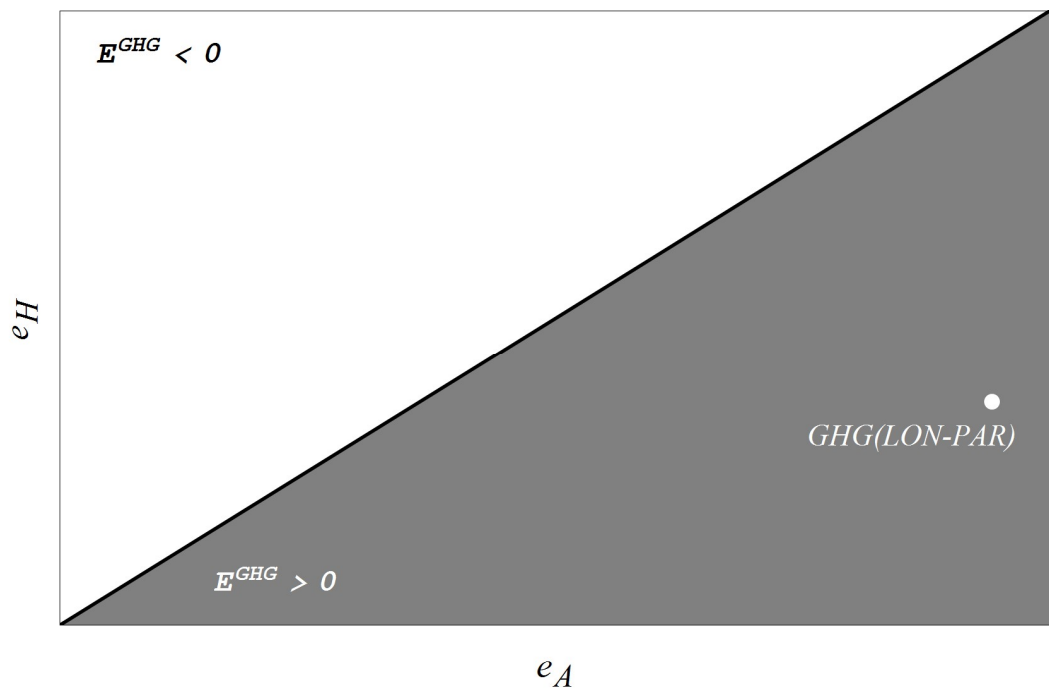

Figure 2. GHG benefits of railway versus air transport per passenger-km, EU average. Source: adapted from Railway Handbook 2012.

(Panel a)

(Panel b)

Figure 3 Sensitivity analysis with respect to e_H/e_A of the environmental impact of HSR impact when $\delta = 1$.

List of Tables

Parameters estimation		
α	600	
β	0.71	
	i=**A**	i=**H**
$e_i^{GHG} g\ CO2/seat$	122084	15097 $s_H^*/250$
$e_i^{LAP} tox/seat$	123	67.01 $s_H^*/250$
γ_f	6	
γ_s	0.3	
$\mu[€/(kph*pax)]$	0.031	
$v\tilde{T}_i[€]$	149.8	21.05
$c_i[€/pax]$	3.89	10.20
$K_i[€/(flight\ or\ ride)]$	5685	22444

Table 1 Parameter estimations for numerical analysis.

	Results		
q_M^*	212.72		
p_M^*	245.99		
f_M^*	1.42		
π_M^*	43439.3		
	$\delta = 1$	$\delta = 0.5$	$\delta = 0$
q_A^*	0	$102.26 - 0.08\,s_H^{max}$	$137.53 - 0.06\,s_H^{max}$
q_H^*	$568.99 + 0.27\,s_H^{max}$	$328.36 + 0.22 s_H^{max}$	$232.98 + 0.16 s_H^{max}$
p_A^*	$67.27 - 0.19\,s_H^{max}$	$139.95 - 0.08 s_H^{max}$	$173.81 - 0.06 s_H^{max}$
p_H^*	$35.56 + 0.03 s_H^{max}$	$201.67 + 0.14 s_H^{max}$	$271.24 + 0.19 s_H^{max}$
f_A^*	0	$0.68 - 5.43 \cdot 10^{-4} s_H^{max}$	$0.92 - 3.85 \cdot 10^{-4} s_H^{max}$
f_H^*	$0.76 + 3.64 \cdot 10^{-4} s_H^{max}$	$0.44 + 2.94 \cdot 10^{-4} s_H^{max}$	$0.31 + 2.08 \cdot 10^{-4} s_H^{max}$
s_H^*	s_H^{max}	s_H^{max}	s_H^{max}
π_A^*	0	$10039.20 - 15.99 s_H^{max} + 6.37 \cdot 10^{-3} s_H^{max\,2}$	$18157.60 - 15.26 s_H^{max} + 3.21 \cdot 10^{-3} s_H^{max\,2}$
$(1-\delta)\pi_A^* + \delta W^*$	$159278.27 + 153.06 s_H^{max} + 0.04 s_H^{max\,2}$	$99550.9 + 93.65 s_H^{max} + 0.03 s_H^{max\,2}$	$53844.70 + 72.23 s_H^{max} + 0.02 s_H^{max\,2}$
$q_M^* - q_A^* - q_H^*$	$-356.27 - 0.27 s_H^{max}$	$-217.89 - 0.14 s_H^{max}$	$-157.79 - 0.098 s_H^{max}$
E^{GHG}	$2.6 \cdot 10^7 - 34.36 \cdot 10^3 s_H^{max} - 16.51 s_H^{max\,2}$	$1.35 \cdot 10^7 - 98.86 \cdot 10^2 s_H^{max} - 13.30 s_{max}^2$	$9.18 \cdot 10^6 - 70.14 \cdot 10^2 s_H^{max} - 9.43 s_H^{max\,2}$
E^{LAP}	$26.16 \cdot 10^3 - 152.67 s_H^{max} - 0.07 s_H^{max\,2}$	$13.59 \cdot 10^3 - 78.09 s_H^{max} - 0.06 s_{max}^2$	$92.48 \cdot 10^2 - 55.41 s_H^{max} - 0.04 s_H^{max\,2}$

Table 2. Results of the numerical analysis.